Water-Energy-Food Nexus

Principles and Practices

P. Abdul Salam, Sangam Shrestha,
Vishnu Prasad Pandey, and Anil Kumar Anal
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PREFACE

Water, energy, and food are the vital resources that sustain life as well as global, regional, and national economies. The three resources share a lot in common, are interlinked in many ways, and actions in one sector could inadvertently affect the other sectors. Exacerbating demands of the three resources combined with concerns over environmental and climate change presents a set of scientific, policy, and management issues that are critical for achieving the 2030 agenda of "Sustainable Development Goals (SDGs)." It was acknowledged in the Bonn 2011 Conference that the term "nexus," which reemerged as the "new kid on the block" of development disclosures, can best describe the interconnections between the three resources. Since then, it has become a highly debated topic in most of the international fora. However, these fora are mostly focused on the "water-energy" or "water-food" or "energy-food" domain. To get the real benefit of the nexus approach in terms of resource use efficiency, it is necessary to understand, operationalize, and practice the nexus of all the three resources, that is, water-energy-food (WEF). However, there is a limited knowledgebase and few publications in this arena. In this context, this book attempts to contribute to the global debate on the WEF nexus through knowledgebase generation.

This single-volume peer-reviewed book covers the theoretical and/or conceptual aspects of the WEF nexus, ways to overcome operational challenges of the nexus approach of the resources management, cases of the nexus in practice from different regions of the world, and opinions on the future of the nexus agenda. The book is divided into 4 sections and 19 chapters. They are contributed by notable authors from different parts of the world who are at the forefront of the nexus agenda.

Because the multidisciplinary nature of the book covers interconnections and management of the three key resources (water, energy, and food) it will be relevant to a broad audience in environment and earth sciences. In addition, it could be an excellent reference for students, scholars, and professionals in the field of sustainability science, international development, natural resources management, and ecological economics. The book can benefit a wide range of readers with a keen interest in interdisciplinary research on resources management. These could include, but are not limited to, students, research scholars, practitioners, I/NGOs, donor agencies, UN agencies, policy-makers, and decision-makers.

We would like to acknowledge that this book is one of the outputs of the SEA-EU-NET Project (Phase-II), which was funded under the Seventh Framework Programme (FP7) of the European Union (EU). This publication was possible due to highly dedicated contributions from 41 contributing authors, 39 anonymous reviewers, representatives of the publisher, and direct/indirect helping hands of members at the Asian Institute of Technology (AIT).

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ACRONYMS AND ABBREVIATIONS

ADB	Asian Development Bank
ADPJ	Agriculture Development Project Janakpur
AIT	Asian Institute of Technology
AMD	Acid Mine Drainage
APE	African Points of Excellence
BCM	Billion Cubic Meters
BINA	Bangladesh Institute of Nuclear Agriculture
BRRI	Bangladesh Rice Research Institute
BUREC	US Bureau of Reclamation
CA	California
CC	Climate Change
CVP	Central Valley Project
DoNRE	Department of Natural Resources and Environment
DPSIR	Drivers, Pressures, State, Impact, and Response
DTWs	Deep Tube Wells
DWR	Department of Water Resources
EC	Electric Conductivity
EPI	Environmental Policy Integration
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
GCC	Gulf Cooperation Council
GCMs	Global Circulation Models
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
GHG	Greenhouse Gas
GIS	Geographic Information System
HP	Horsepower
HW	Healthy Waterways
ICIMOD	International Center for Integrated Mountain Development
ICSU	International Council for Science
IDA	International Development Aid
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
IISD	International Institute for Sustainable Development
ILO	International Labor Organization
IMF	International Monitory Fund
INATE	International Network for Advancing Transdisciplinary Education
INRM	Integrated Natural Resource Management
IPM	Integrated Pest Management
IR	International Relations
IRENA	International Renewable Energy Agency
IRRI	International Rice Research Institute
IUCN	International Union for the Conservation of Nature
IWA	International Water Association
IWRM	Integrated River Basin Management
kcal	Kilo Calorie
kWe	Kilowatt Equivalent
kWh	Kilowatt Hours
L	Liters
LEAP	Long-range Energy Alternatives Planning System
m^3	Cubic Meters
MAR	Mean Annual Runoff
mbgl	Meters Below Ground Level
MBIs	Market-Based Instruments
MCM	Million Cubic Meters
MDF	Mediterranean Development Forum
MDGs	Millennium Development Goals
MERFI	Mekong Region Futures Institute
MG	Million Gallons
MJ	Mega Joule
ML	Mega Liters
MLD	Million Liters a Day
MNC	Multi National Cooperation
MRB	Mekong River basin
MWh	Megawatt Hour
NBI	Nile Basin Initiative
NGO	Nongovernmental Organization
NSVC	Nepal Solar Volunteer Corps
ODA	Official Development Assistance
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPT	Occupied Palestinian Territories
PES	Payment for Ecosystem Services
PIIP	Priority Infrastructure Investment Project
PJ	Peta Joule
PVC	Photo Voltaic Cells
RBF	Riverbank Filtration
RDP	Rural Development Programme
RMS	Resource Management Strategies
SALT	Southern African Large Telescope
SAP	Structural Adjustment Programmes
SAWS	San Antonio Water System
SDGs	Sustainable Development Goals
SE4ALL	Sustainable Energy for All
SEI	Stockholm Environment Institute

SG	Stakeholder Group
SHG	Self-Help Group
SKA	Square Kilometer Array
STI	Science, Technology, and Innovations
STWs	Shallow Tube Wells
SWP	State Water Project
TDH	Total Dynamic Heads
TVA	Tennessee Valley Authority
TWh	Terawatt Hours
U.S.	United States
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNCECAR	University Network for Climate and Ecosystem Change Adaptation Research
UNCLOS	United Nations Convention of the Law of the Seas
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNESCAP	United Nations Economic and Social Commission
UNFCCC	United Nations Framework Convention on Climate Change
UNU-FLORES	The United Nations University Institute for Integrated Management of Material Fluxes and or Resources
UNU-ISP	United Nations University, Institute for Sustainability and Peace
UOG	Unconventional Oil and Gas
USAID	United States Agency for International Development
VDC	Village Development Committee
WB	World Bank
WCED	World Commission on Environment and Development
WCRP	World Climate Research Programme
WEAP	Water Evaluation and Planning Model
WEF	Water-Energy-Food
WWC	World Water Council
WWF	Worldwide Fund for Nature
WWTP	Wastewater Treatment Plant

Section I
Understanding the Nexus

1

The Need for the Nexus Approach

P. Abdul Salam[1], Vishnu Prasad Pandey[2], Sangam Shrestha[3], and Anil Kumar Anal[4]

ABSTRACT

The water, energy, and food resources share a lot in common; they have strong interdependencies and are inadvertently affected by action in any one of them. Therefore, the nexus approach (integrated policies related to water, energy, and food) is required in the face of growing concerns over the future availability and sustainability of these resources. The nexus approach can help achieve at least some of the "Sustainable Development Goals (SDGs)" (e.g., SDG 2, 6, 7, 12, 13, 15). This chapter discusses trends in availability and consumption of the three key resources (i.e., water, energy, and food) and interactions between them, and finally provides some reasons why the nexus approach can help achieve social and economic development goals.

1.1. INTRODUCTION

The water, energy, and food resources share a lot in common, including inaccessibility to billions of people, rapidly growing demand, strong interdependencies with climate change, different regional availability, and variations in supply and demand [*Bazilian et al.*, 2011; *Walsh et al.*, 2015]. Apart from the similarities, there is a growing sense of awareness of the linkages among water, energy, and food sectors (Figure 1.1) and that the actions in one sector would inadvertently affect one or both of the other sectors. The growing population, rapid economic growth, and changing consumption trends has increased the urgency to act through the utilization of integrated approaches that encompasses all three sectors. This ensures that there is a proper balance among the different user goals and interests while at the same time protecting the ecosystem.

It was acknowledged at the Bonn 2011 Nexus Conference that integrated policies related to water, energy, and food are required in the face of growing concerns over the future availability and sustainability of these resources. The continuation of isolated policies which are predominant in developing countries will unavoidably affect other sectors and eventually lead to the acceleration of ecosystem degradation. Hence, a better understanding of the strong linkages and trade-offs with respect to the water-energy-food (WEF) nexus is important for sustainable long-term development growth as well as for human well-being. A nexus approach is based on three guiding principles [*Bonn 2011 Conference*, 2011]:

1. Placing people and their basic human rights as the basis of the nexus
2. Creating public awareness and the political will for successful implementation
3. Involving local communities in the planning and implementation processes in order to create a sense of participation and ownership

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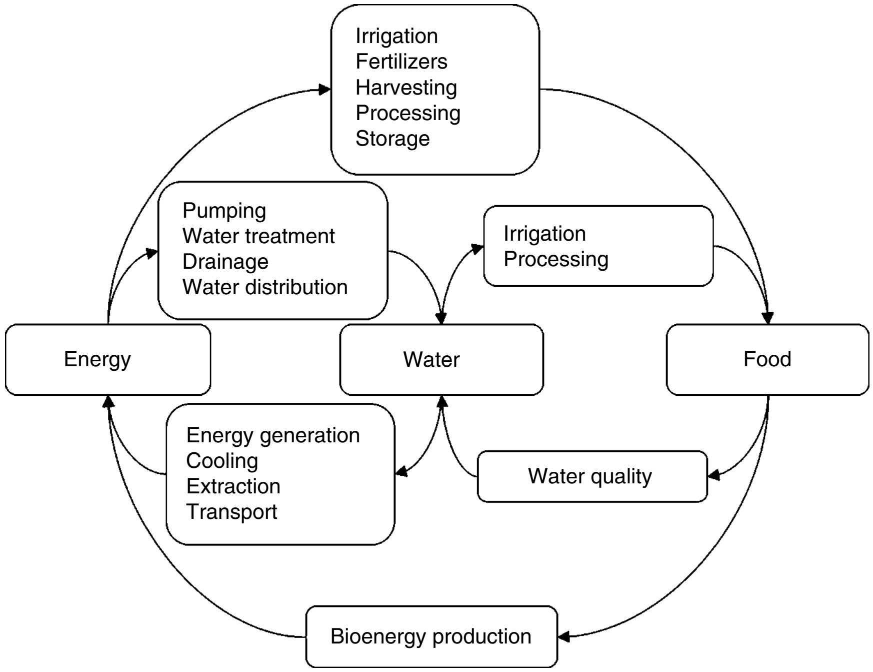

Figure 1.1 Interactions of the water-energy-food nexus. Source: *IRENA* [2015], "Renewable Energy in the Water, Energy & Food Nexus."

The practical implementation is proven as difficult mainly due to the vastness of the individual sectors, the multidimensional interlinkages among the sectors, and the fact that stakeholders in all disciplines and at all levels need to be involved. In addition, significant financial investment would also be required in the restructuring of existing infrastructure to suit the nexus approach. The development of robust analytical tools, conceptual models, and robust data sets which can be used to supply information on the future use of energy, water, and food is vital toward making the WEF nexus a reality [*Bazilian et al.*, 2011].

The Sustainable Development Goals (SDGs) have set targets for each of the nexus sectors explicitly under SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 7 (affordable and clean energy). In order to satisfy the stipulated goals, a shift to more sustainable production and consumption patterns (SDG 12) will be required while tackling climate change (SDG 13) and ensuring a balance in ecosystem both on land and water (SDG 14 and SDG 15). The interconnection between the SDGs emphasizes the need for a nexus approach in achieving the individual goals.

1.2. AVAILABILITY AND CONSUMPTION TRENDS OF THE NEXUS COMPONENTS

The growing demand for water, energy, and food are driven by common factors: population growth and mobility, sustainable development, international trade, urbanization, changing lifestyles, cultural and technological changes, and climate change [*FAO*, 2014]. The exploitation of more resources will definitely be required to meet the growing demand. However, it is possible to slow down this growing demand by reducing wastage and loss incurred in the water, energy, and food stream, which would also help in saving embedded resources during production and reducing environmental impacts. Reduction of water and energy through conservation and efficient use will be crucial in the coming decade.

1.2.1. Water

The world has enough freshwater to supply the global demand but nonuniform distribution of these reserves and other reasons have led to shortages in certain locations. The United Nations (UN) estimates indicate that there are 1.2 billion people living in areas of physical water scarcity and another 1.6 billion people facing economic water shortage [*Walsh et al.*, 2015]. In terms of water quality, there are 748 million people who lack access to an improved drinking water source [*UNESCO*, 2015]. The shortage in both quantity and quality may likely spread and become more acute due to growing demands, unsustainable withdrawal rates, degradation of source water quality, and changing climate patterns. Understandably, the main impact of water shortage is on direct human consumption but other indirect impacts include those on energy supply, food production, and ecosystem.

Traditionally, the expansion of water resources mainly depended on the need of the expanding population for food, clothing, and modern energy. More recently, the rising standards of the middle-income group has led to sudden and sharp increases in the water consumption in both production and use. Economic growth coupled with higher living standards could be the reason that the growth of water demand is double that of population growth in the twentieth century.

The global water withdrawals in 2009 stood at 4500 billion m^3 (BCM) of which 70% was used for agriculture, 17% for industry, and 13% for municipal and domestic purposes [*2030 Water Resources Group*, 2009]. According to the *2030 Water Resources Group* [2009], the projected demand of 6900 BCM in 2030 under the business-as-usual scenario is 40% more than the currently assessed water supplies (ground and surface) that are accessible, reliable, and sustainable. In another report by UN Water, the water demand is projected to increase by around 55% in 2050, which will mainly be attributed to growing demands in the manufacturing sector, thermal power plants, and domestic use [*UNESCO*, 2015].

The gap between future availability and demand can be closed not through the discovery of more water supplies but through effective demand-side management, which will definitely need effective policy interventions.

1.2.2. Energy

Energy demand is increasing primarily due to drivers like growth in population and gross domestic product (GDP). Though there are diverse sources of energy, fossil fuels are expected to continue as the dominant fuel source and would account for almost 80% of the total energy supplies in 2035 [*BP*, 2016]. Gas is expected to gain popularity along with renewable energy though the share of the latter would still be below 10% in 2035. On the other hand, coal will exhibit a decreasing trend while oil remains steady. The additional energy demand will come from growing and emerging economies while Organization for Economic Cooperation and Development (OECD) countries will hardly show any growth. Apart from the need of energy to support the increased GDP in the developing countries, the push for global electrification will drive the steady growth for power generation. China will be a key player in the future energy demand as Figure 1.2 indicates that they will move toward a more sustainable rate compared to the past.

Most energy projections by various organizations follow the trend as depicted in Figure 1.2. There are international initiatives which look at reducing the demand and dependency on fossil fuels. One such initiative is the Sustainable Energy for All (SE4ALL), which was launched by the UN Secretary-General in 2011. The SE4ALL has set three main objectives to be achieved by 2030: ensure universal access to modern energy services, double the global rate of improvement in energy efficiency, and double the share of renewable energy in the global context.

1.2.3. Food

There are concerns on whether the world would be able to produce enough food for the growing population. The amount of arable land and water required for agriculture is declining and at the same time has to compete with urbanization and industrialization for the same resources. The most popularly used indicator for measuring and monitoring the world food status is food consumption in kcal/person/day. The world average per capita availability

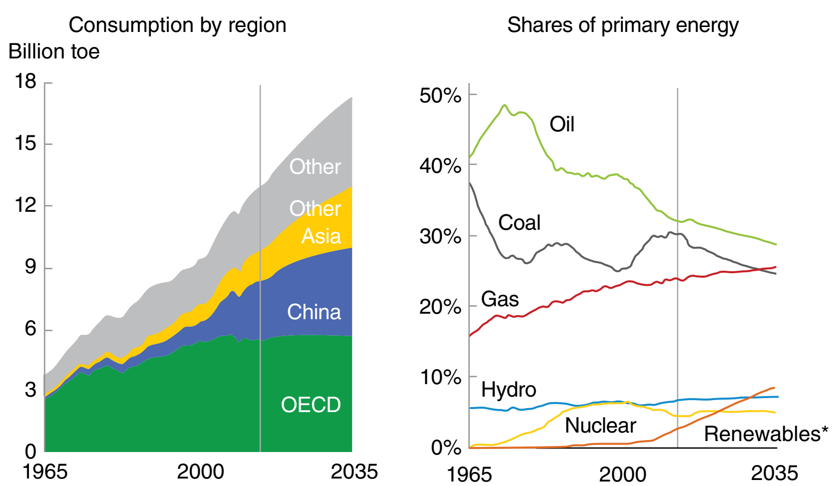

Figure 1.2 Projected growth in energy consumption. Toe is ton equivalent. * includes biofuels. Source: Reproduced with permission of *BP* [2016]. (*See insert for color representation of the figure.*)

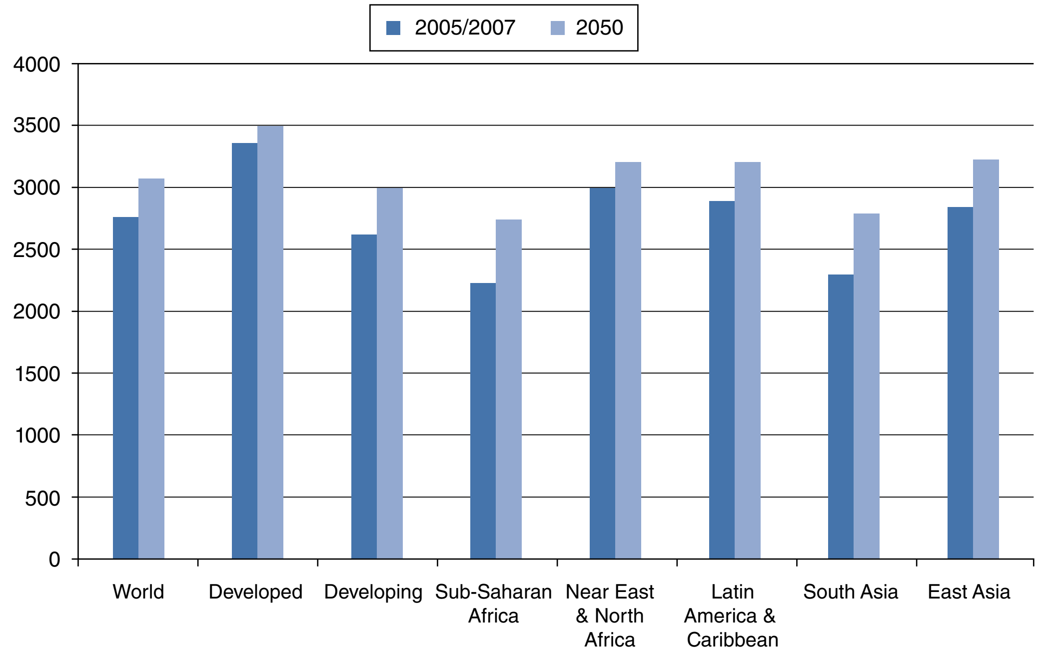

Figure 1.3 Per capita food consumption (kcal/person/day). Source: *Alexandratos and Bruinsma* [2012]. Reproduced with permission of FAO.

of food for direct human consumption was 2770 kcal/person/day in 2005/2007 (Figure 1.3). This world average is, however, misleading as there are areas where the value falls below 2500 kcal and other areas where it is way above 3000 kcal.

By 2050, food production in the global context and for developing countries will need to be increased by 60 and 100% respectively from 2005/2007 figures [*UNESCO*, 2015]. This translates into a 1.1% annual growth rate increment of total world consumption [*Alexandratos and Bruinsma*, 2012]. The projected values in million tons for some of the major food groups with respect to 2005/2007 figures are illustrated in Figure 1.4. The drivers for increase will mainly result from increasing population and income as well as structural changes in diet (i.e., shifting to a meat-based diet) and overnutrition.

1.3. SECTORAL INTERACTIONS

Water, energy, and food are interlinked in many ways. Water is required to produce energy and food. Energy is required to produce water and food. Food can be a source of energy (e.g., biofuel). Therefore, action in one sector will have implications on the others.

1.3.1. Water–Energy Interactions

The water intensity in the energy sector varies depending on the choice of technology, source of water, and type of fuel. Water is used for the production of fuels originating from fossils, growing of biomass-related fuel stocks, and generation of energy (e.g., electricity from fossil fuels). Thermal power plants utilize large amounts of water for cooling, of which a fraction is lost to evaporation depending on the type of cooling system employed. On the other hand, hydropower plants utilize a large area, which in turn increases the surface area of the water body, further facilitating evaporation. In 2010, energy production accounted for 15% (580 BCM of water annually) of global freshwater withdrawals, of which 66 BCM was consumed [*Walsh et al.*, 2015]. In the United States, power plants account for the largest share (41%) of freshwater withdrawal [*Union of Concerned Scientists*, 2010]. The global energy demand is projected to increase by 35% in 2035, which would increase water withdrawal in the energy sector by 20% and water consumption by 85% [*IRENA*, 2015]. The life cycle water consumption (gallons/MWh) for some selected electricity generation technologies is illustrated in Figure 1.5.

Renewable energy is very slowly replacing fossil fuels, especially in the power sector, but it is still projected that 75% of the expected energy increase by 2030 will be from fossil fuels [*ADB*, 2013]. Renewable energy alternatives may be climate-change-friendly but may not be favorable when considering water and land requirements. As illustrated in Figure 1.6, the water requirement for biofuel production is much higher than that required for fossil-fuel-based products. The promotion of biofuels in the

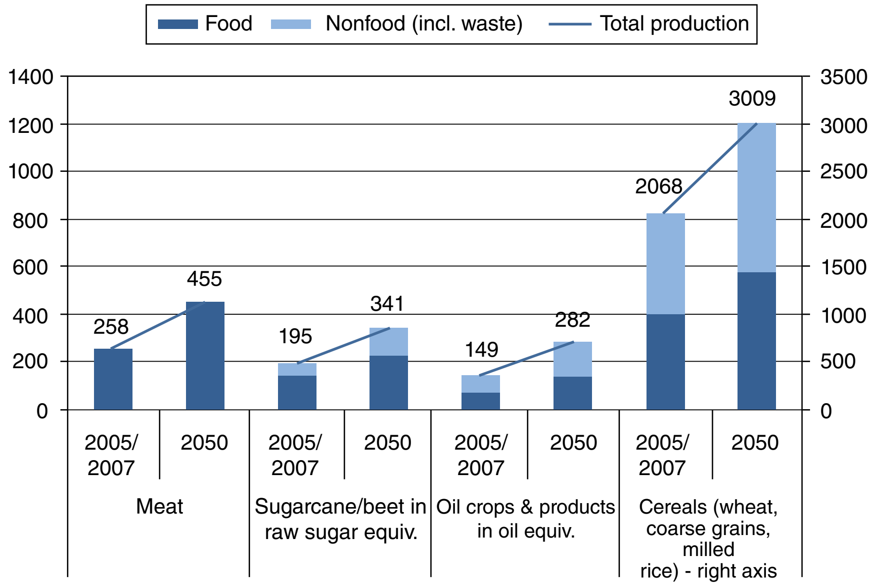

Figure 1.4 World production and use of major agricultural products (million tons). Source: *Alexandratos and Bruinsma* [2012]. Reproduced with permission of FAO.

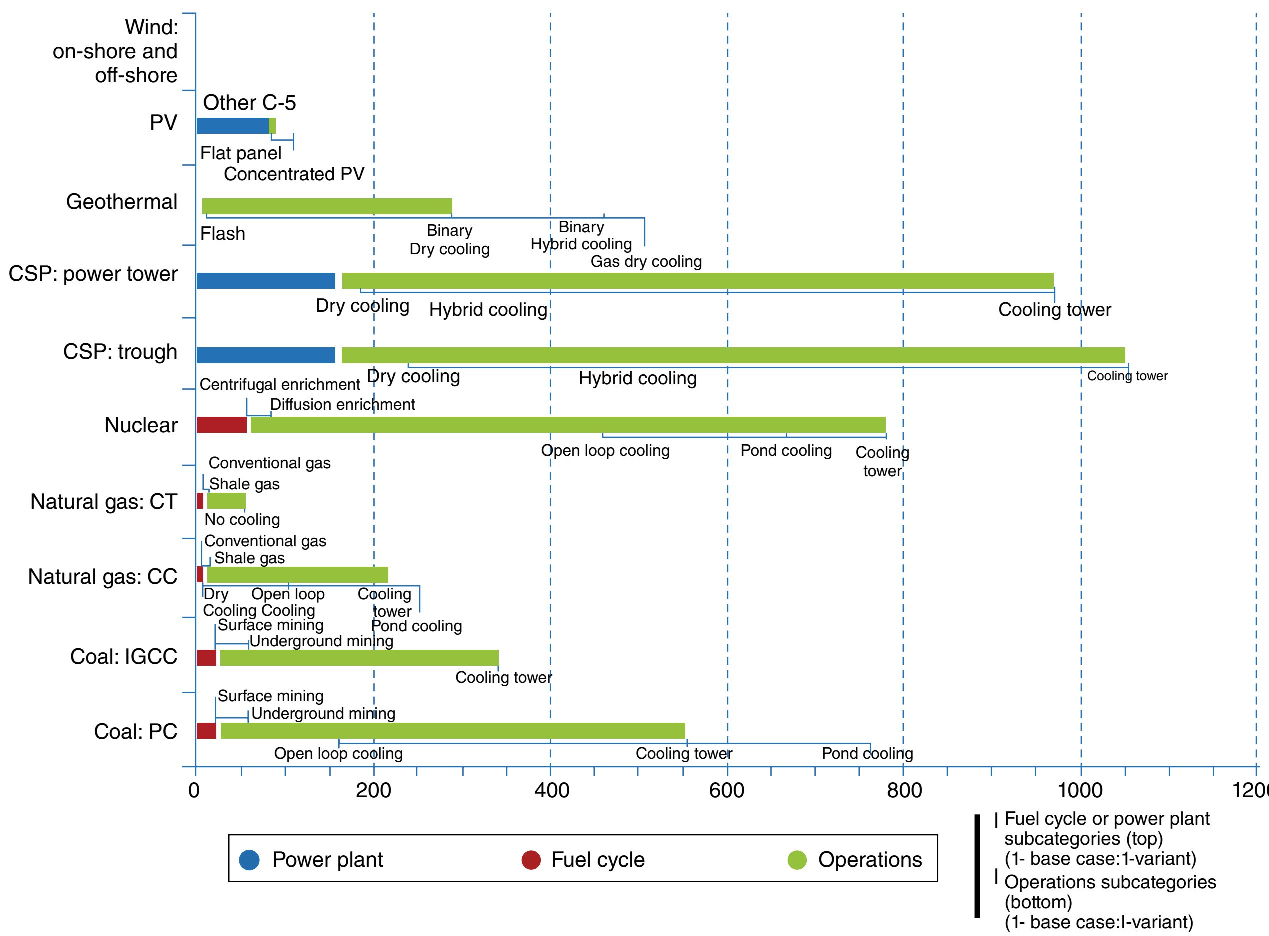

Figure 1.5 Life cycle water consumption for selected electricity generation technologies (gal/MWh). Source: *IRENA* [2015], “Renewable Energy in the Water, Energy & Food Nexus.”

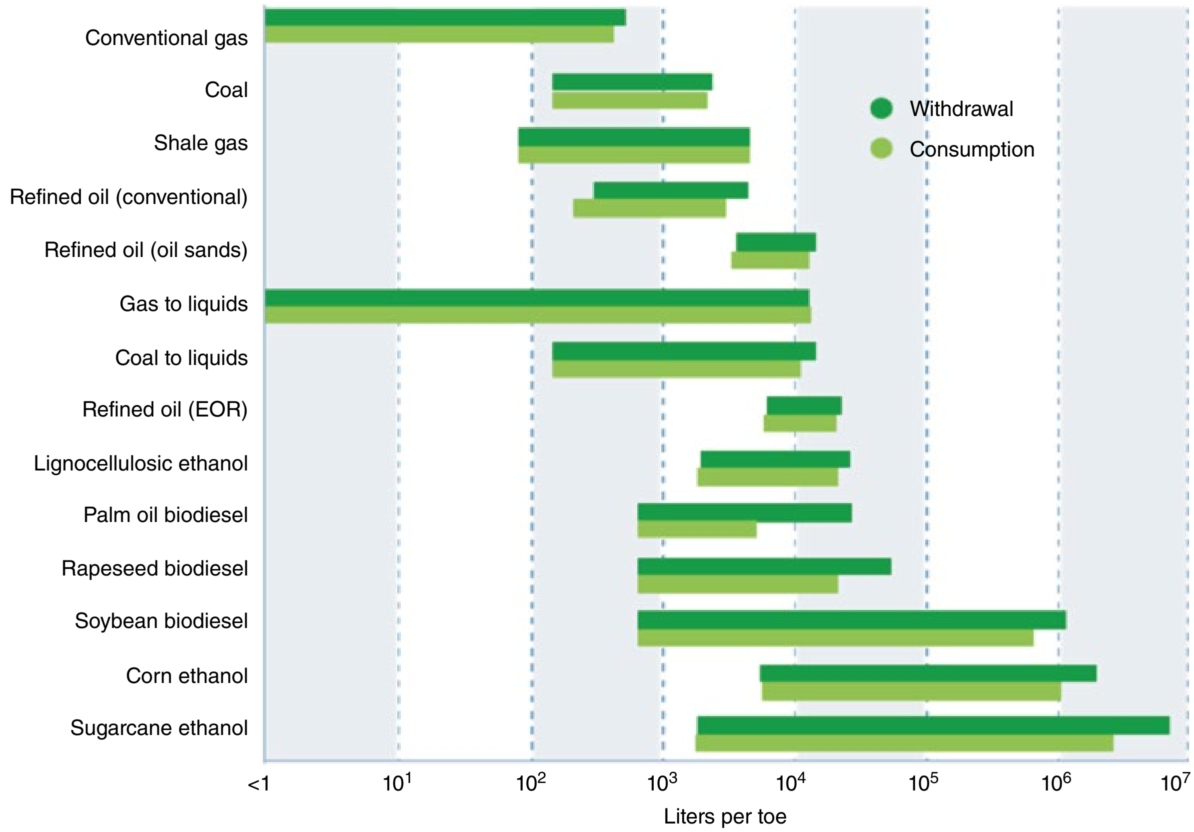

Figure 1.6 Water withdrawal and consumption for primary fuel extraction, processing, and transportation. Source: *IRENA* [2015], "Renewable Energy in the Water, Energy & Food Nexus."

transport sector through subsidies has led to greater competition for land and water use [*ADB*, 2013].

Energy is required for the extraction, transportation, and treatment of water. The energy intensity for water will vary depending mainly on the source of water, quality of water, and efficiency of the water system. For example, desalination of seawater would be more energy-intensive than utilizing surface or groundwater. Surface water was traditionally used for agricultural irrigation but with advances in technologies and inaccessibility to surface water, the use of groundwater has increased steadily. This shift to groundwater use comes with increased energy demand and lowered groundwater levels.

Energy is a dominant cost factor in the provision of water and wastewater facilities with estimates of 55% of water utilities operating budget being attributed to the energy cost [*IRENA*, 2015]. Water purification for industrial processes and human consumption requires energy and the amount of energy required depends on the source of water. For example, the purification of lake, river, or groundwater consumes less than 1 kWh/m^3 of potable water while purification of seawater can be as high as 8 kWh/m^3 [*IRENA*, 2015].

1.3.2. Water–Food Interactions

The accessibility and availability of water determine the agricultural characteristics of a given locality and the world as a whole. Water is necessary for food production, preparation, and consumption while changes in food consumption patterns or agricultural practices can create a strain on water security. Agriculture can be considered as the largest consumer of freshwater supplies, accounting for approximately 70% of consumption [*Ooska News*, 2011]. Water is not only used for growing food crops (i.e., irrigation) but also for processing, distribution, retailing, and consumption [*IRENA*, 2015]. Agricultural practices also affect water resources via water pollution through fertilizers and pesticides, which in turn affects agriculture itself, thus forming a vicious cycle. Though agriculture accounts for a large share of freshwater withdrawal, most of the water is returned to the surface or groundwater along with pollutants [*IRENA*, 2015].

The generation of waste or polluted water is unavoidable whenever food is handled, processed, packed, distributed, or stored. It was estimated that the consumption of water in the food industry in England is around 250 million m^3

(MCM) for 2006 [*Klemes et al.*, 2008]. The cost incurred during supply and disposal could be minimized by reducing the amount of wastewater, which can also lead to saving the loss of potential revenue.

1.3.3. Energy–Food Interactions

The energy–food interaction is more visible and easily felt in the modern context as the variations in food prices are strongly linked to oil price variations [*Bazilian et al.*, 2011]. This is not surprising as the agri-food supply chain accounts for 30% of the world's energy consumption [*IRENA*, 2015]. The main share of the energy consumed in the food sector is required for activities related to processing, distribution, preparation, and cooking. Energy is also accounted for in energy-intensive products such as pesticides and fertilizers. High-yield agriculture is heavily dependent on synthetic nitrogen-based fertilizers, which are almost entirely produced using natural gas [*ADB*, 2013].

The growing demand for food will be due to the growing population, improved lifestyle, and further mechanization of the food supply chain. The main challenge in the food sector with meeting the growing demand is not actually an increase in food production but rather a reduction in food wastages. The Food and Agricultural Organization (FAO) reported that approximately one-third of edible food produced for human consumption is lost or wasted [*IRENA*, 2015]. This accounts for a loss in not only embedded energy but also embedded water and contributes to greenhouse gas (GHG) emissions.

Food-processing industries also consume a significant amount of energy for heating and cooling during processing and storage of food products. For example, 20% of energy in the dairy industry is used for cooling and 80% for heating purposes. Energy consumption of the food industry in the United Kingdom is estimated at 126 TWh/year, which is equivalent to 14% of energy consumption in the country [*Klemes et al.*, 2008]. Similarly, the premium energy in the form of biogas can be produced from the effluent of food-processing plants by running anaerobic digestors. The quality and quantity of gas production depends on the balance of organic materials and process management ranges from 150 to 600 L/kg of volatile solids [*Burton and Turner*, 2003]. Pure methane has a thermal energy of 53 MJ/kg. Studies show that fuel can be generated from the utilization of organic waste [*Bianchi et al.*, 2006].

1.4. THE NEED FOR THE WATER-ENERGY-FOOD (WEF) NEXUS

There are still 1.2 billion people who lack access to electricity, 783 million people without access to potable water, and 842 million people who suffer from chronic hunger [*IRENA*, 2015]. Developing countries are expected to see a rise in population and consumption in both developing and developed countries is becoming more resource-intensive. By 2050, it is expected that global energy demand will double, with water and food demand increasing by over 50% [*IRENA*, 2015]. Climate change impacts such as global temperature increase and extreme weather conditions further compound the challenge of meeting the growing demand.

As the planet approaches the sustainable limit of its resources, competition and scarcity of the resources will become more predominant. There is a likely possibility that economic growth will soon be constrained by shortages of one or more of these resources. Therefore, water security, energy security, and food security have already been on national and international agendas for quite some time.

The amalgamation of water, energy, and food in a "nexus" framework in order to increase resource efficiency can be considered as a necessary way forward in achieving the SDGs. It enables us to take into consideration the impacts of a decision for one sector on itself as well as on the other sectors.

The best case example of a complex interaction of the nexus is the emerging trend of biofuels as an energy source in the transport sector. Biofuel production raises the conflict of the use of limited water and land against growing food for human consumption.

1.5. STRUCTURE OF THIS BOOK

In the context of the need to better understand, operationalize, and practice the nexus approach for resource use efficiency vis-à-vis the lack of adequate knowledgebase and publications in the arena, this book aims to contribute to the global debate on WEF nexus through knowledgebase generation. A single volume of the book covers theoretical and/or conceptual aspects of the WEF nexus, ways to overcome operational challenges of the nexus approach to resources management, cases of the nexus approach in practice from different regions of the world, and opinions on the future of the nexus agenda. The book is divided into four sections and 19 chapters. The first section on "understanding the nexus" contains five chapters focusing on the need of a nexus approach; its evolution as a policy and development discourse; its contribution to better water management and limitation; the emergence of a new paradigm in the nexus approach; and the urban nexus. The second section "operationalizing the nexus" contains six chapters focusing on modeling techniques; available tools/models in practice; governing the nexus; the role of international cooperation in operationalizing the nexus; framing nexus cooperation issues in the transboundary context; and cases of energy-centric operationalization of the nexus. The third section on the theme of "nexus in practice" covers seven chapters and focuses on various types of case studies of WEF nexus in various geographical regions of the world. Finally, the fourth section called "future of the nexus agenda" contains only one chapter focusing on how the nexus approach can help achieve the SDGs or the 2030 Agenda.

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2

Evolution of the Nexus as a Policy and Development Discourse

Vishnu Prasad Pandey[1] and Sangam Shrestha[2]

ABSTRACT

The key resources that sustain life and the ecosystem (e.g., water, food, energy, and others) are linked in many ways. Action in one sector might have impacts on others, thus forming a policy nexus among them. The relationships between the resources were realized long back; however, the nexus concept is still evolving as a policy and development discourse with the involvement of many actors. It is generally considered as a "multicentric" approach, the advancement of "water-centric" Integrated Water Resources Management (IWRM). This chapter presents a systematic review on how the nexus concept emerged and is now spreading to cover wider sectors; it then discusses key actors involved in raising the profile of the nexus as a policy and development discourse.

2.1. INTRODUCTION

Water, energy, and food are the key resources that sustain life as well as economies at various scales (e.g., global, regional, and national). Major decisions around food, water, and energy are highly political, and take place within arenas of unequal power relations that often lack democratic equalizers such as transparency and public participation [*Middleton et al.*, 2015]. Characterizing the linkages between the three resources, quantifying them, and analyzing them critically may provide good insights into efficient use and sustainable management of these resources. The term "nexus," which emerged in the international forum as the "new kid in the block" of the development discourse, can best describe the interconnections between the three resources [*Allouche et al.*, 2015].

Water, food, and energy resources are tightly interconnected, forming a policy nexus [*Vogt et al.*, 2010]. As water is the central focus for securing both energy and food, the term "water-energy-food (WEF) nexus" is preferred in the area of water resources management. As detailed in Chapter 3 of this book, the WEF nexus may best be understood as a pragmatic response to the disappointing outcomes of a series of political interventions in water policy in the 1990s, which were driven by the global politics of the times. It has shifted the focus of water resources management from "watersheds" to "problem-sheds" and from "what society should do for water" to "what water can do for society" [*Muller*, 2015]. It addresses the concerns of key constituencies, governments, and their citizens (who need services derived from water to be reliable), and businesses (which need security of supply and stability of markets). It has therefore been the highly debated topic in most of the international fora.

The "nexus" has been discussed, researched, and advocated widely since the term reemerged in 2008. From its root in water-food issues, it has now expanded to include several components such as energy, carbon, climate change, agriculture, and more. This chapter aims to synthesize historical paths of the nexus approach by shedding light on the roots of the nexus concept, its spread, and its key actors.

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Edited by P. Abdul Salam, Sangam Shrestha, Vishnu Prasad Pandey, and Anil Kumar Anal.

2.2. EMERGENCE OF THE NEXUS

The word "nexus" refers simply to a connection or series of connections linking two or more things. It emphasizes interlinkages among and between the environment (natural resources and ecosystems) and human development (food, energy, and water security), and the need for coordination, integrated management, and governance across the sectors. Despite the apparent "newness" of the nexus concept, elements of this approach are historically evident. One early example of a recognizable nexus is the Tennessee Valley Authority (TVA), created in 1933 [*Andrews*, 2006], where a US federal government agency was created to holistically manage water resources while generating energy, supporting agriculture, and promoting wider socioeconomic development. As early as 1970, water-stressed South Africa identified the interaction of urban, energy, and industry water needs to be its critical focus; agricultural needs were considered to be secondary [*South Africa Commission of Enquiry into Water Matters*, 1970]. Multiple linkages and interactions between water, food, and energy were also discussed in the 1977 United Nations (UN) Water Conference convened at Mar del Plata in Argentina, the first global conference of the governments dealing exclusively with water resources [*UN*, 1977]. This event reveals that the world governments were aware of the nexus concept right from the 1970s. The conference also discussed the need for an intensive land and water management program, consideration for many dimensions of water-energy and water-energy-agriculture linkages, and the need of a call for low-energy methods for waste management.

By the early 1990s, these views had been formalized into Integrated Water Resources Management (IWRM) as a step in the progression of the "development versus environment" debate. Codification of IWRM via a set of universal principles, which prioritize water as a finite resource, promote stakeholder participation, and treat water as an economically valuable good, came in the Dublin Conference held in 1992 [*ICWE*, 1992]. However, the Dublin approach could not achieve its intended results in either human development or environmental protection [*Biswas*, 2004; *Suhardiman et al.*, 2012]. In this context, the WEF nexus [*Bazilian et al.*, 2011; *Hoff*, 2011; *ICIMOD*, 2012] discourse that acknowledges the links between WEF resources in management, planning, and implementation [*Bach et al.*, 2012] emerged as a "new kid in the block" of development disclosures. A critical difference between the WEF nexus and the IWRM approach, according to *Bach et al.* [2012], is the relative significance attached to sectoral pillars: whereas IWRM tries to engage all sectors from a water management perspective (i.e., *water-centric*), the nexus approach treats different sectors (water, energy, food, and climate security) as equally important (i.e., *multicentric*) at its point of departure.

In the late 1990s, *Allan* [1998] introduced the concept of "virtual water" as the water content embedded in food products and presented the "water footprint" to make the concept operational. After Allan's work on "virtual water" [*Allan*, 1998, 2003], the nexus concept reemerged in the context of water and food to explain how regional water scarcity can be addressed by trade in food. The term nexus was used by the agricultural economist Alex McCalla during the 1997 Mediterranean Development Forum (MDF) to describe the connection, or nexus, between water scarcity and food security provided by trade in the Middle East [*McCalla*, 1997]. At the Third World Water Forum in Kyoto in 2003, it was concluded that "virtual water trade between nations could help relieve the pressure on scarce water resources and contribute to the mitigation of water scarcity at both local and global levels" [*WWC*, 2003]. The concept was then taken up by *Kumar and Singh* [2005] in the context of "the ongoing global debate on water-food security nexus, particularly on factors concerning national policy-making with regard to food security and water management." But they warned that the relationship between water and food trade might not be equally relevant to all the regions and therefore could not be generalized without due consideration of other factors of production.

Quite separately, attention to the "water-energy" nexus was increasing in South Asia in the context of groundwater overuse, depletion in groundwater levels, and increasing cost of energy for groundwater abstraction. As documented in *Shah* [2010], rural electrification programs in India solved the problem of water availability by enabling farmers to abstract far more groundwater than the resource could sustain, but created a new one of overexploitation. While the primary problems were land availability and institutions rather than water scarcity, *Shah* [2010] concluded that "managing the energy-irrigation nexus is the region's principal tool for groundwater demand management." The challenge in this context was less about water and food and more about water and energy, specifically the impact of energy prices on water availability, food production, and incomes.

Building on advances in integrated assessment models [e.g., *Bazilian et al.*, 2011], policy discourse around the need to understand linkages between climate, land, energy, water, and food (i.e., "resource nexus" or "the nexus") reemerged around 2011, with a series of conferences in Bonn, Germany. The reemergence of the new nexus-framed policy paradigm was in response to the 2008 global food, energy, and economic crisis including the price shock [*Allouche*, 2011; *Allouche et al.*, 2015], which created turbulence in the global economy and had severe consequences for the poor. It was further backed by alarmist scenarios about the relationship between food, energy, water, and the climate, such as global demand for food and energy will grow by 50% and for freshwater by 30% by 2030 [*Beddington*, 2009]. Furthermore, this was enhanced by climate-related uncertainties including the failure to arrive at a global consensus at Copenhagen.

There are divergent framings of the nexus between its various proponents [*Bizikova et al.*, 2013]. However, the dominant approach is through socio-ecological systems thinking, which seeks to understand trade-offs and synergies, increase efficiency, and improve governance between WEF systems [*Hoff*, 2011; *Smajgl and Ward*, 2013; *Davis*, 2014]. Nexus thinking has a variety of influences including input-output analysis and systems analysis of *The Limits to Growth* [*Meadows et al.*, 1972; *Bazilian et al.*, 2011] and normative principles (e.g., sustaining ecosystems and their services, creating more with less, accelerating access, and integrating the poorest) [*Hoff*, 2011]. These principles are driven by the argument that population growth, economic development, and urbanization have increased demand for resource-intensive foods such as fruits and vegetables, oils, and animal protein [*Muller*, 2015].

The preceding discussion reveals that the WEF nexus has now been promoted as an emerging global development paradigm and research agenda [*Allouche et al.*, 2015]. The nexus debates in global policy arenas have advocated an ecological modernization approach toward resolving food-water-energy contradictions, emphasizing innovation in technology, efficiency, market, and societal institutions aiming at broadly defined goals of sustainability and poverty reduction [*Hoff*, 2011].

2.3. SPREAD OF THE NEXUS

The term nexus is used in different contexts to describe a set of interrelated activities and their linkages and to place a boundary around them. In an early use in the water context, *Lofman et al.* [2002] suggested that, for California, the critical nexus is between water, energy, and the environment although the system they consider is driven equally by urban demands. The nexus rooted in the "water-food" context [*Mu and Khan*, 2009] has now spread in the context of other resource components as well, such as the "water-energy nexus" [*Scott et al.*, 2011; see also *Perrone et al.*, 2011; *Hussey and Pittock*, 2012], the energy-water nexus [*Marsh and Sharma*, 2007; *Murphy and Allen*, 2011; *Stillwell et al.*, 2011], the bioenergy-water nexus [*UNEP*, 2011], the energy-irrigation nexus [*Shah et al.*, 2008], the water-energy-food security nexus [*Bazilian et al.*, 2011; *ICIMOD*, 2012; *Bizikova et al.*, 2013; *Lawford et al.*, 2013], the water-food-energy-climate nexus [*World Economic Forum*, 2011; *Beck and Villarroel Walker*, 2013], the land-climate-energy nexus [*Dale et al.*, 2011], and a range of development-related nexus approaches [see *Groenfeldt*, 2010]. The nexus discourse has also been adopted by the mainstream sustainability discourse, including within the Sustainable Development Goals (SDGs).

The components of the WEF nexus are interlinked in various ways as illustrated through a simplistic diagram in Figure 2.1. The interlinks are also impacted by various drivers, governance, management, and stakeholder's actions (Figure 2.2). Therefore, solutions for intended public policy outcomes are not universal. The nexus concept is far from unified and seemingly varies according to the focus of the sectoral integration studied and the geopolitical context. Some neologisms adopt an energy, climate, or food focus but all these sectors are invariably linked to water resource protection. Though water and energy are closely linked in the production phase, water security is prioritized in the nexus debates. *Bazilian et al.* [2011] reveal the complexity of this interconnectedness in identifying both analytical and policy-making entry points. If a water perspective is adopted, then food and energy systems are users of the resource [see *Hellegers and Zilberman*, 2008]; from a food perspective, energy and water are the inputs [see *Khan and Hanjra*, 2009; *Mushtaq et al.*, 2009; *UN-DESA*, 2011]; from an energy perspective, water as well as bio-resources (e.g., biomass in the form of energy crops) are generally an input or resource requirement and food is generally the output. Food and water supply as well as wastewater treatment requires significant amounts of energy. Of course, areas such as food-as-fuels (i.e., biofuels) tend to blur these descriptions.

The nexus is also very much linked to the concept of "green economy," with human beings and social equity as two key pillars. More components are being added with expansion in the uptake of the concept. All nexus conceptions, however, share general perceptions of present and future crises and offer solutions for more efficient resource management within a green economy, thereby specifically calling for integrated solutions with regard to water, energy, and food [*Leese and Meisch*, 2015].

With the spread of the nexus approach, ways of implementing and operationalizing the nexus approach are also widely discussed. For a nexus approach to be implemented, it needs to support and be "mainstreamed" into ongoing processes, such as national development plans and strategies as well as institutions further connected to resource user groups. These principles have been laid out in *Hoff* [2011] and subsequently elaborated in *Mohtar and Daher* [2012], *Bleischwitz et al.* [2012], *ECD* [2012], *ADB* [2013], *Howells et al.* [2013], *Ringler et al.* [2013], *Rodriguez et al.* [2013], and *Flammini et al.* [2014].

Despite the buzz in global circles, however, the nexus and the debates around it have permeated relatively less into the level of national governments, as the nexus bureaucracy has not yet been constructed and enforced. On the other hand, among the practices of local communities,

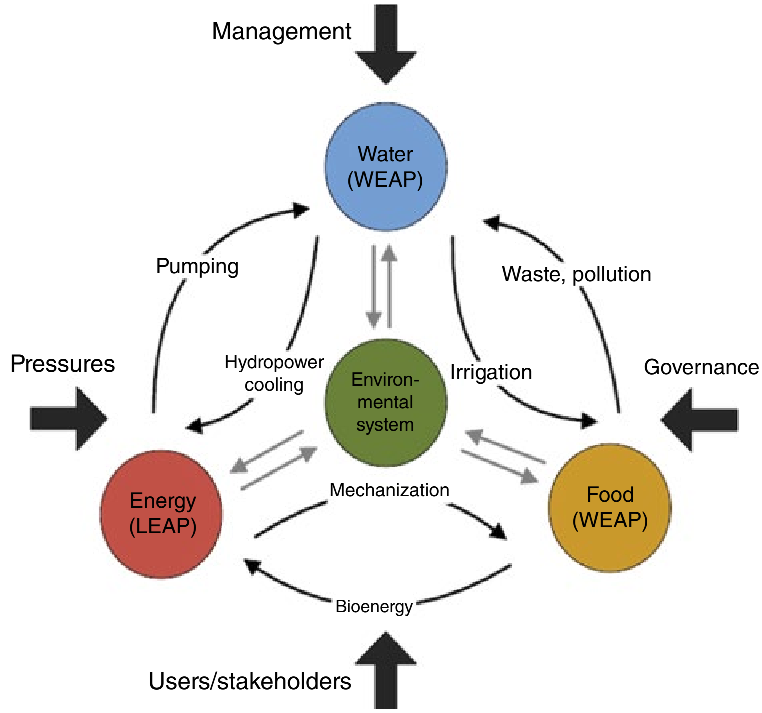

Figure 2.1 Illustration of interlinkages within and between sectors and environmental systems. LEAP, long-range energy alternatives planning system and WEAP, water and evaluation and planning model. Source: Reproduced with permission of *Karlberg et al*. [2015].

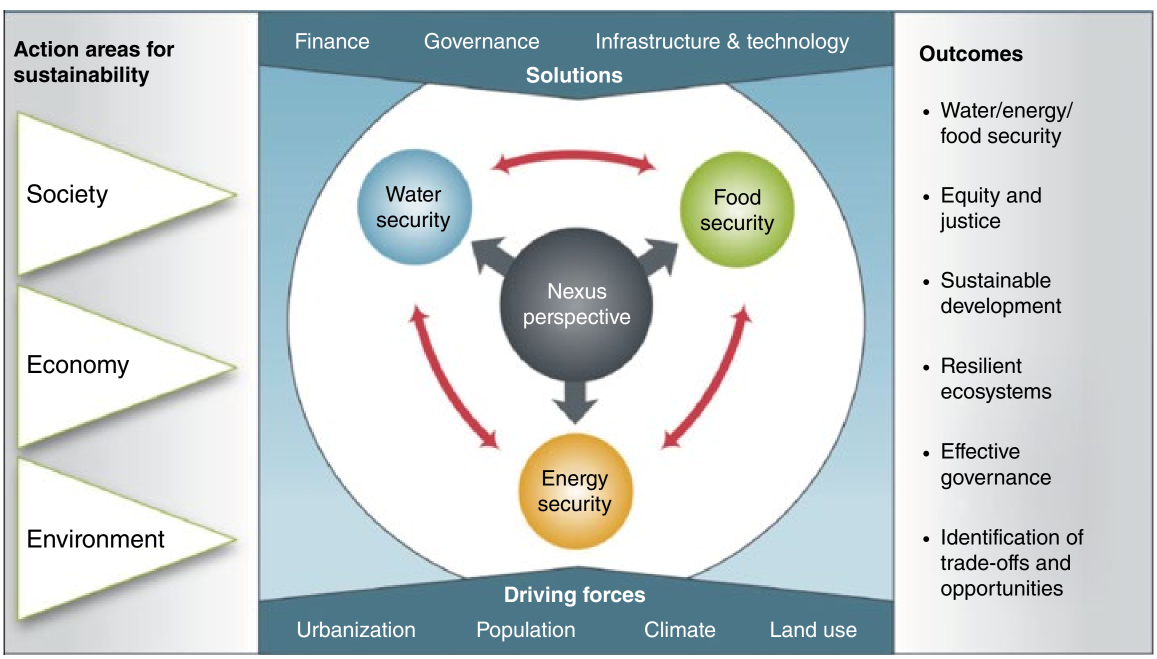

Figure 2.2 The complex links between nexus components, driving forces, solutions, and outcomes. Source: Adapted from *Hoff* [2011]. Reproduced with permission of Stockholm Environment Institute.

the relationship between water, food, and energy has often not been fragmented in the way that experts have siloed the sectors in conceptual and policy debates.

2.4. ACTORS IN THE WEF NEXUS ADVOCACY

The idea of the nexus has been put forward by a range of proponents, with their own perspectives and agendas, as a new framing of these interdependent problems, demanding new and innovative solutions [*Middleton et al.*, 2015]. Business communities as well as policy-influencing international events are seen as key actors in the WEF nexus advocacy.

2.4.1. Business Communities

The WEF nexus has been central in many talks by international business elites. It is within the nexus discourse that “many actors see a logical, sectoral entry point for themselves in compelling new, multi-sectoral, interdisciplinary and transboundary deliberations” [*Dore et al.*, 2012]. Growing momentum on seeing water security as central in the WEF dialogue has led to a proliferation of special bodies within the WEF to deal with water issues, including the creation of a *Global Compact CEO Water Mandate* and the *Water Security Global Agenda Council*. The emergence of the WEF nexus has made a wide and powerful business community realize the following limits to growth [*UN*, 2011], and protect its resource base from possible vulnerabilities:

1. Biophysical limits: What is possible within planetary limits and according to the laws of nature?
2. Economic limits: What is affordable?
3. Scientific-technical limits: What is doable technically?
4. Sociopolitical limits: What is socially and politically acceptable?

The WEF’s formulation of the nexus has been primarily driven by international private actors, who see both the nexus and, subsequently, the concept of green economy as an opportunity and a constraint to their business. The WEF’s approach to the nexus stresses the business imperative and the need to prepare for investment scenarios in the near future. The actors involved underline that the economics of water is both compelling and challenging and that water security, economic development, and gross domestic product (GDP) are interlinked [*World Economic Forum*, 2009]. They thus argue for the recognition that future global investments will be significantly driven by the consideration of water, and will become a mainstream theme for investors; global financial regulators, therefore, will have to develop clear-cut rules to manage the flow of innovative water funds.

Large transnational corporations such as Coca Cola, Nestlé, and SABMiller are putting forward the private sectors’ “comprehensive value-chain viewpoint” to tackle nexus governance. The business logic is as follows: to grow, economies should shift their water allocations away from farming toward uses that deliver higher economic value per liter, especially energy production, industry, and manufacturing [see *Allan*, 2001]. Within this logic, governments are encouraged to pursue high-value water uses with regard to the allocation of water between sectors. These shifts, at the same time, mean that they become more reliant on water-use-efficient agriculture alongside food imports. To respond, the world system will need more trade flows in agriculture across more countries and virtual water flows [*World Economic Forum*, 2011].

The WEF in particular emphasizes market mechanisms as the solution to resource scarcity. Indeed, one of several explanations that the WEF gives for claims of a growing water scarcity and its risk to economic growth is the underpricing of water as a resource. This, for example, has led to some regional “bubbles” of agricultural prosperity, which in the long-term are not sustainable, as water resources become depleted beyond the rate of replenishment. It is also argued that a weak international trade regime and a complex arrangement of tariffs and subsidies amplify the cost of food shortage [*World Economic Forum*, 2011].

Nexus language has thus sought to frame debates around acute pressures on the world’s natural resources generated through a combination of factors, including climate change, global demographic trends of burgeoning population size, and increased consumption levels. From a business perspective, crises in food and energy, and their relationship with water security, lie in that these resources are not given proper market value and clear ownership entitlements, which would enable nimble market reaction and adjustment to resource scarcity. From a public policy perspective, these crises have revealed the limits of existing institutional approaches that have hitherto sought to manage these resources by compartmentalizing them into individual silos and using market-based economic policy tools to address the issue.

The promotion of water-saving devices is still lacking in developing countries which would have helped reduce per capita water consumption and energy cost [*ADB*, 2013]. The neglect of the water sector can be attributed to the fact that the business of energy is considered much greater and hence policies are usually in favor of the energy sector.

2.4.2. Nexus-Focused Scientific and Policy Debates

The concept of the nexus has gained salience as a new vocabulary to define sustainable development, with a proliferation of high-level workshops, seminars, and conferences. The Bonn 2011 Conference, the Sixth World

Table 2.1 Chronology of key nexus-focused global events

SN	Name of the event	Date	Type of event
1.	United Nations Conference: Mar del Plata, Argentina	1977	Policy Conference
2.	United Nations Conference: Dublin, Ireland	1992	Policy Conference
3.	World Economic Forum: Davos, Switzerland	2008	Policy Conference
4.	9th Royal Colloquium focused on "Climate Action: Tuning in on Energy, Water, and Food Security": Bonham, Sweden	2009	Academic Conference
5.	Bonn Conference: Bonn, Germany	2011	Policy Conference
6.	World Economic Forum: Davos-Klosters, Switzerland	2011	Policy Conference
7.	World Water Forum's Ministerial Roundtable on Water, Energy, and Food Security: Marseilles, France	2012	Policy Conference
8.	World Water Week: Stockholm, Sweden	2012	Policy Conference
9.	Mekong2Rio International Conference on Transboundary River Basin Management: Vientiane, Lao PDR	2012	Policy Conference
10.	South African Water, Energy, Food Forum: Managing the Mega-Nexus: Sandton, South Africa	2012	Policy Conference
11.	Water, Energy, Environment, and Food Nexus: Solutions and Adaptation under Changing Climate: Lahore, Pakistan	2012	Policy Conference
12.	RelSource: Food-Energy-Water for All: Oxford University, UK	2012	Academic Conference
13.	Planet Under Pressure: New Knowledge Towards Solutions: London, UK	2012	Academic Conference
14.	The Water Summit: Bringing WEF Nexus to Life: Abu Dhabi, UAE	2013	Policy Conference

Water Forum in Marseilles in 2012, the Rio +20 negotiations in the same year, and the 2014 Stockholm Water Week all had the nexus as a key topic. They have helped to enhance understanding of interrelationships among the resources as well as implications of action in one sector on another (Figure 2.1), and also of how externalities such as global climate change might reshape the discussion around the nexus concept (Figure 2.2). New policies and perspective papers from the World Economic Forum, the European Commission's Report on Development for 2011/12, the Global Water Partnership, and the World Bank among others are indicators of growing interest in the nexus. Key nexus-focused scientific and policy events at global/regional levels are summarized in Table 2.1.

Like climate change, the nexus has also been scrutinized, with the US National Intelligence Council highlighting in its "2030 Global Trends Report" the important geopolitical consequences (for conflict, national security, and global economy) if the nexus were not properly managed. To avert such issues, the Annual Meeting of 2008 World Economic Forum agreed upon a "Call to Action on Water" aimed at reexamining the relationship between water and economic growth. Business leaders and policy-makers subsequently developed the nexus concept, resulting in the 2011 report of World Economic Forum, which provides a major source of guidance. The following Bonn 2011 Nexus Conference then became the first internationally recognized event held on the WEF security nexus. The Mekong2Rio Conference then took a step forward in exploring the WEF security nexus in a transboundary context, moving from rhetoric to practice [*Bach et al.*, 2012]. Subsequent policy dialogues, such as the Bonn 2013 conferences, promotion by the World Economic Forum and Global Water Partnership (GWP), and an emerging academic research agenda, have sought to finesse nexus thinking, although conceptualizations are still developing. Recently, the European Union along with the German Federal Ministry for Economic Cooperation and Development, the International Food Policy Research Institute, the Worldwide Fund for Nature (WWF), and the World Economic Forum began heavily promoting the nexus approach to governments. In addition, the WEF nexus was one of the main approaches considered by the United Nations in setting its SDGs. Given this high-level support, it could be anticipated that the nexus discourse should be influencing national resource governance strategies.

2.4.3. Nexus Elements in Key Initiatives of International Agencies

The WEF security nexus is now a part of the international development canon and is a recognized policy paradigm. Investment/lending organizations, sustainable development organizations and research institutes, and conservation organizations (e.g., International Union for the Conservation of Nature (IUCN) and the WWF) are involved as actors in such various initiatives. Table 2.2 shows the central position of the WEF nexus in key initiatives of international agencies.

Indeed, the World Economic Forum, the main nexus promoter, views securing water resources as depending on the consideration of multiple sectors, namely energy, trade, national security, cities, people, business, finance, climate, and economic frameworks [*World Economic Forum*, 2011].

Table 2.2 Nexus elements in key initiatives of international agencies

SN	Organization/body	Documents/meeting	Position on nexus or its elements
1.	Food and Agricultural Organization of the United Nations (FAO)	The Energy and Agriculture Nexus 2000. Energy and Natural Resources Working Paper No. 4	Energy-agriculture nexus is a coherent system. Bioenergy could boost agriculture productivity for rural development. Link between energy, biomass, and carbon flow
2.	United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP)	Low Carbon Green Growth Roadmap for Asia and the Pacific 2012	Water, food, energy security is mentioned as one of the resource efficiency strategies
3.	Asian Development Bank (ADB)	Asian Water Development Outlook 2013: Measuring Water Security in Asia and the Pacific	Embraces the nexus perspective in one of its 12 key messages
4.	Transatlantic Academy	The Global Resource Nexus: The struggles for Land, Energy, Food, Water, and Minerals	Broadens the debate on WEF security to include land and minerals
5.	Stockholm Environment Institute (SEI)	Prepared the background paper for Bonn 2011 Nexus	Promotes reduction of trade-offs and generates additional benefits that outweigh transaction costs
6.	International Food Policy Research Institute	A co-organizer of the Bonn 2011 Nexus Conference	Publishes on the food-water-climate change nexus in scientific journals
7.	International Energy Agency (IEA)	World Energy Outlook 2012	Examines water for energy relationships and estimates. Total freshwater needs by energy source and region
8.	The World Bank	Overcoming Barriers to International Cooperation of River Basins Critical for Food, Water, and Energy Security	A report on the importance of river resources for the WEF nexus
9.	United Nations Conference on Sustainable Development	Outcome document "The Future We Want"	Paragraphs 108–129 cover the topics of food security, water and sanitation, and energy
10.	Asia Pacific Center for Water Security, Tsinghua and Peking Universities	Established a regional program on R&D on WEF security	Collaborating with ADB to publish the Third Water Development Outlook for Asia and the Pacific

Source: Adapted from *UNESCAP* [2013].

Donors such as German Ministry for Education and Research, Global Water System Project, and UNEP played a key role in raising the profile of the WEF nexus agenda by sponsoring the Bonn Conference (2011). The German government has supported research and knowledge dissemination of nexus information via the GIZ Water, Energy and Food Security Resource Platform. Launched at the "Bonn 2011 World Water Forum Nexus Conference," the Platform aimed to promote greater understanding of WEF security interactions while providing online access to nexus information [*GIZ*, 2015a, 2015b].

The United Nations Economic Commission for Europe (UNECE) has also become an active promoter of the water-food-energy-ecosystems nexus, with an emphasis on reconciling water resource use with other sectoral priorities, particularly in river basins [*UNECE*, 2015]. UN-Water is also actively supporting the WEF nexus through its interagency approach to coordinating action on water development [*UN-Water*, 2014]. Meanwhile, the IUCN and the International Water Association (IWA) have established a Nexus Dialogue on Water Infrastructure Solutions that provides a platform for information dissemination on the water nexus, including a section on best practice case studies [*IUCN/IWA*, 2015].

Various nongovernmental organizations (NGOs) and think tanks are also disseminating nexus knowledge, including the Stockholm Environment Institute (SEI), the WWF, and the International Food Policy Research Institute. International River Basin Commissions represent large-scale institutions that promote integrated thinking across the water, energy, and food domains. For example, water-food-energy-ecosystems assessments were undertaken for selected river basins by parties to the UNECE Water Convention [*UNECE*, 2015].

2.5. SUMMARY

Three major resources that sustain life and the ecosystem (i.e., water, food, and energy) are highly interlinked in many ways, thus forming a policy nexus. Recognition of the relationship between the resources has the potential to add significant value toward resource management policy and practice. The interconnections were understood by the world governments as early as in the 1970s. The Dublin Conference in the early 1990s formalized the nexus views into IWRM; unfortunately, the Dublin approach could not achieve its intended results either in human development or in environment protection. In this context, the term nexus emerged in the international forum as the "new kid in the block" of policy and development discourse. There is a critical difference between IWRM and WEF nexus approaches; IWRM is "water-centric" whereas the nexus approach is "multicentric" at its departing point.

The term nexus which found its roots in the "water-food" context has now spread into different contexts to describe a set of interrelated activities and their linkages and to place a boundary around them. It is expanding in terms of connecting more components such as water, energy, food/land, environment/ecosystem, irrigation, climate, health, and others. The interlinkages are also impacted by various drivers, governance, management, and stakeholder's actions; therefore, solutions for intended public policy outcomes are not universal.

The nexus has now been a highly debated topic in most of the international policy, development, and academic forums. It is because major decisions around food, water, and energy are highly political, and they take place within arenas of unequal power relations that they are often influenced by various actors such as business communities, nexus-focused policy debates, and internal agencies. The emergence of the WEF nexus has made a powerful international business community realize the various limits to growth, such as biophysical, economic, scientific-technical, and sociopolitical limits. They see the nexus as an opportunity and a constraint to their businesses and therefore consider it as a logical sectoral entry point to generate investment scenarios for the near future. In addition, international investment/lending organizations, sustainable development organizations and research institutes, and conservation organizations are also playing the role of key actors in promoting the nexus as a recognized policy paradigm by including nexus components in their key long-term initiatives.

Nevertheless, despite the buzz in global circles, the nexus and the debates around it are taken up relatively less to the level of national governments, probably because the nexus bureaucracy is yet to be established and enforced. The nexus is a political process rather than just a technical one; it is neither new nor complete, and is still evolving as a policy and development discourse.

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3

The Nexus Contribution to Better Water Management and Its Limitations

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ABSTRACT

Although the water-energy-food (WEF) nexus is neither a coherent theoretical paradigm nor an operational analytical tool, it can still make a useful contribution to better water resource management. It will do this if it is used to highlight the systemic interaction between different water uses in important practical contexts, the challenges that this poses, and effective approaches to address them. In particular, its focus on sectors that are of high priority to fast-growing developing countries will help them find ways to achieve a better balance between socioeconomic development and environmental goals than current, contested, approaches to water resource management.

3.1. INTRODUCTION: CAN THE NEXUS BE USEFUL?

The potential usefulness of the water-energy-food (WEF) nexus as an analytical or operational frame of reference must be understood in the context of the generic goals and challenges of water resources development and management. This chapter considers the contribution that the WEF nexus could make to a paradigm that helps societies to address the multiple challenges of using water resources to meet the food and energy needs of a growing and changing world in an increasingly complex development context.

The challenges as outlined in early presentations of the WEF nexus appear to be obvious. More food will be required to meet the need of a growing world population. Growing prosperity will increase demand for more and better quality food. This will require more water at a time when freshwater withdrawals will also be increasing to support other uses, notably energy production as well as the increased consumption of rapidly growing and more prosperous urban communities. The already often tenuous availability of water to meet these demands will be further challenged by the impacts of climate change [*WEF*, 2011].

Using practical examples from diverse geographies, it is suggested that the WEF nexus is neither a new nor a unique element of water management that demands the explicit attention of resource managers. It is certainly not, in itself, a generic paradigm that offers a policy framework or set of tools to guide the sustainable development and management of water resources to achieve water security. Among its failings, its underlying narratives have limited empirical support; it ignores the fastest-growing water uses and does not adequately address the need to ensure a sustainable aquatic environment or to mitigate disaster risks.

But this is not to dismiss the WEF nexus as a concept of no value. Aside from the fact that it has obvious descriptive value, it is suggested that a focus on this particular set of relationships has served an important function. It has illustrated the practical societal challenges of managing a complex natural resource such as water that supports or impacts upon virtually all areas of social and economic life. In particular, it has highlighted important issues of institutional design and political economy that must be considered in any effective water management paradigm.

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The WEF nexus may thus help refocus discussions about water resource development and management. In particular, it may help recapture the original operational concept of integrated water resource development and management from the determined advocacy that prioritized environmental conservation over the achievement of the wider goal of water security, under the guise of the Dublin version of Integrated Water Resource Management (IWRM). In similar fashion, the WEF nexus provides perspectives that help elucidate the limitations of two other concepts that have attracted wide attention and been proposed as paradigms to guide water management, "virtual water" and "water footprints."

A final conclusion is that the attention paid to the WEF nexus is encouraging a more pragmatic and problem-focused engagement with water management issues. It is contributing to a better understanding of the very diverse and local nature of water resource development, management, and use. It thus reinforces the emerging consensus [*OECD*, 2015] that the governance and management of water remain primarily a context-specific activity that is best guided by broad, overarching principles rather than by narrow normative prescriptions.

3.2. IS THE NEXUS NEW?

It cannot reasonably be claimed that an understanding of the nexus between water, food, and energy is new. There are many examples from early history where the linkages have been recognized. Perhaps the oldest is simply in relation to the evolution of irrigated agriculture. The structured application of water made it possible to produce substantially more food energy per unit input of labor energy; this increase in productivity enabled the growth of societies that could support specialized economies. Wittfogel famously, if controversially, attributed the rise of "hydraulic societies" to their ability to achieve and enforce control of water for agriculture [*Wittfogel*, 1955]. While the causal effect has been challenged [see, e.g., *Carneiro*, 1970], the association between the rise of ancient civilizations and irrigation is not.

But the WEF nexus went beyond this. Inland and marine navigation, powered by labor and wind, made it possible to distribute the food energy produced by these societies more widely. Water energy, in the form of water wheels, continued this process, enabling more efficient processing of agricultural products [*Lucas*, 2005]. Where water energy could not be harvested, other sources of energy were harnessed to lift water to where it could productively be used [*Oleson*, 1984].

The WEF nexus is also evident in the next great step in economic specialization, the industrial revolution in Europe, which enabled rural emigration, agricultural transformation, and urban expansion. Early productivity increases from mechanized industrial processes were powered directly by water, albeit only briefly until replaced by coal-fueled steam power. Even then, water remained important as an efficient means of transporting fuels like coal as well as the raw materials for industry.

In the modern era, there continue to be many different examples of the linkages between water, food, and energy. Some of the best known examples come from the USA. While navigation was the focus of earlier development in the humid east, the initial objective of the major water schemes developed on the rivers of the American west was to support agricultural settlement and expansion by enabling irrigation. The emergence of technologies for generating hydroelectricity (the world's first commercial hydropower plant was commissioned in Wisconsin in 1882) changed this focus. In the early twentieth century, the US Bureau of Reclamation (BUREC), which was responsible for much of this development, had begun to use hydroelectricity in the construction of irrigation works and to power their later operation. Demand for this power from neighboring mines and towns drew attention to hydropower's potential to meet the growing demands of a rapidly industrializing economy [*Swain*, 1970].

The use of hydropower spread rapidly across the world. In 1883, Brazil's first hydropower station was commissioned at Ribeirão do Inferno, near Rio de Janeiro, to supply electricity for mines; commercial generation was established in Germany and Austria a few years later [*IHA*, 2015].

In the USA, over the first decades of the twentieth century, it became apparent that using flowing water to produce hydropower was financially more valuable than applying it to fields. Since it was proving difficult to achieve the initial policy goal of recouping the costs of new irrigation schemes from farmers, BUREC focused increasingly on hydropower generation. One consequence was that farmers began to complain that water allocation for power production was being given priority over agricultural requirements. But by 1920, hydropower generated 25% of the USA's electricity and, by the time the USA declared war on Germany, BUREC's dams were described as "giant war weapons" and the organization was said to be the largest power producer in the world [*Sloan*, 2008]. Similar developments, which addressed navigation and flood control as well as power production and irrigation, continued with the development of the USA's Tennessee Valley (TVA) scheme.

However, in other countries, the promotion of explicitly multipurpose schemes was slower. So Egypt's landmark development, the Aswan Low Dam built at the start of the twentieth century, was intended only to support agriculture by providing flood protection and flow regulation. While the potential for very limited power production had already been noted in 1913 [*New York Times*, 1913], it was only in the 1960s that the Low Dam was retrofitted with turbines, augmenting the 2100 MW generated by the Aswan High Dam by nearly 500 MW.

In China, war and political upheaval in the first half of the twentieth century was not conducive to the promotion of major civil engineering projects. Even after the establishment of the Peoples' Republic of China in 1949, the initial focus of policy was on the promotion of agriculture and the construction of small dams to support it. While some multipurpose projects were undertaken, the initial priority of the new government was to support agriculture and control floods rather than to generate power. Nonetheless, by 1980, over 20,000 MW of hydropower capacity had been built. During the subsequent period of economic liberalization and growth, the pace of construction increased: hydropower capacity almost quadrupled to 77,000 MW in 2000 and again to 300,000 MW in 2015. Initially, priority continued to be given to agriculture, flood control, and water supply since energy needs could still be met quickly and cheaply from coal-fired sources; even the Three Gorges Dam, inspired in part by the TVA scheme, is explicitly operated to prioritize flood control over power production. While more recently there has been greater emphasis on the development of hydropower as a source of clean energy, the complementary benefits for agriculture and flood control continue to be important [*Kang*, 2012].

In India, the historic focus on irrigated agriculture, encouraged during the colonial period (1850–1947) and continued subsequently by independent governments, saw the linkages between energy and water evolve in a different way. Despite substantial investment in surface irrigation supplied from dams through canal networks, groundwater has become the major source of irrigation water, often recharged by leakages from poorly managed surface water systems. In some areas, this groundwater has been overexploited leading to significant declines in water levels; energy demands for pumping have also placed a strain on energy supplies. The more or less functional interrelationship between the management of agriculture's groundwater use and that of electricity supply systems has been a defining feature of India's WEF nexus [*Shah*, 2010]. Hydropower development has not kept pace with the growing demand for electricity; in 2014, there was only 36,000 MW installed (17% of total generating capacity), just a third of the potential [*PWC*, 2015; *Madan*, 2016].

Meanwhile, another set of linkages between water, food, and energy has emerged in Brazil, the use of biomass from sugar production for thermal power generation. Brazil has a longstanding focus on hydropower, which accounts for 62% of the country's 133,000 MW of generating capacity. It is proposed that it will continue to play an important role with 28,000 MW of new hydroelectric capacity planned to be commissioned by 2024 [*Brazil*, 2014]. However, although the quantities involved are relatively small (perhaps 7000 MW), the inclusion of sugar biomass into the energy mix is attractive. Peak production of electricity as a by-product of sugar milling coincides with the dry season during which there is a greater risk that hydropower generation may be constrained [*Barroso et al.*, 2008]. The converse risk is that the production of sugar-based biofuels may have a negative impact on water resources availability as well as on food prices [*de Fraiture et al.*, 2008]. But the inclusion of electricity in the sugar industry's product mix helps to reduce its commercial risks.

3.3. HAS THE WEF NEXUS BEEN ADDRESSED BEFORE AS A MATTER OF POLICY?

These examples show that there are indeed many cases in which the food and energy sectors interact through the medium of water. But are these a consequence of deliberate policy or merely a response to specific opportunities that have arisen?

In the twentieth century, the potential for water resource development to serve multiple purposes was increasingly recognized and, in some jurisdictions, became the basic principle in the development of water resources. Integrated approaches to planning had already been formally mandated by the US Congress in the 1920s. Reflecting concern about the impact on other water users of a narrow focus on hydropower, the so-called "308 reports" were designed to pay specific attention to the promotion of multipurpose projects [*BUREC*, 2005; *Priscoli*, 2013]. Here though the initial concern was the interaction between hydropower and navigation rather than with food production, improved navigation did facilitate the transport of agricultural products.

The WEF nexus is more directly evident in policy approaches elsewhere in the world. Australia's Snowy Mountain Scheme was conceived in the 1940s, with the objective of diverting rivers from southeast Australia to the west to provide water for irrigation and generate electricity for the urban states of New South Wales and Victoria. In the former Soviet Union, water resource development in Central Asia in the 1960s was coordinated to produce hydropower in the republics of Tajikistan and Kyrgyzstan and support irrigation in downstream Uzbekistan and Turkmenistan.

While these cases illustrate the growing recognition of the benefits of combining hydropower and irrigation development in new water projects, in other regions, the potential conflicts between resource use for agriculture and energy had already been explicitly recognized.

In the Philippines, the Angat dam which supplies most of the water for the capital city of Manila also generates significant hydropower, provides irrigation water, and flood protection. The operating rules for the dam, which determine the allocations for different uses, are set by the country's National Water Resources Board. They aim to balance the needs of these different users while offering them predictable and acceptable levels of security [*Sankarasubramanian et al*., 2009].

A more systemic example comes from South Africa. Since much mining-led urban and industrial development was occurring in the interior of this relatively dry country, a "Commission of Enquiry" was established in 1966 to consider "all aspects of water provision and utilization within the Republic as well as the broad planning in this connection." Its terms of reference specifically addressed water needs for energy generation and irrigation and called for a master plan to include "a rational allocation of the available water among the various water users."

The review led South Africa to a strategy that saw dry cooling identified as a requirement for new thermal power stations near inland coal fields and the decision that any nuclear power should be built at the coast where seawater could be used for cooling. It also found that expansion of irrigation was not a priority and recommended that, since the existing use of water for irrigation was inefficient, "it will be from this sector that the biggest contributions to reduced water consumption can be expected." It prioritized instead the development of sources for urban and industrial development, a controversial position in a country where the locus of political power was traditionally rural. The water-energy nexus was already a preoccupation; in relation to urban needs, it was noted that desalination would be able to meet the needs of coastal cities once more energy-efficient processes had been developed to reduce its operational costs [*South Africa*, 1970].

The approach taken by South Africa reflected emerging good practice in many countries around the world where reliable availability of water for development presented a challenge. Much of this was based on the work of the interdisciplinary Harvard Water Program in the early 1960s, which brought together engineering, economics, and public administration specialists. They produced the massive guide *Design of Water-Resource Systems: New Techniques for Relating Economic Objectives, Engineering Analysis, and Governmental Planning* [*Maass et al*., 1962]. While this had significant limitations [*Reuss*, 2003], it provided a structured approach that has underpinned water resource development and management practice, if not prescription, around the world. It also linked the engineering and economic considerations to public planning and administration processes. Much of this approach was subsequently codified at the first (and only) formal meeting of the United Nations devoted specifically to water.

The UN Conference on Water in Mar del Plata in 1977 recognized the importance of addressing, in a coordinated, if not always integrated, manner the water requirements and impacts of user sectors as diverse as domestic users and navigation; agricultural production and recreation; commerce, industry, and the natural environment; energy generation, waste disposal, and protection against floods and droughts. It also highlighted the need to manage the natural resource as a single system; within that, integrating the management of water quantity and quality was critical.

To this end, the Conference recommended a "shift from single-purpose to multipurpose water resources development as the degree of development of water resources and water use in river basins increases, with a view, inter alia, to optimizing the investments for planned water-use schemes. In particular, the construction of new works should be preceded by a detailed study of the agricultural, industrial, municipal, and hydropower needs of the area concerned." It also called for the use of systems analysis techniques, which would "take into account interactions between the national economy and regional development, and linkages between different decision-making levels" [*UN*, 1977].

This approach provided an overarching paradigm that comfortably accommodated more operational preoccupations. So where, as in many parts of the developing world, the primary water resource challenge is to build the infrastructure needed to meet rapidly growing urban water needs while protecting rivers from pollution, the focus falls on water supply and sanitation systems. But it can also inform the requirements of European countries which have developed most of the infrastructure that they need and now seek to balance the needs of inland navigation and the demands of citizens to protect the riverine environment while also maintaining, inter alia, the capacity to cool thermal power stations and protect communities from floods.

There have subsequently been significant deviations from this approach, driven by normative considerations, which will be discussed later. But the technical framework that was established has continued to inform policy, notwithstanding ideological objections, and remains, arguably, the dominant operational paradigm in growing societies.

3.4. IS THE WEF NEXUS SPECIAL? WHAT ABOUT OTHER USES?

As the examples presented earlier demonstrate, there is indeed a nexus between water, food, and energy which manifests itself in many different ways in different locations. But these examples also show that there is a wide variety of other water uses that create different "nexuses" which may be more important than the WEF nexus in their particular local circumstances.

Since water resources constitute in themselves the aquatic ecosystem, an important consideration must be the environmental dimensions that emerge from competing uses of water. Certainly, environmental organizations have already asked "What about nature?" in the nexus [*Krchnak et al.*, 2011]. Treating environmental systems as water users is still controversial, not least when it is suggested that demand management could be applied to wetland ecosystems [*Pittock and Lankford*, 2010] as well as to domestic, industrial, and agricultural water users. However, this is the practical effect of the increasingly widespread practice of determining and reserving environmental flows as an integral part of water allocation processes.

But aside from the environmental lacuna inherent in the WEF nexus, any generic paradigm to guide water management must reflect the dominant water uses in the system under consideration as well as a range of interventions to reduce disaster risks.

This is important in the light of forecasts of global trends in the demand for water. Contrary to the underlying assumptions that drew attention to the WEF nexus, water use in agriculture is not expected to increase dramatically. Rather, according to the Organization for Economic Cooperation and Development's (OECD's) Environmental Outlook 2050, the 55% increase in global demand for water is expected to come from manufacturing, up by 400%; electricity production, up by 140%; and domestic use, increasing by 130% (see Figure 3.1). Largely because of these increases, agricultural use is expected to decrease as the growing demand from the other uses will compete with demand for irrigation in some places [*OECD*, 2012].

In many parts of the world, the defining trend is thus related to the growth of urban water demand and the requirements for meeting rising standards of living through manufacturing and, to a lesser extent, electricity production. The OECD Outlook further highlights the fact that a significant proportion of water "used" in these sectors will be returned to water bodies after use, which will create a growing set of quality problems rather than volumetric scarcity per se.

In this context, it would seem that the primary nexus challenge in many parts of the developing world is the relationship between urban and industrial water use and that of agriculture. The urban-agriculture nexus was investigated as part of the larger Comprehensive Assessment of Water Management in Agriculture. The final conclusion of this review is worth presenting in detail:

> Our contention is that the causal association between, on the one hand, the insufficient and precarious conditions of access to water in "thirsty cities," highlighted in times of crises, and, on the other, water scarcity allegedly caused by a wasteful irrigation sector, is largely misleading. Rather than considering that urban masses lack water because it is difficult to take water away from agriculture (generalizing the particular case of the western USA), we argue that transfers do occur and are volumetrically limited, and that the problem (in developing countries) lies elsewhere: not so much in the lack of water per se but, rather, in the lack of capital, itself a notion relative to the local political economy and distribution of power in society. [*Molle and Berkoff*, 2006]

This highlights both the danger of generalizing conclusions from one water management context (the western USA) to the global level, as well as accepting the easy narrative that there will be widespread water shortages for agriculture. The more important conclusion is one based on the empirical observation that, in most cases where cities need more water, it will be reallocated from agriculture, but only where that is a physically feasible alternative.

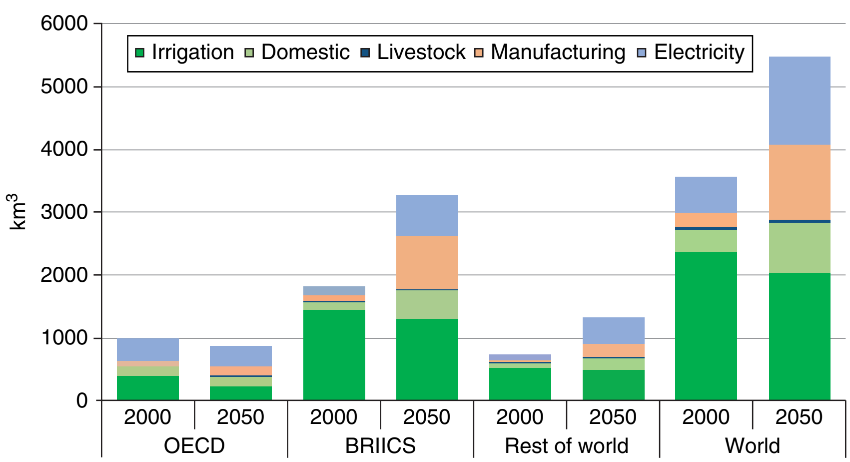

Figure 3.1 Global water demand: Baseline scenario, 2000 and 2050. Note: this figure only measures blue water demand and does not consider rainfed agriculture. Source: Data Obtained from OECD Environmental Outlook to 2050. © OECD 2012. (*See insert for color representation of the figure.*)

The broad conclusion remains, however, that agriculture in many parts of the world will have to adapt its water use as a function of increased demands from other sectors. This is not a new development. The general problem had already been enunciated at a policy level by FD Roosevelt in 1938 when he told the US Congress that "Changing public interest, first in navigation, then in irrigation, and then in flood-control, water power or pollution, has produced a collection of unrelated water policies. The recommendations in this report define in broad strokes an integrated water policy for the country as a whole. Such a Federal water policy is needed" [*Roosevelt*, 1938].

In this changing landscape of water use, he already included not just irrigation and power but also navigation, flood control, and pollution (referring at that stage principally to pollution from industrial activities).

This leads back to the original nexus which located trade as the node that linked water and food. This nexus is best known from Allan's work seeking to explain how regional water scarcity was addressed by trade in food [*Allan*, 1998, 2003]. He took the term "nexus" from agricultural economist Alex McCalla, who used it to describe the connection, or nexus, between water scarcity and food security provided by trade in the Middle East [*McCalla*, 1997]. This analysis has been generalized. One stream of work has focused on another concept now in wide use, that of virtual water, the limitations of which are outlined later. Arguably more important although less well known has been the stream of economic analysis that has sought to understand how trade in agricultural products will respond to the emergence of water shortages in specific localities where overall water use will exceed availability.

Among the most comprehensive work to date is that of *Liu and her colleagues* [2014]. Unlike many other econometric analyses, they began by considering trends in water use in 216 separate river basins, recognizing that water availability is a local phenomenon and not a national aggregate. They provided in their model for the possibility that production from irrigated agriculture might be shifted to rainfed locations if irrigation water becomes scarce. They also linked the potential to use locally available water to the availability of land and possible crop mixes. With these physical constraints, they then used econometric analysis to determine how global trade flows and price effects might respond to the growing demand for food.

Their results suggested that, even as consumer tastes change to, for instance, consume more meat, future local water shortages might not have as dramatic an impact as feared, because production could be transferred to other areas in which land and water will still be available. The net economic impact, in terms of lower productivity, was small although the local impacts of production losses could be significant. But this relatively benign outcome depended on a well-functioning global trading system. In these circumstances, it is reasonable to accept the thesis advanced by *Molle and Berkoff* [2006] that "where other human uses do, in fact, compete for significant amounts, the balance shifts and irrigation almost always becomes the residual human use after other needs have been met." Using an animal metaphor, they suggest that agriculture, rather than taking the lion's share of the world's water, gets the hyena's share, the leftovers.

3.5. THE NEXUS IN A CONTESTED CONTEXT: IWRM

Given the wide variety of different "nexuses" involving water and energy, food, industry, urbanization, navigation, and recreation as well as the aquatic environment itself, how is the priority between different water uses determined? There are different configurations of uses and the trade-offs between them will vary from place to place and from time to time, depending also on the nature of available water resources. As described earlier, the desirability of planning and managing these activities in a coordinated or even integrated manner has been recognized for almost a century. And, since 1977, the recommended global approach has been characterized as one of "integrated water resource development and management."

Yet this characterization has become increasingly unhelpful because, as many authors have remarked, there is not sufficient consensus about what such integrated water management entails to guide its operationalization [*Biswas*, 2004; *Conca*, 2006; *Stålnacke and Gooch*, 2010; *Giordano and Shah*, 2014; *Priscoli*, 2013]. It is suggested that the primary reason for this is that the integrated water resource management label has been appropriated, by a variety of actors, in support of their particular priorities and normative preferences.

The currently dominant version of integrated water management, which is described in *Muller* [2015] as "Dublin IWRM," emerged after a preparatory technical meeting on water and the environment ahead of the 1992 World Summit on Sustainable Development, the so-called Rio Earth Summit. The four principles of Dublin IWRM focused on the need to treat water as an economic good; to ensure full public consultation and involvement of users in the planning and management of water projects; and for a holistic approach to management linking water and land use with management focused at a watershed level. It also gave a ritual nod to the role of women in water management (reportedly, in order to gain the support of some Nordic delegates).

The developed countries failed to have the Dublin Principles included in Agenda 21, the 1992 Rio Earth

Summit's action plan. Despite this, and ignoring the progress that had been made since 1977 in achieving greater intersectoral coordination [*Biswas*, 1988], the developed countries promoted Dublin IWRM energetically, not least by establishing new organizations, outside the formal multilateral structures. The Global Water Partnership (GWP) was established through a process described as "… a negotiated agreement among major world lenders, donors, and stakeholders in the water and aid business in the mid 1990s" [*Priscoli*, 2013]. At a time when many developing countries, the targets of this approach, were under the whip of structural adjustment, they were conspicuously absent from the decision; GWP's mandate was specifically to promote IWRM and to enforce the Dublin principles on them.

If only through the sheer volume of sponsored literature and meeting activity, Dublin IWRM eclipsed the more practical and operational approaches agreed in Mar del Plata in 1977 and achieved a degree of hegemony in academic and donor discourse. But its policy status was not as clear-cut. While lip service has been paid to Dublin in international fora, investigations suggest that the more pragmatic and functional Mar del Plata approach to water management continued to guide practice in countries that were not dependent on Dublin-oriented donors [*Lenton and Muller*, 2012].

The evidence suggests that the key differentiators between the two approaches were those that dominated the Rio Summit: the tension between the socioeconomic development priorities of poorer countries and the prioritization by the rich of environmental protection. Related to this, Dublin gave priority to economic objectives and instruments (which, incidentally, were favored by environmental advocates since they could be counted on to reduce water use while creating opportunities for private sector involvement) while Mar del Plata advocated a balanced approach between social and economic objectives and maintained a leading role for governments.

So one diagnostic characteristic of Dublin IWRM was the removal of the word "development" from the original 1977 formulation of "Integrated Water Resource Development and Management" and the omission of the word "infrastructure" from much of the GWP's literature. As a "participant-observer" (a member of the GWP's Technical Committee (TEC) for 6 years, from 2006 to 2012), I repeatedly drew attention to this. But despite agreement in the TEC and increasingly loud calls from the African "partners," GWP continued to avoid the inclusion in its literature of any substantive reference to the approaches needed to support the development of infrastructure.

The perception of an environment-development tension is reinforced by students of water governance such as Conca who states simply that the real objective of IWRM has been to promote the environmental goal of, as he put it, "dismantling the practices of the era of damming, diverting, draining and dumping" [*Conca*, 2006, p. 162]. This is consistent with Priscoli, who reports that "I have observed that, for many, IWRM was coming to primarily mean including/adding ecology."

This enforced prioritization of environmental conservation and economic instruments has resulted in predictable divergences of approach and more or less apparent conflicts. As Conca reports, the top priorities of governors of the World Water Council (WWC, another Dublin institution) were substantially different from those of the WWC's ordinary members. While the governors placed "moving to the pricing of all water services" as the highest priority, WWC members put it at the bottom of their lists; they wanted priority for human needs, safe water and sanitation, and water for food security [*Conca*, 2006, p. 158]. More significantly, African Water Ministers through their collective body AMCOW signaled their continued intention to develop infrastructure by setting as their goal raising the proportion of Africa's water that is actually used from 5 to 40% by 2030 [*AMCOW*, 2013].

For the WEF nexus, one consequence of this disjuncture has been that Dublin IWRM is unhelpful. To the extent that irrigation and power generation need to be coordinated, this has to be done in the context of the development and management of the relevant infrastructure. This process cannot usefully be informed by a paradigm that is inherently anti-infrastructure and prioritizes an overarching goal that is at odds with the political priorities of most developing countries.

3.6. POLITICS, ECONOMICS, AND INSTITUTIONS: IWRM, VIRTUAL WATER, AND THE NEXUS

Effective decision-making about water management in the WEF nexus requires an institutional framework that can function within the broader political economy of the society concerned. To the extent that the issues addressed are primarily in the economic realm, decisions must also be informed by sound economic analysis. In this regard, IWRM is also of limited assistance. Through their challenge to the role of the state, "IWRM advocates have reframed water. They have moved it from the unquestioned domain of sovereign states to the realm of a more diverse array of stakeholder participants" [*Conca*, 2006, p. 162].

Indeed, one of the strongest recommendations of Dublin IWRM was for the resolution of water-related disputes at the lowest possible level in institutions in which users had a strong voice. Specifically, "… the role of governments needs to be reviewed to ensure that users, local institutions and the formal and informal private sectors can play a more direct part."

This approach relies heavily on concepts of collective resource management developed by Elinor Ostrom, who showed that, contrary to pessimistic predictions of the "tragedy of the commons" [*Hardin*, 1968], it was possible for common pool resources like water to be sustainably managed by their users [*Ostrom*, 1990]. In IWRM, this is translated into management at the "lowest appropriate level" within the geographic frame of river basins. However, this ignores the empirical basis of Ostrom's work, which focused on relatively small and homogeneous groups in which stakeholders can observe the behavior of their peers and in which there is limited potential use of the resource by outside parties. Even in this context, she found that local systems of cooperative management were generally only effective when they were nested within and empowered by overarching systems of governance [*Ostrom*, 2009].

However, where there are substantial differences in power, resources and interests, external pressures and demands, and/or an absence of a central framework, collective voluntarism is unlikely to work. This has been demonstrated in practice at the regional scale by the disputes that have emerged between nation states over water allocation and use in Central Asia. While there was a strong central government in the Soviet Union, it set a framework within which the disparate water uses of different states could be coordinated. But when that central authority disappeared with the collapse of the Soviet Union, water management cooperation collapsed in its wake [*Juraev*, 2013; *Jalilov et al.*, 2013].

The limitations have also been demonstrated at other scales. *Giordano and Shah* [2014] provide a range of examples at national and more local scales where a formulaic institutional approach to water management has failed because it did not take account of local political economies. In consequence, they conclude that "decision makers can do best by focusing on solutions to specific problems rather than on universal, water-centred approaches. This involves understanding the physical, social and especially political context of the challenge."

This builds on *Mollinga et al.* [2007], who proposed "a politically informed 'strategic action' perspective, which we develop around the notions of 'problemshed' and 'issue network'." As a first step, they call for recognition of the "centrality of the political" in water management. This is in keeping with the focus of the WEF nexus which, in its essence, calls attention to the need for pragmatic approaches to dealing with both opportunities and conflicts that may arise between interested parties, within and between the different sectors.

If Dublin IWRM's institutional paradigm neglects basic political economy dynamics and understates the role of governments, it also overstates the significance of water's status as an economic good. Its narrow economic focus has encouraged the use of concepts such as "virtual water" (the water embedded in goods such as agricultural produce) and related methodologies such as "water footprinting" (the amount of water used in the production of particular goods and services) to guide water resource management policy and planning.

While this cannot be dealt with in detail here, its implications for the WEF nexus are sufficiently important to make brief mention of the theoretical limitations.

First, the apparently attractive idea that water resource management decisions can be guided by treating water as an economic good whose efficient use can be achieved in markets is theoretically flawed. While acknowledging that water markets may work in specific circumstances, such as in trade between farmers on the same irrigation scheme, *Dellapenna* [2012] argues that the public good nature of water as well as the many externalities involved in its various uses limits the extent to which markets can be created.

Similarly, proposals that "virtual water" flows should be analyzed and used to guide water use for productive purposes (away from water-"stressed" regions and toward regions where water is plentiful [*Hoekstra*, 2011]) is fundamentally flawed from an economic perspective. As Wichelns has pointed out, "By focusing on the water resource endowment, alone, virtual water represents an application of absolute advantage, rather than comparative advantage…. For this reason, policy prescriptions that arise from virtual water discussions are not those that will maximize the net benefits of engaging in international trade. Comparative advantage is the pertinent economic concept, and virtual water considers only absolute advantage" [*Wichelns*, 2010].

Other authors highlight the need to consider the opportunity cost of water in different situations as a likely driver for production decisions. The relevance of this for the WEF nexus is clear from the title of the paper by Liu and her colleagues: "International trade buffers the impact of future irrigation shortfalls" [*Liu et al.*, 2014].

3.7. CONCLUSION: THE NEXUS AS A RETURN TO BETTER WATER MANAGEMENT

The WEF nexus is a convenient concept. It captures some of the impacts that global change will impose on societies through the medium of water, ranging from the uncertainties about water availability caused by energy-related climate change to the need for robust trade regimes to deal with food supply shocks that may be occasioned by extreme weather. It highlights both the dangers to food security of opportunistic expansions of biofuels production and the potential to optimize social benefits through the coordinated use of water storage for hydropower and irrigation.

But it fails to address many other key challenges. Most notably, it does not consider the impact of rapid global urbanization, which is likely to be the most significant change to impact on water resources over the next century and it misses the contribution of water resource development and management to disaster risk reduction. By conflating the nonconsumptive use of water for energy (in hydropower) with the consumptive use (in cooling thermal power stations), it distracts from important challenges, such as the management of water quality impacts from urban and industrial development. In general, it detracts from a more systematic consideration of environmental issues and misses the opportunity to support the construction of a sustainable Anthropocene aquatic environment rather than simply to protect what is left of nature.

Through its narrow focus, it risks repeating the errors of approaches such as Dublin IWRM and assessment tools such as virtual water and water footprints which seek to locate water as central to development decision-making. Contrary to both theory and evidence, it encourages consideration of water as a primary factor determining the geographic distribution of agricultural production, ignoring the economics of comparative advantage. It focuses attention on decision-making regarding water uses at a watershed scale without due consideration of the institutional and political economics of development decision-making in the broader "problem-shed."

At worst, too narrow a focus on the WEF nexus could contribute to a disintegration rather than an integration of water management, reversing the important gains in policy coherence over the past half century.

Nonetheless, it has significant value as a communications tool. It highlights systemic interactions and the need to consider different sectoral water uses as elements of a system rather than in isolation. As policy debates over climate change give more attention to adaptation, it will help to prioritize the practical contributions that hydropower can make as a tool for the integration of other renewable energy sources. Similarly, a focus on the need for flood protection for high productivity agricultural land as well as for cities will, it may be hoped, strengthen the moves toward a more positive and less polemic discussion about the role of dams and related infrastructure in the Anthropocene environment of the twenty-first century.

So consideration of the challenges in the WEF nexus may help strengthen moves to manage water in a more practical, while still integrated, fashion: addressing water quality and quantity as a single system; recognizing that underground water and surface streams are part of a single hydrological system; and coordinating the planning of the needs of different sectors and doing so within the wider development governance and planning systems of each society. In these ways, the nexus may indeed make a useful contribution to the achievement of more sustainable water security in the world's fast-growing developing countries.

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4

Dynamic, Cross-Sectoral Analysis of the Water-Energy-Food Nexus: Investigating an Emerging Paradigm

Alex Smajgl[1] and John Ward[2]

ABSTRACT

Development-focused debates increasingly employ the water-food-energy nexus concept as a new perspective to diagnose conflicting sectoral objectives and improve the assessment of large-scale investments in energy, water, or food security. Current frameworks largely approach the nexus from a static-comparative, water-centric perspective. In this chapter, we argue that a dynamic nexus framework that assigns equal weight to the water, food, and energy sectors introduces an emergent paradigm that yields novel cross-sectoral interactions. The chapter describes a comparison of a static nexus analysis with a balanced and dynamic investigation of nexus interactions in the Mekong River Basin (MRB). A key advantage of the dynamic approach compared to static analyses is an improved capability to identify and diagnose how cross-sectoral connections emerge and are altered as a consequence of single-sector interventions.

4.1. INTRODUCTION

Development-focused debates increasingly use the emerging water-food-energy nexus concept as a new perspective to structure large-scale investments. Many policy makers have emphasized the relevance and utility of the nexus approach during various supranational fora. Developing strategies based on the nexus architecture demands a clearer focus of integrated research, continuing the process introduced by the sustainability paradigm of the 1980s. Since gaining political momentum in 2008, conceptual variants and revisions have been developed in the science domain and one explicit nexus study has been implemented in the Mekong River Basin (MRB) [*Smajgl and Ward*, 2013d]. However, we argue that current nexus frameworks are largely water-centric and therefore represent a partial analysis [*Smajgl et al.*, 2016]. We propose a nexus approach with equal weighting to the water, food, and energy sectors and argue that such a balanced framework can provide novel insights into understanding cross-sectoral dynamics. In this chapter, we describe the development of a sectorally balanced, dynamic nexus framework and application in the Mekong basin. In conclusion, we examine the additional benefits a nexus perspective yields by testing implementation options and results to move the debate from a largely conceptual, abstract domain to policy-relevant initiatives. The results provided in this chapter emphasize the improved capability to diagnose and analyze novel cross-sectoral interactions as the primary advantage of a dynamic nexus approach compared to static-comparative assessments. The proposed dynamic approach reveals how the occurrence, sign, and magnitude of sector connections emerge and are altered as a consequence of single-sector interventions in the water-food-energy nexus.

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4.2. FROM A WATER-CENTRIC TO A TRULY INTEGRATED CONCEPTUALIZATION OF THE NEXUS

In 2008, the World Economic Forum identified the need to improve the coordination of investments in water, food, and energy, thereby establishing the nexus as a policy-relevant perspective. The Bonn Conference [*Hoff*, 2011] presented the nexus as a more focused conceptualization of integrated assessment. This event triggered the development of several concepts, frameworks, and methodologies that looked at the interlinkages between water, energy, and food [*Mohtar and Daher*, 2012; *ADB*, 2013b; *Bizikova et al.*, 2013; *UN-ESCAP*, 2013], but also land and soil (*European Report on Development*, 2012; *Hoff et al.*, 2013), minerals [*Andrews-Speed et al.*, 2012], and ecosystems [*ICIMOD*, 2012; *UNECE Task Force on Water-Energy-Food-Ecosystems*, 2013].

Although this has helped broaden the focus, the approaches and conceptualizations are far from unified and differ greatly in their scope, geopolitical context, objectives, and understanding of sectoral drivers [*Benson et al.*, 2015]. *Leese and Meisch* [2015] argue that current nexus conceptualizations fail to address distributional disparities and *Foran* [2015] argues that current approaches fail to account for historical social and political trajectories that give rise to contemporary water, food, and energy planning and regulatory regimes.

The majority of nexus frameworks reviewed by *Smajgl et al.* [2016] take a water-centric viewpoint shifting the focus to specific trade-offs between water and the production of either food or energy, neglecting analysis of the interactions between food and energy security. In contrast, we describe a balanced nexus framework that demands analysis of all potential sectoral trade-offs by equally weighting water, food, and energy security. We argue and present evidence that by privileging the water sector, analyses remain partial and insufficiently cross-sectoral, in contrast to the stated intent of the nexus paradigm. Additionally, most frameworks are designed to provide the practitioner with the diagnostics to compare two points in time, before and after a specific change, which we refer to as a static-comparative perspective. A dynamic nexus approach emphasizes the continuous interaction between (i) the three nexus sectors (water, food, and energy) and between (ii) the nexus core and the three nexus sectors.

In this chapter, we depart from both a water-centric conceptualization and static nexus approaches, emphasizing the identification and characterization of critical development nodes of change as the primary loci of nexus interactions (Figure 4.1). The nexus core (Figure 4.1) consists of factors critical for water, food, and energy security dynamics and cross-sectoral feedbacks. For the purpose of this chapter we limit the complexity of interacting factors and their hierarchical feedbacks to population growth and climate change as the core drivers that determine the status of ecosystem services. Such a nested conceptualization is critical for nexus-type analyses to develop a better understanding of multisector interactions as interdependent and dynamic. In turn, sectoral outcomes feedback on and influence the attributes of core drivers, creating sustained interactions. Later in the chapter, we argue that dynamic processes cause the constituent nexus factors (illustrated within the diagram) to improve/expand or deteriorate/contract. Amendments to nexus factors are expressed as the qualitative or quantitative change of sector outputs, the characteristics of sector interaction, or the condition of the core drivers, that is, ecosystem services.

Figure 4.1 depicts a range of typical interactions in the cross-sectoral connections. Later we argue that a nexus perspective provides most benefit in intersector negotiations if these connections are understood as continuously evolving linkages, disaggregated to correspond to the application context. Policy interventions can be made in any one of the food, water, or energy sectors and we assume that, historically, decision-making has been largely sector specific and independent. Figure 4.1 depicts three discrete entry points, introducing sector-specific interests. The central rationale for the nexus discussion is that previous sector investments have generally been made without cross-sectoral coordination, targeting prescribed, often non-commensurate, sector-specific optima, thereby exposing the nexus to a high risk of unintended side effects and negative sector trade-offs. Application of a balanced nexus approach acts as a device to stimulate debate to improve sector coordination, potentially to reconcile investments that would be treated as suboptimal by individual sectors, but that ultimately improve overall system outcomes. Sustained debate can reveal three possible classes of interventions: those targeted at single sectors, those targeted at intersector links manifesting as critical nodes, and those targeted at altering the status of core nexus drivers. In the Mekong analysis discussed here, the latter option is constrained to affecting population change, investment in climate change mitigation strategies, or safeguarding ecosystem services and functions.

From a cross-sectoral perspective, a nexus conceptualization guides development investments and their analytical support toward an explicit consideration of trade-offs. In the past, some advanced work in one sector such as food security has considered some linkages to associated sectors, among other things irrigation. However, our nexus conceptualization demands of the researcher and decision maker an explicit and extensive consideration of sector interdependencies. As a corollary,

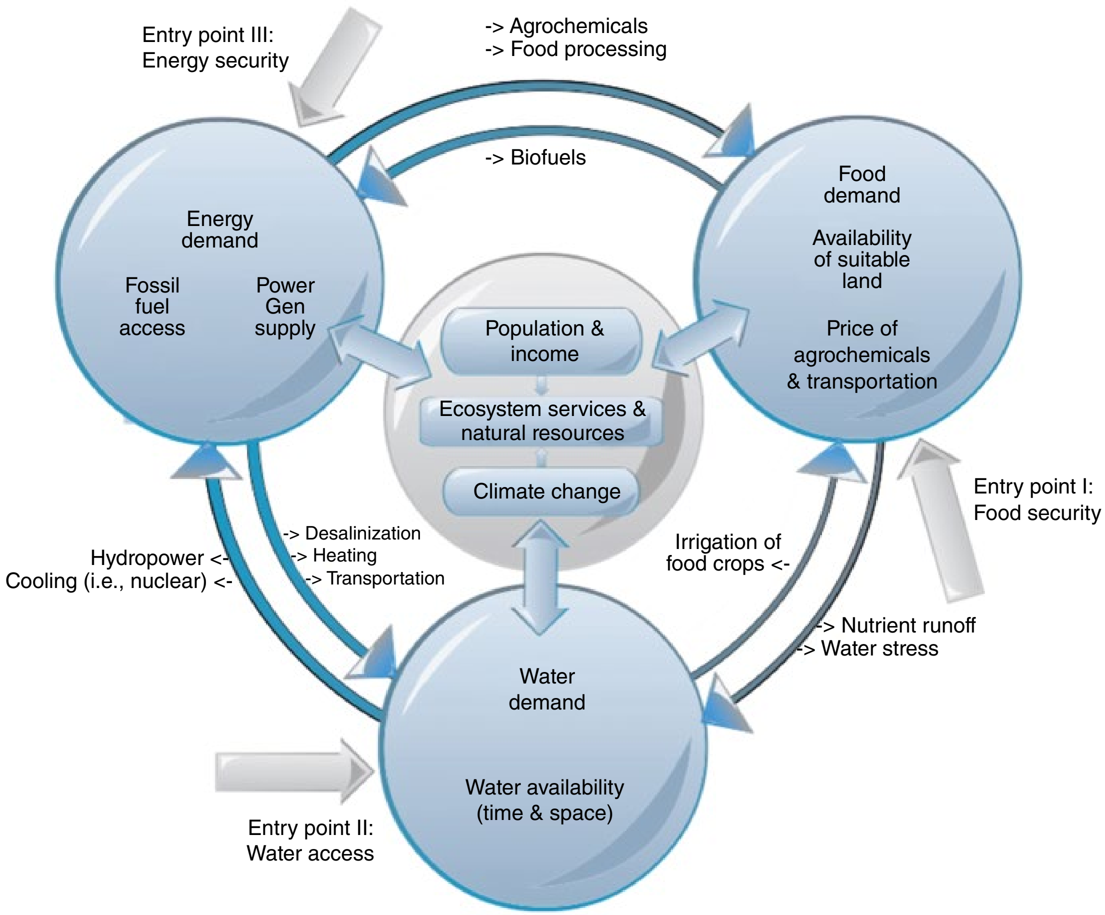

Figure 4.1 The water-food-energy nexus. Source: Adapted from *Smajgl and Ward* [2013c].

a comprehensive nexus-based food security analysis would also explicitly address the potential trade-offs between energy and water. Such trade-offs might offset or complement expected economic or social dividends of investments in the food security space. Coordinating investments and developing consistent policies that allow for sustainable development would ideally involve the following:

1. A diagnosis and subsequent understanding of all sector connections
2. Specifying potential trade-offs and synergies for the specified context
3. The design of effective measures that help mitigate or reconcile trade-offs and exploit synergies
4. Ongoing monitoring and assessment of investment consequences on nexus dynamics

We implemented the nexus framework in the transboundary context of the MRB, first, to translate the nexus conceptualization from the abstract to application and, second, to empirically test the hypothesis that nexus-framed negotiations lead to novel policy insights and decisions.

4.3. ANALYZING THE NEXUS IN THE MRB

The Delphi technique was deployed to initially diagnose nexus interactions in the MRB, representing one element of a mixed method participatory approach, described in *Smajgl et al.* [2016]. Expert panels or Delphi techniques are commonly defined as "a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem" [*Linstone and Turoff*, 1975, p. 3]. Consistent with *Linstone and Turoff* [2002], structured and facilitated deliberation, iterative amendments based on meeting discussions, and information refinements of the initial expert appraisals were introduced to assist the panel to identify and address subjective biases and promote more impartial assessments.

Six sector-specific analysts were commissioned to assess the impacts of national development initiatives previously nominated by Mekong specialists and decision makers with potentially nexus-related consequences at both the national and regional levels [*Smajgl and Ward*, 2013d, pp. 13–16]. The impending developed initiatives were (i) a series of 12 hydropower dams on the lower mainstream Mekong; (ii) water diversion from Lao PDR into Northeast Thailand; (iii) adaptation to sea-level rise in the Mekong Delta; (iv) expansion of monoculture rubber plantations in Yunnan; (v) railway expansion; and (vi) bauxite mining and possible alumina production. The assigned sectors were water [*Pech*, 2013]; food security [*Fullbrook*, 2013]; the Mekong energy system [*Foran*, 2013]; livelihoods and migration [*Bouapao*, 2013]; land use [*Lu*, 2013]; and mining [*Lazarus*, 2013]. Each expert was asked to conduct a desktop assessment specific to their assigned sector of each of six individual investments followed by a cumulative assessment assuming all six development investments would simultaneously occur. This first step employs a traditional static comparative perspective. The dynamic cross-sectoral nexus assessment commenced with a structured and facilitated workshop comprised of the 6 invited experts and 10 additional regional and agency experts to promote broader assessment.

Experts were first presented with the suite of sectoral assessments. Second, experts were only confronted with the effects of development investments, independent of proposed causal factors and determinants. Third, the effects systematically listed within individual sectoral assessments were presented and experts asked to identify likely sectoral reactions and events activated by these changes. The process allowed for an effective interaction and intersecting of sectoral assessments and was repeated to specify second- and third-order impacts. Finally, cause-effect chains were constructed that were independent of individual sectoral perspectives and arranged in system diagrams. The final step for conducting the cross-sectoral assessment included the analysis of all six system diagrams, one for each chosen investment.

4.3.1. The Status of Nexus Dimensions in the MRB

4.3.1.1. Nexus Core

This section provides a snapshot of the framework dimensions, the nexus core, and the three nexus sectors. Table 4.1 presents information about the nexus core at the level of Mekong countries and the Chinese province of Yunnan.

Population growth averages around 0.98% per annum (p.a.) with Cambodia having the highest growth rate of 1.67% p.a. followed by Lao PDR with 1.63% p.a. [*CIA*, 2013; *China Perspective*, 2014]. Ecosystem-service-related information for Mekong countries is scarce. Table 4.1 lists deforestation and freshwater utilization for agriculture as two relevant indicators.

The Climate Risk Index [*Harmeling and Eckstein*, 2012] ranks countries based on annually occurring human and economic losses due to climate events (floods, droughts, other extreme events). The index is used as an indicator that better reflects the current status of the climate change dimension, compared to a singular reliance on climate projections. Myanmar, Thailand, and Vietnam rank among the 10 countries with the highest climate risk when the long-term average is considered (1992–2011). Thailand was ranked the country with the highest risk and Cambodia with the second highest risk worldwide in 2011. This indicates that existing capacity of Mekong countries to protect human lives and economic assets from climate-related events is extremely low. Climate projections point at a further increase of climate-related vulnerabilities in the Mekong region [*ICEM*, 2013].

4.3.1.2. Water

The Mekong River today is at the forefront of experiencing large-scale, rapid development interventions. Until the late twentieth century, the Mekong River remained a relatively unmodified river system of low impoundment, connecting the primary livelihood pursuits of agriculture, fishing, and forestry of a predominately rural population [*Molle et al.*, 2009]. However, the steep elevation gradients of the headwaters and upper catchments of the main tributaries have provided opportunities for impoundments and hydropower generation, tentatively coexisting with biodiversity hotspots, small-scale localized irrigation, and swidden agriculture. The rapid gradient transition to the extensive plains and deltas has allowed water diversions for agrarian

Table 4.1 State of nexus core variable for Mekong region countries

	Population			Ecosystem-related uses		Climate risk index
	M	Δ %	Area (km^2)	Forest area change (annual average)	Freshwater withdrawal for agriculture	1992–2011 (average)
Thailand	67.5	0.5	513,120	0% (2000–2010)	90% (2007)	9
Vietnam	92.5	1.0	331,210	+1.6% (2000–2010)	95% (2009)	6
Lao PDR	6.7	1.6	236,800	−0.5% (2005–2010)	90% (2010)	68
Cambodia	15.2	1.7	181,035	−1.2% (2005–2010)	94% (2006)	28
Myanmar	55.2	1.1	676,578	−0.9% (2000–2010)	91% (2010)	2
Yunnan (2010)	46.0	1.2	394,000	+1.34% (2000–2010)	65% (2010)	23

Sources: *CIA* [2013], *China Perspective* [2014], *ADB* [2012], and *Harmeling and Eckstein* [2012].
M, millions and Δ, population growth.

landscapes, including extensive irrigation in the delta, inland, and coastal fisheries, and river-based transport.

The transboundary situation is critical for understanding water resource availability. The mean annual runoff from China into the Mekong River is 77.7 km^3 [*MRC*, 2010]. Myanmar contributes on average 13.7 km^3/year, while Thailand contributes 68.6 km^3/year further downstream [*MRC*, 2010]. The mean annual contribution occurring in Lao PDR is 146.2 km^3/year, while Cambodia contributes 121.8 km^3 and Vietnam about 29 km^3 on an annual average [*MRC*, 2010; *FAO*, 2011a]. The total mean annual discharge into the South China Sea is 457 km^3 [*MRC*, 2010].

4.3.1.3. Energy

Foran [2013, table 21] uses a vector of eight dimensions, described by 13 measurable indicators to account for the multiple factors influencing the status of national energy security of Mekong countries. *Foran* [2013] estimates average annual growth rate of primary energy supply for 2005–2025 at 4.9%, moderating to 4.4% in 2025. Supply is estimated to increase from approximately 10,000 PJ (PJ is petajoule = 10^{15} J) in 2005 to approximately 25,000 PJ in 2025. The top three sources of primary energy in 2005 were crude oil, biomass, and coal; by 2025 they are projected to be coal, crude oil, and biomass. The share of hydroelectricity in the region's primary energy supply was projected to grow from 2 to 5.5% during 2005–2025, an annual growth rate of almost 10%. Final aggregate energy demand for the Mekong countries in 2025 was estimated at 20,000 PJ. *Foran* [2013] estimates that the supply contribution of hydropower generation to meet aggregate electricity demand will increase from 20% in 2005 to 35% in 2025.

4.3.1.4. Food

Fullbrook [2013] describes four primary dimensions that influence the status of food security in Mekong countries: availability, accessibility, utilization, and stability. From the Global Hunger index, *Fullbrook* [2013] derives that national food security has improved for all Mekong countries from 1990 through 2011; however, food security in Cambodia, Laos, and Myanmar remain classified as serious or alarming. Around 25 and 31% of the Cambodian and Laos population, respectively, were classified as undernourished [*FAO*, 2011a, 2011b]). *Hall and Bouapao* [2010] argue that the daily calorific intake of Mekong communities in Cambodia, Isan, and the Vietnam Delta is especially sensitive to estimated fish catch reductions (and associated protein loss) and is likely to result in nutrition levels below the recommended 1864 calories per day.

4.3.1.5. Development Strategies

In consultation with national decision makers and decision influencers across the Mekong basin (details of the participatory process can be found in *Smajgl and Ward* [2013b, 2015] and *Smajgl et al.* [2015b]), the following development strategies were identified:

1. Hydropower (led by the energy perspective)
2. Energy crops (led by the energy perspective)
3. Irrigation projects (led by the food perspective)
4. Diversion of dry season flows (led by the water perspective)

There is a potential for substantial trade-offs for each of the three sectors, which we analyze in the following section. Many of these trade-offs occur in the transboundary context, as the Mekong region is highly connected, allowing effects to ripple quickly and widely through the "system." Connecting dynamics include human migration, natural resource flows, and increasing levels of private and state financial investments [*Dore*, 2003; *Harima et al.*, 2003; *Theeravit*, 2003; *Contreras*, 2007]. For example, investors from China, Thailand, and Vietnam increasingly replace traditional donor organizations in order to source natural resources or manufacturing capacity in neighboring countries [*Middleton et al.*, 2009; *Molle et al.*, 2009].

The effects of large-scale investments in weakly connected regions are generally constrained to locales proximate to the initial investment area within a particular country and tend to be limited to the investing sector. In contrast, high connectivity implies that investment factors (or drivers) interact, transmitting the effects of substantial changes from one part of a region to another and to other sectors.

4.3.2. Static Comparative Nexus Analysis

As a first step, we describe water resource development, food production, and energy security as examples of the synthesized results of a static comparative analysis of the four development options in the Mekong, derived from a Delphi expert panel methodology implemented to elicit nexus interactions [*Smajgl and Ward*, 2013d]. Biophysical and economic assumptions underpinning development-directed interventions were derived from available scientific evidence. Sector experts identified and assessed the direct primary impacts of development investments on their designated sector. First-order sector effects were subsequently assigned to other sector experts and imputed as changes to identify probable second-order effects. This methodological step was repeated to identify tertiary impacts within the nexus to trace some possible feedback dynamics.

The implementation of a nexus analysis of development strategies in the MRB disclosed a range of likely trade-offs. Hydropower development has been identified as the dominating intervention [*Smajgl and Ward*, 2013d], likely to substantially alter the hydrological regime and, as a consequence, the availability of water during the year and between countries. If combined with planned large-scale irrigation projects, the dry season flow is likely to increase by 70% in Thailand and Lao PDR but only by 10% in Vietnam's Mekong Delta [*Pech*, 2013]. *Pech* [2013] argues that the upstream advantage to Thailand and Lao PDR of increased flows available for dry season irrigation is moderated by the increased risk of flash flooding arising from uncoordinated dam releases replacing the cycle of natural floods. Based on recent experiences, dam releases can rapidly increase river water levels by up to 6 m for 40–50 km downstream from a reservoir. *Thorne et al*. [2013, table 3] argue that substantial economic losses would occur for farmers in the Vietnam Mekong Delta as the approximately $160-200\times10^6$ t/year of sediment are estimated to be reduced by 55–100%, depending on how many planned dams are constructed. Reductions in associated nutrient loads are estimated at 20–65%, requiring substantial investments to replace fertilizer inputs to maintain current production levels [*Smajgl et al*., 2015a].

From a food perspective the cumulative consequences of the development decisions outlined earlier are likely to include a substantial reduction in fish stocks and fish diversity, increasing regional dependence on imported food, thereby increasing food prices [*Hortle*, 2007; *Fullbrook*, 2013]. The two latter consequences are likely to intensify as more irrigation potential is utilized for energy crops instead of food crops.

From an energy perspective power generation capacity is likely to increase and, by lifting power constraints for the manufacturing sectors, gross domestic product is likely to increase [*Foran*, 2013]. However, energy prices are also likely to increase as a function of rising infrastructure and implementation costs [*Foran*, 2013].

Some of the insights listed above could have been identified without an explicit water, food, and energy nexus investigation. However, the iterative expert panel process revealed a novel and critical aspect: the occurrence, sign, and magnitude of cross-sectoral connections that emerge and are altered as a consequence of single-sector interventions in the water-food-energy nexus. Thus, identifying nexus dynamics emerged as the most critical step.

4.3.3. Dynamic Nexus Analysis

The improved understanding of cross-sectoral linkages and nexus-wide dynamics reveals a set of elements that are important in "transmitting" ripple effects throughout the nexus system [*Smajgl and Ward*, 2013a]. The MRB investigations revealed that what is typically conceptualized as a simple arrow (e.g., in Figure 4.2) is more accurately described as a series of convergent links of variable stability.

We refer to those conjunctions of links that substantially influence the sign and magnitude of cross-sectoral connections and the overall nexus outcomes as *system criticalities*. This concept is derived from network theory [*Newman*, 2010; *Estrada*, 2011] and complex systems theory [*Funtowicz and Ravetz*, 1994; *Miller and Page*, 2008], which introduce critical nodes as particularly important nodes of a network (or system) at hand. The degradation (or "failure") of these critical nodes can trigger a decline in the robustness of the system or even a complete fragmentation or collapse of the overall system [*Buldyrev et al*., 2010; *Cohen and Havlin*, 2010]. The dynamic attributes of nexus interactions and the probability of more sustainable outcomes is contingent on the state of such critical nodes, or *system criticalities*. Prioritizing development investments to manage and sustain the state of system criticalities is therefore an alternative approach to direct investments in the food, water, or energy sector. Such an approach would ensure that decisions are based on the nexus as a dynamic system and allow for management of the nexus as a holistic entity, rather than independent sectoral elements.

The investigation of nexus relations and properties in the MRB identified five system criticalities:

1. Transboundary fish stock management
2. Risk management for monocultures
3. Migration policies
4. Sectoral labor transition policies
5. Energy demand management

4.3.3.1. Transboundary Fish Stock Management

If fish stocks were explicitly managed in the transboundary context of the Mekong basin, the outcomes of development interventions in the water-food-energy nexus are likely to be more sustainable. This is largely due to the positive side effects of safeguarding fish stocks; these include the circumvention of transboundary changes of water flows, the shifting flood risks, and the relocation of sedimentation dynamics and reduction of sediment/nutrient loss. The annual fish catch in the Mekong basin is about 3.9 million tons, which translates to \$3.9 billion to \$7.0 billion and covers about 49–82% of animal protein consumed [*Baran et al*., 2013].

4.3.3.2. Instruments to Manage Risks from Monocultures

The substantial push toward economic efficiency in land use planning coincides with increasing social, economic, and ecological risks as diversity in land use planning declines. The phenomenon of increasing monocultures largely concerns energy crops and rubber emerging as central interlinkages between water, food, and energy security. Monocultures reduce income diversification and expose households to either economic or productivity-related risks [*Duangmany*, 2014; *Häuser et al*., 2015]. For instance,

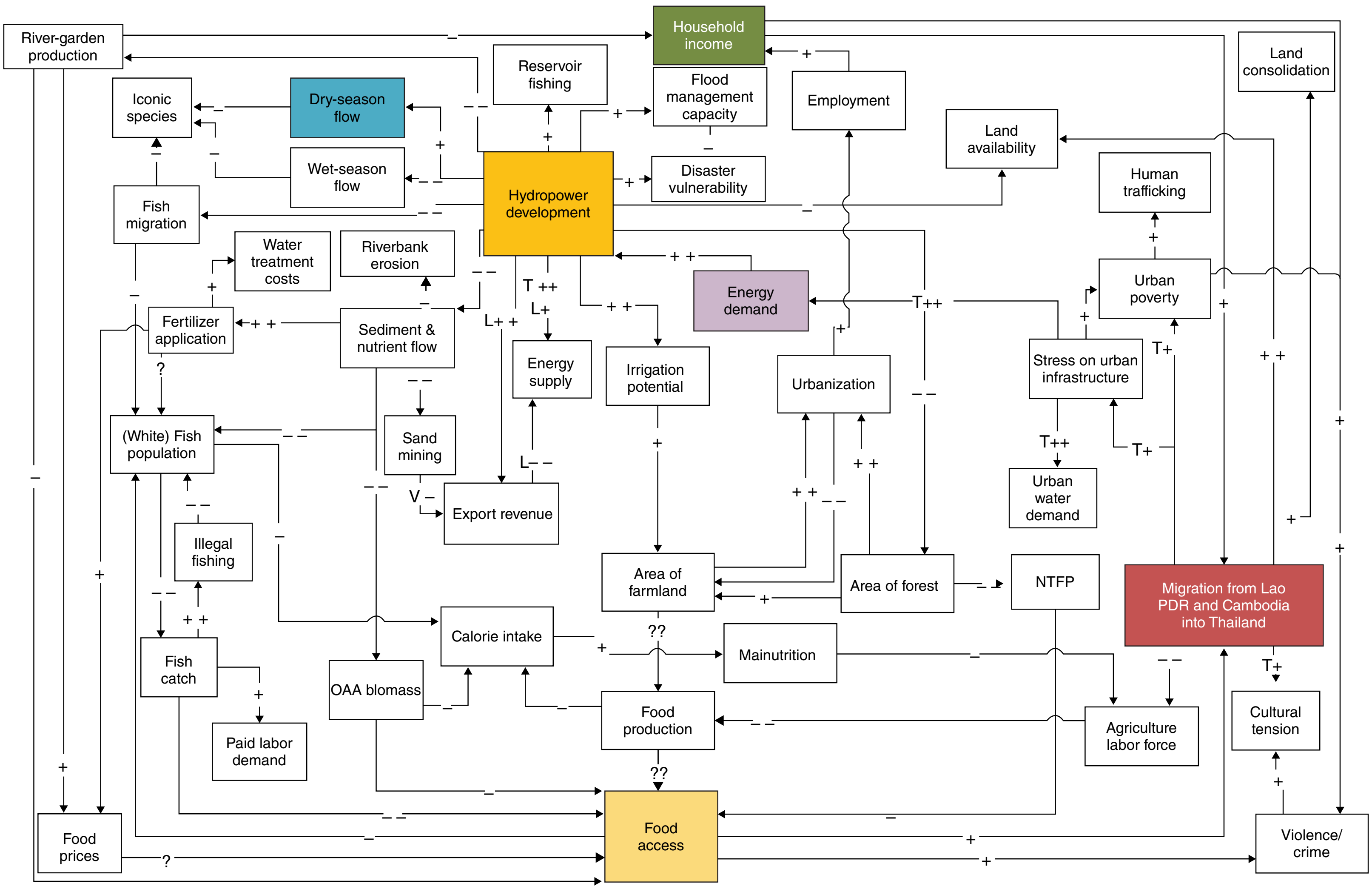

Figure 4.2 Systems diagram developed by connecting primary, secondary, and tertiary impacts of hydropower. Source: *Smajgl and Ward* [2013d]. Reproduced with permission of Springer.

the recent drop in rubber prices (also in 2011–2013) caused substantial income losses [*Fernquest*, 2016]. Focused management of monoculture development through risk management instruments could be vital to avoid substantial breakdowns between nexus sectors. Community-level micro-insurance systems could be explored as one possible instrument for safeguarding this specific system criticality [*Newbrander and Brenzel*, 2002; *Churchill*, 2008]. The expansion of monocultures often coincides with land-grabbing [*Hirsch and Scurrah*, 2015], which requires institutional improvements and robust land titles [*Leach et al.*, 1999] to avoid negative nexus-wide ripple effects.

4.3.3.3. Strategies to Avoid Migration Peaks due to Change in Access to Natural Resources

Environmental, economic, political, social, and demographic factors can trigger substantial displacements [*Black et al.*, 2011; *Dun*, 2011]. In the Mekong region, migration dynamics can be amplified by a combination of development decisions and climate change (e.g., sea-level rise, flash floods). Putting anticipating strategies in place to manage migration and mitigate such peaks would help avoid unsustainable trajectories as sudden forced migration dynamics are associated with attendant changes to natural resource utilization. Anticipating migration dynamics and adapting institutional arrangements, for example for fishing, could prevent resource collapse. For instance, results from social simulation modelling and a large-scale household survey reveal that sea-level rise and upstream development (hydropower and irrigation projects) could trigger large-scale emigration to Vietnamese urban centers and across the Cambodian border to the Tonle Sap (where many ethnic Vietnamese reside) [*Smajgl et al.*, 2015a]. This forced migration would then have consequences in the peri-urban system of Ho Chi Minh City and also increase the pressure on already stressed fish stocks in the Tonle Sap. Data for the actual basin boundaries are not available. However, recent UN estimates suggest that the number of people emigrating from lower Mekong basin countries has increased since 1990 by 150% [*UN*, 2015]. This does not include domestic migration.

4.3.3.4. Labor Transition from Primary to Secondary Sectors

The transition from primary to secondary and tertiary production emerges as another system criticality from the analysis. The more households that engage in secondary and tertiary sectors and the more that reside in urban centres, the more the urban electricity demand is likely to grow. Also, the introduction of institutional arrangements to fairly distribute secure and enforceable rights and entitlements to land (and possibly water) and the more that management anticipate labor transitions from primary to secondary and tertiary sector livelihoods, the more likely it is that unproductive land and inefficient irrigation (e.g., in Northeast Thailand) can be avoided. However, without adequate institutional settings, policies, and government programs, the increased conurbation is likely to translate into urban poverty and unemployment, which in turn encourages potential back migration to rural regions but with potentially degraded land and supporting social institutions (and often forgotten skills) or dispossession of returnees. Basin-specific employment data are not available. However, for lower Mekong basin countries, primary sector employment ranges from 73% in Lao PDR and 48% in Cambodia to 32% in Thailand and 17% in Vietnam. The range suggests a looming transition potential, in particular in Lao PDR and Cambodia.

4.3.3.5. Management of Energy Demand Instead of a Singular Focus on Energy Supply

Many energy sector intervention options currently target an expansion of power generation capacity and supply. However, many of the negative side effects emerging from the Mekong analysis of nexus-wide dynamics could be avoided if supply options were combined with a genuine consideration of demand management and interventions, such as energy-saving campaigns or monetary incentives to change consumptive behavior and habits that underpin increasing energy demand. If compared internationally, Mekong region countries seem to underutilize demand side management (DSM). *ICEM* [2010] reports DSM-based reductions of peak demand in Thailand by 1435 MW and in Vietnam by 120 MW. Unfortunately, quantified estimates for the potential of aggregate DSM to reduce (peak) electricity demand have not been developed for the Mekong basin. Potential electricity demand reduction for New Zealand (one of very few countries that quantified DSM potential) has been estimated at 22% [*Treasury*, 2005]. Reliable translation of the New Zealand estimates requires among other things an accounting of Mekong country development status, consumer behavior, and willingness of generators and governments to amend supply investments. However, recent electricity demand forecasts for the lower Mekong basin countries suggests that the potential of DSM would lower a business-as-usual forecast by approximately 60 billion kWh [*ADB*, 2013a; *CIA*, 2013], approximating eight Xayaburi dams.

In synthesis, identifying the ensemble of system criticalities and understanding them as intervention points could, if effectively managed, guide nexus interactions to yield more sustainable outcomes.

4.4. DISCUSSION

This chapter describes a nexus framework and conceptually consistent analysis geared to the sectoral attributes and impending development imperatives in the MRB.

We tested a working hypothesis that a balanced and dynamic nexus framework, compared to a hydro-centric or static approach, introduces a new operational paradigm. Testing of the balanced nexus frameworks provided supportive evidence, revealing novel, emergent insights when deliberations treat sectors as elements of a dynamic rather than a static nexus system. The equal weighting of the water, food, and energy sectors was introduced as an initial analytical condition central to the analytical rationale. Competing approaches that privilege one specific sector, for example water resources, tend to constrain analysis to the connections of one or possibly two of the other sectors.

The dynamic nexus analysis demands that researchers initially consider the links between their sector of expertise and explanatory variables and a comprehensive assessment of connectivity between all of the three sectors. In addition, analysis of the interactions and trade-offs that occur between the two other sectors exposes novel and potentially important feedbacks for the initial sector under investigation.

The dynamic analysis revealed that interventions in the nexus could change the magnitude and sign of cross-sectoral interactions, demanding increased attention to improve the understanding of nexus interdependencies. With the amended focus and subsequent understanding of the expert panel, system criticalities were diagnosed, locating potential intervention or governance nodes for managing the nexus toward more sustainable outcomes. The focus on system criticalities potentially overcomes the reduced system dividends of development investments geared to a single resource or development sector.

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5

Urban Nexus: An Integrated Approach for the Implementation of the Sustainable Development Goals

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ABSTRACT

Asia's urbanization is unprecedented and this rapid transformation is having a profound impact on the region's key natural resources, such as water, energy, and food/land. Urban nexus, an integrated framework focusing on the dynamic interaction of these three key sectors, addresses the gaps in linear resource use patterns and builds on the three pillars of sustainability. It aims to integrate systems, underpinned by policy coherence and collaborative governance, while redefining spatial relationships of cities with their surrounding areas and resources. Such an integrated approach to resource management can also play a key role in the implementation of the newly adopted sustainable development goals (SDGs), reducing potential trade-offs and strengthening synergies across goals and targets. A review of experiences in the region, and in particular three case studies (Nashik, Da Nang, and Shenzhen) highlight the enabling factors, mechanisms, and policies required to facilitate the adoption of an urban nexus approach.

5.1. INTRODUCTION

5.1.1. Urban Transformation of the Asia Pacific Region

In 2018, the Asia and Pacific region will pass a historic threshold, in which over half of its population will be living in urban areas. All subregions in this area are experiencing urban growth at higher rates than overall population. Between 1980 and 2010, the region's cities grew by around one billion people. United Nations projections show they will add another billion by 2040 [*ESCAP and UN-Habitat*, 2015]. Noting this transformation, the development prospects of the region will increasingly depend on how its cities are managed. This is an especially acute challenge for the region's medium-sized and small cities, as it is in these cities that the region's urban transition is largely unfolding. This is a critical trend and dynamic in the region.

Urban transformation has been rapid and is having a profound impact on the region's natural resources. The high resource intensity of the region's economies and the levels of waste and emissions across the region call for urgent action to improve efficiency in the use of water, energy, land, raw materials, and ecosystem services [*ESCAP*, 2015a]. Meeting this goal will be a key planning challenge in the future. We argue that a nexus framework, one that cuts across sectors such as water, energy, and food/land, placed in the context of meeting the region's urbanization and sustainability challenges, provides a useful framework which moves beyond sector-specific policies and planning. An integrated or nexus approach advocates a resource-efficient path to economic growth which is people-centered and respects planetary boundaries while concurrently meeting the needs of both present and future generations, as detailed in the following sections.

Cities are no longer bounded entities and are far from being the compact entities that many urban plans and

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Edited by P. Abdul Salam, Sangam Shrestha, Vishnu Prasad Pandey, and Anil Kumar Anal.

models aspire to. The region's urban areas have large footprints extending into peri-urban and rural areas. This spatial diffusion, or urban sprawl, is a characteristic especially of the region's larger cities, but emerging smaller urban centers have fluid and blurred *desa-kota* (village-city) growth patterns. Defining urban areas has thus become a problematic epistemological and planning exercise. Though recent studies have revealed increasing density and the emergence of compact urban design in East Asia, even here an estimated 350 urban areas spill over local administrative boundaries. In 135 of these urban areas, no single jurisdiction encompasses even half of the total urban area [*WB*, 2015]. One pronounced example is the Pearl River Delta, now considered to be the world's largest urban area/city. In 2000, the Pearl River Delta covered 4500 km^2, but grew very rapidly to nearly 7000 km^2 in 2010 [*WB*, 2015] and to 55,000 km^2 in 2014 [*Citiscope*, 2014]. It now comprises an "urban system" of at least 11 cities [*Citiscope*, 2014].

Overall, urban development patterns in the region have been characterized by unbridled expansion, in which development has been increasingly driven through informality and private sector development. Both these drivers have undermined or exposed the limitations of formal planning frameworks and boundaries, and development increasingly takes place in the absence of effective monitoring, regulation, and enforcement.

Such trends are evident in terms of land use. Urban land cover is projected to increase more than twofold between 2010 and 2050 in South and Central Asia [*Angel et al.*, 2010]. Additionally, it has been estimated that Southeast Asia may lose more than 10% of its cultivated lands; Western Asia close to 10%; South and Central Asia 8%; and East Asia close to 7% due to the urban expansion that will take place between 2000 and 2050 [*Angel*, 2012]. Conversely, the Food and Agriculture Organization (FAO) has noted that some developing countries in the region will need to increase their food production by up to 77% to feed their people in 2050 [*FAO*, 2014]. Such trends and tensions are evident in even wealthier contexts. According to the "Sydney Food Futures project," farms in the surrounding regions of Sydney produced around 20% of the city's agricultural food needs in 2011, a share that will drop to 6% by 2031 due to industrial growth and suburbanization, and increasing land prices [*University of Technology Sydney*, 2015].

5.1.2. Impacts of Urban Transformation on Resource Systems

Unprecedented urbanization and infrastructure growth are rapidly degrading and destroying peri-urban ecosystems. The resulting loss of ecosystem services is happening on a global scale, but drivers and symptoms are concentrated locally. The absence of planning for such peri-urban places and systems/resources has also contributed to the absence of effective response. Flooding disasters in mega cities including Jakarta in 2007, Bangkok in 2011, and Chennai in 2015 provided a lesson that the encroachment on a natural drainage system for developmental purposes is a threat to urban life. As unplanned structures proliferated in the city and suburbs bypassing regulations, water bodies disappeared. The impact of such irreversible destruction of the city's natural water paths can be seen in urban flooding in several major urban areas in the region that have developed on wetlands or around river basins.

Such evident trends, and their impacts on water, energy, and food security, as well as vulnerability to natural disasters, have resulted in greater awareness and efforts to respond. In recent years, greater attention is being paid to the expansionary patterns of urbanization in the region, and to the need for an integrated approach to minimize its negative impact on resources and ecosystem services. For example, New South Wales Government through its "A Plan for Growing Sydney" implemented in 2014 seeks a sustainable and resilient city that can protect the natural environment and have a balanced approach to the use of land and natural resources. In Tokyo, local agriculture produces enough vegetables to feed almost 700,000 city dwellers and is also home to the world's biggest indoor farm, which covers 25,000 ft^2. Efficient technologies and policies are being utilized so that the farm uses 40% less power and 99% less water than outside fields [*Web Urbanist*, 2015]. Some national policies are also taking into account resource efficiency, climate change, and resilience. *Thailand's Eleventh National Economic and Social Development Plan* [2012–2016], for example, integrates various dimensions, including the management of natural resources and the environment toward sustainability, as well as the linkages between agriculture, food, and energy. It places "people at the center of development," and promotes "balanced development" along with "resource efficiency." It integrates and incorporates economic, environmental, and political dimensions so as to attain well-defined outcomes at all societal levels and to position the country's development on the middle path.

We argue in this chapter that a fundamental shift is required in the management of both natural resources and structures of urban planning and governance. There is an urgent need for new planning, management approaches, and multilevel and collaborative governance systems based on integrated planning, of land use and resources, in order to balance demands from increasing urban populations and meet the needs of changing consumption and production patterns. This was clearly reflected in the 2030 Agenda for Sustainable Development and its sustainable development goals (SDGs), unanimously adopted by all 193 member countries of the United Nations in September 2015. Resource management remains one of the cross-cutting issues fundamental to the achievement of sustainability in cities and across a number of other sustainable development goals and targets.

5.2. CONCEPT OF THE URBAN NEXUS

5.2.1. Urban Nexus and Related Concepts

The concept of urban nexus, or integrated resource management in cities, focuses on the interlinkages among key sectors (water, energy, and food/land) and their interconnected conversion pathways (extraction, production, supply, distribution, end use, and disposal). It aims to integrate systems, services, policies, operational "silos," and jurisdictions to achieve water-energy-food (WEF) security in cities to meet multiple urban policy objectives. It also aims to deliver greater benefits with equal or less resources, and minimize negative trade-offs [*GIZ and ICLEI*, 2014].

Urban nexus is an approach to analysis, assessment, policy development, and implementation that builds around two or more key sectors (mainly water, energy, and/or food/land). Typically it involves a set of coordinated and integrated measures in a broad range of areas (such as policy, planning, finance, institutional design, science, technology, and innovation (STI), communications and data sharing, and legal frameworks) leading to a "solution set." As illustrated in Figure 5.1, it builds on the three dimensions of sustainable development (SD) by ensuring equitable development and access, and moving from short-term resource exploitation to long-term investments, in support of national economies. It also highlights the importance of and the challenges associated with governance.

Challenges associated with the nexus approach involve governing the trade-offs between the different sectors and dealing with the plurality and interactions of policies that are in place. It requires appropriate legal, political, and administrative arrangements and decisions on applicable and suitable instruments (fiscal and otherwise) to mitigate trade-offs and ensure access to high-quality water, energy, and food services for all, while safeguarding the ecosystems that provide these services.

Urban nexus draws from and extends the concept of "urban metabolism," which is defined as the analysis of all the technical and economic flows of energy and materials

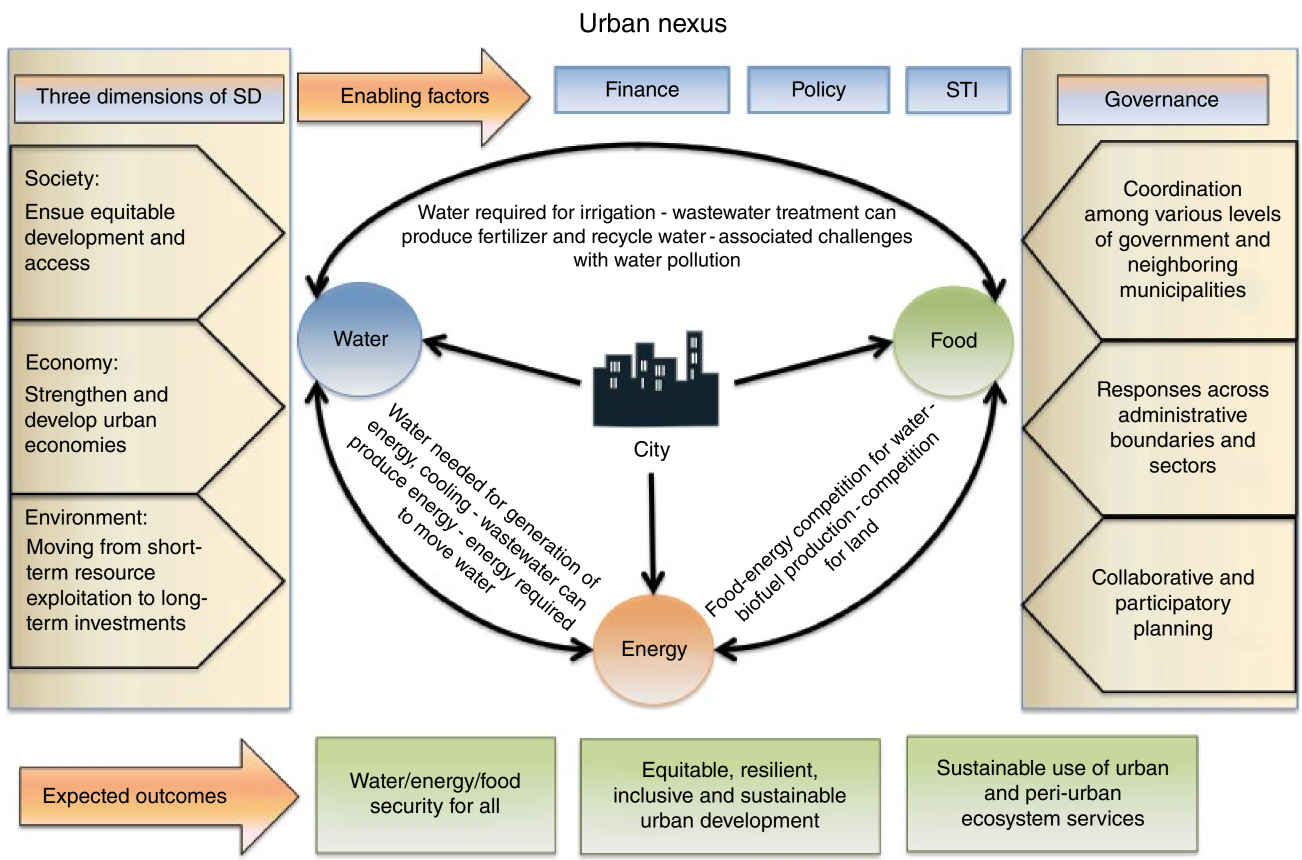

Figure 5.1 Conceptual framework of urban nexus. Source: ESCAP.

associated with the production and consumption activities in the cities [*Kennedy et al.*, 2010]. In today's world, intensive and changing consumption and production patterns threaten the sustainability of cities, which depend on spatial relationships and resource interlinkages with their surrounding areas.

In 2008, when the food and fuel crisis hit many developing countries, coupled with the global financial crisis, it exposed the vulnerability of developing economies to the trade-offs in the use in these critical resources. An urgent need to look at resources in an integrated manner emerged globally. In 2011, United Nations Secretary-General Ban Ki-moon underlined the importance of a "nexus approach" noting that "As the world charts a more sustainable future, the crucial interplay among water, food and energy is one of the most formidable challenges we face" [*UN*, 2011].

The landmark Bonn 2011 Nexus Conference "The Water-Energy-Food Security Nexus – Solutions for the Green Economy" was the first to present and discuss the concept of the nexus as a viable and alternative policy approach. Understanding the importance of integrated approaches in dealing with resource efficiency, a number of subsequent programs and conferences were held to address the governance and policy challenges and translate ideas into actions. For example, integrated approaches to food security, low-carbon energy, sustainable water management, and climate change mitigation are among the topics of the "Horizon 2020 Programme," [2014] the largest European Union Research and Innovation program to date, with a funding of nearly €80 billion. Its major project on "Urban Nexus" advances strengthened and enabled strategic urban research on integrated, smart, sustainable, and inclusive growth, underpinned by good governance. It is being used to address real challenges and further sustainable urban development and planning toward reduction of the "urban ecological footprint."

Research programs, knowledge platforms, and conferences have highlighted the relevance of the nexus approach for sustainable development and have raised awareness that more systemic thinking is needed. Thus, rather than focusing on the individual resource footprints of an urban ecosystem, the "urban nexus" is concerned more with the dynamic interaction among key resources, using a systemic approach to optimize the interconnections within the whole urban system.

5.2.2. What Is "Urban" about Urban Nexus?

According to United Nations estimates, by 2030 the world's population will need 30% more water, 45% more energy, and 50% more food, and climate change will exacerbate this stress even further [*UN*, 2012]. Cities are increasingly becoming national development assets, producing an estimated 80% of global gross domestic product (GDP) on just 2% of the land's surface [*UNEP*, 2013]. Cities are complex networks of interlocked infrastructures that draw resources in, use these to provide services, generate wealth, and dispose wastes that are generated through production and consumption [*UNEP*, 2013]. Urban areas are net consumers of key resources and the water-food-energy components interact and flow in the cities with a highest density of intersections [*Beck and Walker*, 2013].

The way these material flows are interlinked, transformed, and returned to the environment by the city transcends administrative boundaries, and provides important questions and challenges for sustainability. Synergistic solutions to address the WEF nexus will be vital to develop sustainable and inclusive societies, economies, and ecosystems, specifically within the context of rapid urbanization. The case of Bengaluru city, as detailed in the following section, is one illustration of the need for an understanding of the nexus approach in urban areas.

5.2.2.1. Bengalaru City: Demonstrating the Need for an Integrated Approach

One example to illustrate the urgency for an integrated or nexus approach, as a strategy to address gaps in resource consumption and production patterns, can be drawn from Bengaluru, the "Silicon Valley of India." Bengaluru is a hub for biotechnology-related industry and, in the year 2005, 47% of the biotechnology companies in India were located there [*Ramos*, 2006]. With a GDP of $83 billion, the city is ranked fourth in India by overall GDP contribution [*WB*, 2013]. Bengaluru is the third most populous and the fastest growing city in India.

The urban population grew from 5.7 million in 2001 to 8.5 million in 2011, while the urban area increased by 49% during the same period [*Census Organization of India*, 2011] as illustrated in Figure 5.2. Different sources estimate that in 2015 as much as 30% (1.4 million people approximately) of the urban population lived in slums and lacked basic services. Over the years, the urban expansion to the fringes has led to the decline of agricultural land by 16% [*Kavitha et al.*, 2015]. Such changes in urban population, urban area, and industrialization growth have also resulted in loss of arable land, thus affecting food production, as well as placing high demand on key sectors of energy and water for basic delivery services and rapid industrialization.

In Bengaluru, the projected water demand between 2011 and 2031, for an urban population of 8.52 million and 14.31 million respectively, is estimated to increase from 1683 million liters a day (MLD) to 2831 MLD, while the supply capacity is only up to 1460 MLD, thus creating a severe shortage [*Ramakrishnaiah*, 2014]. In 2007, the power required to pump water to the city was 50 megawatts (MW) and the energy required to transport the

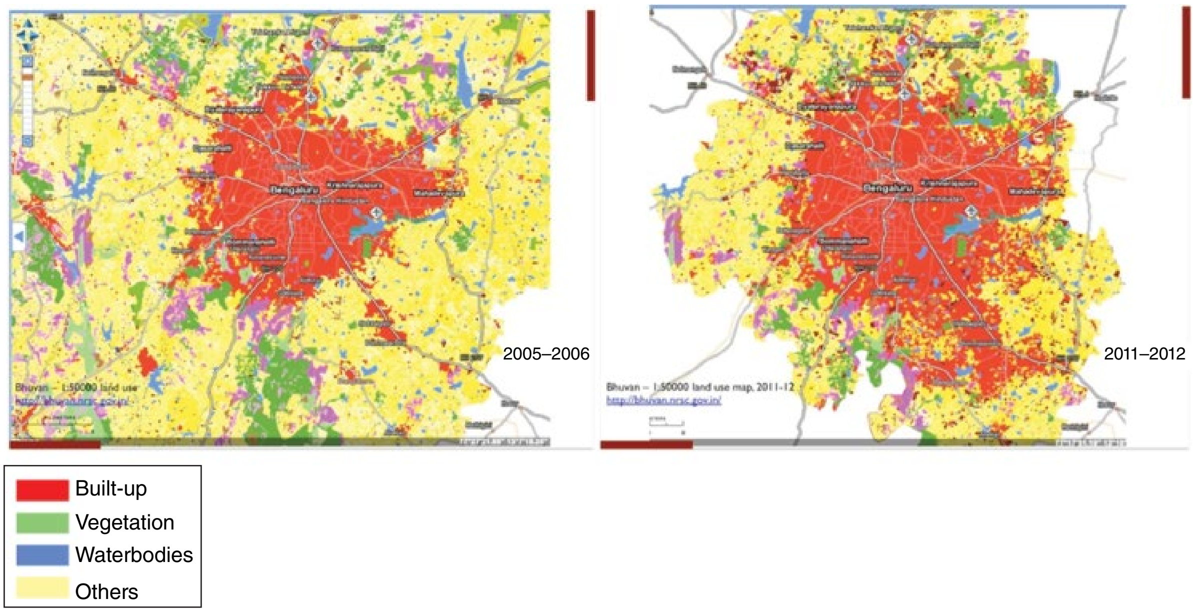

Figure 5.2 Change in land use and land cover. Source: Reproduced with permission from *Indian Institute for Human Settlements* [2011]. (*See insert for color representation of the figure*.)

water consumed 75% of the Bangalore Water Supply and Sewerage Board's (BWSSB) revenues [*The Hindu*, 2007].

With the increase in energy and water demand for industries, urban farming, and residential units, linear resource use patterns result in inefficiencies and negative trade-offs. For example, there is water demand for energy generation, urban agriculture, and supply for residential and industrial purposes; and energy demand for urban agriculture, residential units, and rapid industrialization.

In meeting its present and future needs, Bengaluru is a pertinent case of the urgent need to "close the resource loop." For example, in 2013, the city generated around 4000 tons of solid waste every day [*TERI*, 2015] and the total wastewater generated was estimated to be 1100 MLD while the installed capacity of wastewater treatment plants (WWTPs) was 721 MLD in 2013 [*Jamwal et al*., 2014]. As one example, integrated waste management practices could lead to reduction in water degradation, increase water use efficiency, and improve energy security, and the by-products could be used for agriculture and building purposes. Thus, for a city like Bengaluru, addressing challenges of resource and waste management demands a more devolved and integrated planning strategy. Such planning and management strategies in the changing urban paradigm increasingly return to forms of more circular and location-specific metabolic processes.

5.2.3. Urban Nexus: Opportunities and Challenges

Nevertheless, achieving a circular and integrated metabolism at the scale of the city is challenging. The dynamics of resource use, emissions, and waste generated, as well as the relationship between urban and peri-urban areas is changing, resulting from the huge pressure on urban ecosystems and contested resources, caused by rapid urbanization and industrialization. Resource gaps are ever increasing. As urban areas expand, pressure on peripheral ecosystems is exerted. Within the city, a number of sectors compete for the shared resources and a number of tensions or policy failures surface along time. Thus, integrated approaches can be opportunities to mitigate cross-sectoral competition around resource distribution, while addressing social, economic, governance, and environmental concerns, and to move toward sustainable development.

However, there exist serious conflicts between increasing demand and the waning carrying capacity of resources of an urban area. The question then arises as to what are the strategies to address these conflicts? Political priorities play a critical role for agenda setting. Each city has their own priority over natural resources. For example, local governments often have to raise their own funds to maintain economic growth; thus, land grant fees became the main source of fiscal revenue and with time agricultural land was lost to developmental projects. Within this context, the following could be some of the key questions:

1. How can policies be developed to encourage sustainable and integrated resource management in cities?
2. How is it possible to formulate collaborative problem-solving processes and what are the lessons learnt from systemic failures?

3. Where are the trade-offs, what are the negative impacts, and where are the entry points?

4. What are the enabling factors?

The following sections address and illustrate responses to these challenges, at both the global and local levels.

5.3. MANAGING OUR URBAN FUTURE: THE SDGS AND URBAN NEXUS

January 2016 marked the official launch of the new 2030 Agenda for Sustainable Development, adopted unanimously last year by all 193 member countries of the United Nations. The new Agenda calls on countries to begin efforts to achieve 17 SDGs over the next 15 years [*UN*, 2015]. "The seventeen sustainable development goals are our shared vision of humanity and a social contract between the world's leaders and the people," said UN Secretary-General Ban Ki-moon. "They are a to-do list for people and planet, and a blueprint for success" [*UN News Centre*, 2015]. The SDGs will, therefore, provide the main framework for international cooperation on sustainable development for the next 15 years.

The SDGs recognized the importance of the key resources of water, energy, and food through dedicated goals, namely Goal 2 (End hunger, achieve food security and improved nutrition, and promote sustainable agriculture), Goal 6 (Ensure availability and sustainable management of water and sanitation for all), and Goal 7 (Ensure access to affordable, reliable, sustainable, and modern energy for all). The important role that cities play in the pursuit of sustainable development was also acknowledged with the inclusion of a goal on cities (Goal 11) aiming to "make cities and human settlements inclusive, safe, resilient and sustainable."

With regard to urban areas, the SDGs called for substantially increasing the number of cities and human settlements adopting and implementing integrated policies and plans toward resource efficiency, mitigation, and adaptation to climate change, and resilience to disasters (Target 11.b); regarding water, they called for the implementation of integrated water resource management (Target 6.5); and concerning agriculture, they called for ensuring sustainable food production systems and implementing practices that help maintain ecosystems and strengthen capacity for adaptation to climate change, flooding, and other disasters (Target 2.4). The 2030 Agenda also called for the sustainable management and efficient use of natural resources (Target 12.2).

Given such mandates, there is an important opportunity to further develop and mainstream urban nexus concepts and practices into urban planning and the management of cities with regard to resource use. The urban nexus directly supports the achievement of Target 8.4 to improve global resource efficiency in consumption and production and endeavor to decouple economic growth and environmental degradation.

Synergies developed between nexus approaches and integrative solutions such as peri-urban agriculture, rainwater harvesting, waste management, and sustainable land use planning can not only enhance water, energy, and food security but also improve resilience and livelihoods of urban areas. For example, urban and peri-urban farming is an efficient way to meet the city's food system, reduce the city's external water footprint as well as utilizing runoff water, and offer opportunities for resource recovery (urban wastes to energy: target 7.2; treated wastewater for irrigation: target 6.3) and climate change adaptation (e.g., designating low-lying urban areas and flood plains for agriculture to reduce the impact of floods: target 13.1). Adopting an urban nexus approach would also support the implementation of a number of other targets. For example, by promoting sustainable waste management, clean energy and water, and improved sanitation, the nexus approach contributes to improved health outcomes (Goal 3).

Urban nexus practices acknowledge and reiterate the necessity of integrated strategies and solutions to managing resources vis-à-vis development needs, as urged in the SDGs. Adopting an urban nexus approach would also help strengthen synergies among goals, and minimize potential trade-offs and tensions (e.g., between the promotion of industrialization: Goal 9, the conservation of natural ecosystems: Goal 15, and sustainable cities: Goal 11). Similarly, the nexus approach argues that a sustainable urban land use plan should not only include parks and open spaces in the built-up environment but also accommodate and leverage natural ecosystems, such as wetlands (target 15.1) that can provide economically valuable and sustainable ecosystem services and prevent urban flooding (address target 13.2).

Considering that local governments generally lack the resources (both financial and human), as well as the capacities to implement such a broad agenda, an urban nexus approach can assist local governments in prioritizing initiatives. For example, the promotion of a nexus approach can strengthen the means of implementation of the SDGs, and in particular strengthen domestic resource mobilization (target 17.1) through rationalization of land taxes and water and energy tariffs, enhance regional and international cooperation on science, technology, and innovation (target 17.6), as well as develop coherent policies (target 17.14) to deal with the plurality of sectoral policies that are in place. Such initiatives can deliver multiple benefits and contribute to the achievement of several SDGs at the same time. In this regard, it would be important to strengthen capacities to quantify potential and actual benefits of integrated approaches.

5.4. IMPLEMENTING THE URBAN NEXUS IN PRACTICE

An overview of recent urban transformations indicates an urgent need to address resource gaps in demand and supply, in conjunction with the competition from different sectors for the same resources. An integrated approach is one of the underlining themes in meeting the acute challenges of "closing the resource loop," and "in bridging the resource gaps." It can be applied to improve resource productivity at the local and regional levels, and to avoid unintended consequences of linear sectoral approaches leading to unsustainable utilization of resources, as illustrated through the following case studies of Nashik, Shenzhen, and Da Nang. The three case studies highlight challenges, strategies, and enabling elements that have contributed in bringing about change and in implementing sustainable patterns of resource consumption, production, and utilization at the city level. Such changes are critical for the implementation of the urban agenda in the region.

5.4.1. The Case of Shenzhen, China: Reforms in Local Water Management

Shenzhen, "the first and most successful special economic zone in China," is located in the Pearl River Estuary. From 1979 to 2014, the total population of Shenzhen increased from 300,000 to 18 million; its GDP went from ¥200 million to ¥11.6 trillion, and it experienced a 300-fold urban land expansion from 3 to 968 km^2. From 1995 to 2009, the net loss in the city's arable land was 33.7 km [*Qian et al.*, 2016]. This transformation has brought about significant change in the city's water and energy use, excessive consumption of resources, and regional development imbalances, food security, and other issues. In response, Shenzhen city has adopted an integrated approach to address the severe water and energy shortage and improve utilization efficiencies across critical sectors, as well as address sustainable agriculture and land use patterns as illustrated in Figure 5.3.

The significant drivers underlying the challenges were that current national energy policies failed to adequately address water use and wastewater generation, and water policies did not consider the impact of energy consumption and greenhouse gas emissions. An understanding of the interdependent relationship between water, waste, energy, and agriculture, owing to its industrial transformation, advancement into a megacity, and an urgent need for sustainable land use side by side with agricultural sustainability, helped encourage the city to create new technological advancements and develop supportive policies to improve resource efficiencies on the basis of integration. The following were the key strategies used for dealing with the challenges:

1. The Shenzhen Water Resource Bureau, a government agency, combining all water-related government functions with separated regulatory and operative functions was set up. It has established a relatively complete legal system for water management and is one of the first cities in the country to do so [*Asian Development Bank*, 2010].
2. Shenzhen city is leading the reform of local water management in China. The Shenzhen Water Group (SZWRB) completed its transformation from a fully state-owned enterprise to a joint venture approved by the Ministry of Commerce. The integrated operation of water supply and drainage helped Shenzhen's sewage treatment improve substantially over a short period of time with by-products made available for agriculture. The wastewater treatment sector in Shenzhen made rapid development and increased from 56% in 2001 to over 88% in 2008 [*Asian Development Bank*, 2010].

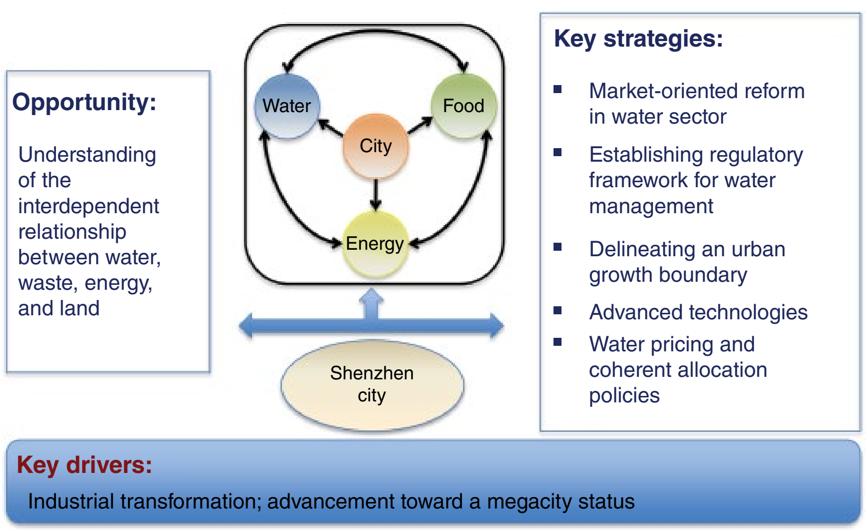

Figure 5.3 Case study of Shenzhen city. Source: ESCAP.

3. A clear regulatory relationship between regulatory departments and enterprises was established. This separation also allowed the SZWRB to regulate the industry without interfering with the normal operations of the water business. In the city of Shenzhen, a new pricing structure was introduced to encourage the use of recycled water, rainwater, and other resources in 2014. In addition, with progressive water pricing, and installing water-saving and energy-saving systems in public buildings, the water and energy saving was increased by 10–30% [*Qiu et al.*, 2014]. The optimization of the water supply system reduced energy demands and greenhouse gas emissions in the municipal water sector.

4. In 2005, Shenzhen delineated an Urban Growth Boundary (UGB), which included first-order water source protection areas, nature reserves, farmland protection areas, and forests, in addition to reservoirs and wetlands, ecological corridors, and green spaces and islands to counter emissions, which is a total of nearly half of the area of the entire city, excluded from the scope of permitted urban development. Thus, the sustainable land use policy of the Shenzhen Government accomplished the arable land protection legal framework issued by the central government and led to improvements in local ecological quality [*Qian et al.*, 2016].

5. New and advanced technologies that were applied in industries and residential areas saved more freshwater and energy use per GDP. New strategies (providing incentives to urban farmers in improving irrigation; water pricing and water allocation policies through establishing water use rights) are being applied to increase the efficiency of energy and water use in urban agriculture.

Thus, innovative institutional and market mechanisms, tailor-fit technologies, extensive policy-related research, two-way communication between central and local governments, formulation of supportive policies and reforms to address challenges raised thereof, private sector participation in financing infrastructure and managing services, and strong leadership were some of the factors behind successful change. Such integrated strategies have facilitated the implementation of the urban agenda and the achievement of cross-cutting goals and targets limiting trade-offs.

5.4.2. The Case of Nashik, India: Optimizing Resource Use

Nashik Municipal Corporation (NMC) is one of the most important agricultural hubs in the State of Maharashtra, contributing a major share to its GDP. Farming in the city is precariously dependent on groundwater as a supplement to the supply from irrigation canals. Owing to overexploitation, the groundwater and aquifers, with limited storage capacity, have been depleted, and in 2013, Groundwater Survey and Development Agency (GSDA) reported the highest recorded dip in Nashik. State energy policies have led to the wastage of both energy and water, negatively impacting both the environment and the economy of the state [*GIZ*, 2014].

Additionally, land once allocated for agricultural use along Nashik's periphery and within the city has been sold for residential purposes, thus reducing land available for food production, while the demand for food has increased due to increasing population. Thus, through the pilot project, NMC introduced the collaborative design and implementation of a set of innovative solutions and programs for optimizing water, energy, and land resources in peri-urban agricultural (PUA) practices in NMC as illustrated in Figure 5.4.

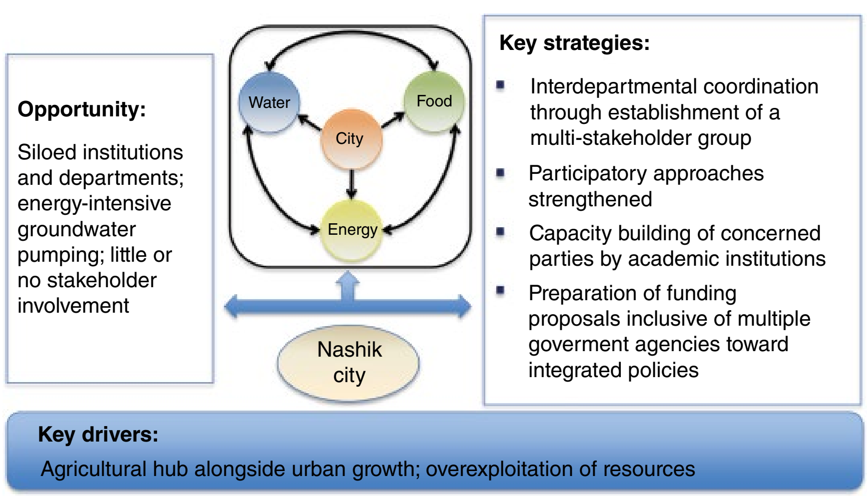

Figure 5.4 Case study of Nashik city. Source: ESCAP.

The significant drivers underlying Nashik's resource challenges are the siloed institutional departments in the city responsible for the diverse sectors and resources. The land once allocated for agricultural use along Nashik's periphery and within the city has been sold for development purposes, and energy-intensive groundwater pumping for agriculture has been prevalent. Conventionally, resource planning and management in Nashik occur in isolation with little to no involvement of relevant stakeholders, including the communities, resulting in increasing inefficiencies. The following key strategies were used for dealing with the challenges:

1. A stakeholder group (SG) was formed consisting of more than 30 representatives from departments and institutions across the various levels of governance (vertical and horizontal). Regular stakeholder meetings facilitated the decision-making process between departments and created stronger alliances among all stakeholders for interdisciplinary collaboration, cross-sectoral knowledge sharing, and institutional, financial, and legal framework.

2. The SG conducted a performance evaluation of agricultural pumps in the pilot area (Makhmalabad), which was followed by training and awareness raising on the most appropriate selection of pumps, their operation and maintenance, and the economic gains from improved energy efficiency.

3. Keeping in mind that one of the key enablers is changing resource use patterns, awareness raising programs were also initiated at the schools and communities to practically introduce the students to the rural-urban interlinkages, as well as water conservation techniques and organic farming practices.

4. NMC along with the Groundwater Survey and Development Agency came forward to create potential groundwater-recharging structures in the city at identified areas. Besides this, an online map with basic attributes was developed with regard to the location, capacity, and usage of all existing biogas plants in the pilot area so that organic wastes could be resourced. One academic institution came forward to provide necessary technical support as well as training and training materials on relevant issues.

5. NMC invested available finances into the project. In addition, the SG decided to raise awareness and prepare funding proposals in an integrated way to leverage funds from national programs such as the National Biogas and Manure Management Programme (NBMMP) under the 12th Five Year Plan.

Thus, improved interdepartmental coordination and collaborative governance, tailor-fit technologies, strengthened participatory approach of multiple stakeholders, and capacity building of concerned parties have been some of the key factors behind this success to improve resource efficiencies of the city.

5.4.3. The Case of Da Nang, Vietnam: Managing Wastewater through an Integrated Approach

Da Nang is one of Vietnam's major port cities and is surrounded by the "third focal economic zone." It is the fourth largest city by population and has a higher urbanization rate than any of Vietnam's other provinces or centrally governed cities. This exerts a rising pressure on urban infrastructure and shared resources. However, the authorities of Da Nang are committed to developing it into a "green" city by 2025. In this context, Da Nang is trying to pursue a sustainable wastewater strategy. To support this change, Da Nang city initiated the adoption of the nexus approach to address one of its priority challenges in dealing with wastewater and sewerage systems [*UN-ESCAP*, 2015b].

The pilot project is situated on the An Hai Bac ward in Son Tra district. The pilot aims to address urban flooding via separate sewerage systems and integrated waste management practice for improved resource efficiency. An integrated approach of wastewater collection and treatment, biogas production from organic wastes, and the use of by-products for urban agriculture in the periphery of the pilot area is being applied, complying with the principles of integrated resource management to optimize benefits and reduce sectorial trade-offs as illustrated in Figure 5.5.

The following were the key strategies used for dealing with the challenges:

1. A Nexus Task Force was established by a resolution of People's Committee of Da Nang City (DPC) with representatives from different key departments and other stakeholders, who were informed of the progress at each stage and were critically involved in the decision-making processes. Significantly, three different departments (DPC, Department of Planning and Investment (DPI), and Department of Natural Resources and Environment (DoNRE)) committed themselves to greater data and experience sharing, mutual consultations, and the implementation of the project.

2. The wastewater collection and treatment pilot in Anhai Bac ward comprising 110 households is proposed to be part of the pilot project for 40,000 households in the framework of the World Bank "Da Nang Sustainable City Development Program." Funded by the World Bank and the Government of Vietnam, the $218 million Priority Infrastructure Investment Project (PIIP) will help to alleviate poverty by upgrading infrastructure in low-income communities; improve resource efficiency; restore the environment with flood control, drainage, and wastewater collection and treatment facilities; and support economic growth with new roads and bridges.

3. A number of consultations were conducted with the citizens of Anhai Bac ward to explain the concept of

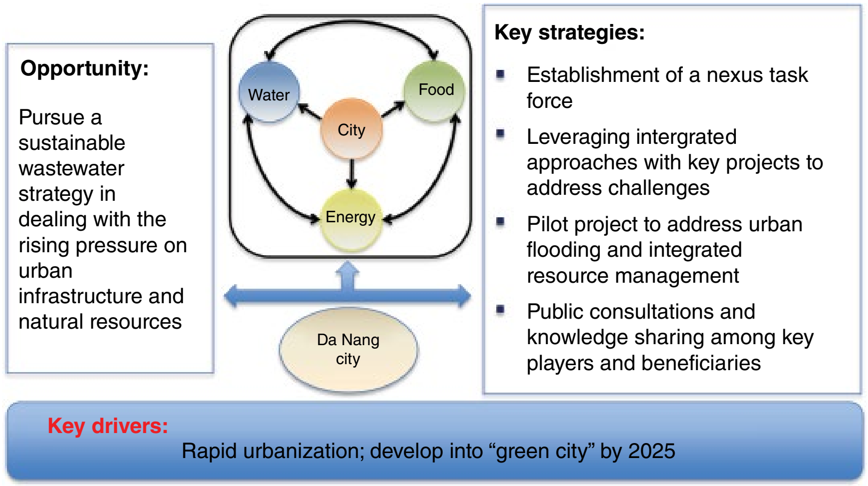

Figure 5.5 Case study of Da Nang city. Source: ESCAP.

separate sewerage systems and how to increase the organic load by recycling organic wastes into the system, which was complemented by cost-benefit analysis and a feasibility study.

Thus, legal establishment of collaborative governance mechanisms, such as the Nexus Task Force, from the initial stage of the process, a systemic approach, public consultations, and knowledge sharing among key players and beneficiaries were some of the key enabling factors for change. In 2015, Da Nang was awarded the “Excellence in City Transformation” by the Financial Times and the International Finance Corporation, reflecting international recognition for cities that adopt an integrated and holistic approach to urban development.

5.5. CONCLUSION

The urban transformation of the Asian and Pacific region will be a dominant narrative in the future, and action, integrated and inclusive, will be essential to address the gaps between urban resource use and sustainability. Drawing from lessons learned in the past, especially in the promotion of natural resource management, waste management, and urban flood management, sustainable urban planning should leverage and balance demands placed on natural systems that provide economically valuable ecosystem services, as well as capture the dynamics of changing peri-urban places, resources, and systems. However, competition across key sectors at different scales and over boundaries can cause trade-offs. Urban nexus can act as a sustainable approach to close the resource gaps and achieve the multiple goals and targets of the 2030 Agenda for Sustainable Development through coherent policies.

While the interaction among water, energy, and food securities is not yet reflected enough in government policy documents, growing confrontations over the use of these resources are evident. With natural resources and cities as cross-cutting issues across SDGs and targets, synergistic solutions will be vital to achieve sustainable societies, economies, and ecosystems. Thus, the imperative of articulating a new urban agenda moves beyond linear resource use and toward multilevel collaborative governance. Cities, through their geographically defined nature and resource use intensity, can do much to strengthen synergies among goals and targets, minimize potential trade-offs and tensions, and advance “policy coherence” models across key sectors.

Governance is a critical factor in success. Mechanisms (both formal and informal) for coordination and dialogue between national, subnational, and local governments should be strengthened. The importance of communication and coordination, and in particular of two-way communication, is critical for the implementation of integrated approaches. While the central government has a key role to play in setting objectives, policies, and standards, implementation is done at the local level, and local governments should provide useful feedback to national policy-makers on challenges encountered and support required. Information sharing is critically important.

As is evident, failure to understand, define, and constrain the scope of integration will almost inevitably lead to ill-conceived implementation and unforeseen problems. The urban nexus approach seeks to move away from systemic failures and acknowledges the links in strategic planning and implementation, and proposes to integrate planning, management, and governance across sectors, scales, and administrative boundaries to improve the security aspects of shared resources.

In evaluating individual city responses to managing ecosystem services and resources, it is essential to more effectively understand enabling factors and document how prioritization was achieved and conflict over trade-offs minimized. This is a critical future research agenda. To date, while some cities have demonstrated an understanding and willingness to address resource use in a more integrated fashion, a lack of baseline data (especially shared across sectors) limits the opportunities of quantifying the benefits of change. Nevertheless, this evidence base is important for policy makers, and remains a gap which research must seek to address.

Such analysis and evaluation could address and better understand several critical factors, among others, what measures and strategies have been developed, and worked; what innovation in technology and design has been employed, and to what quantified benefit; how innovation has been financed; the role of institutional and legal frameworks, including their change; and how urban ecological footprints have been reduced across the entire urban, peri-urban, and territorial system.

This chapter has highlighted that each city requires identification of the most effective entry points, including those with multiple benefits and those engaging a broad range of stakeholders. As each city compromises a unique resource base, and places different pressures of use on these resources, developing responsive, relevant, and effective interventions based on integrated solutions, or "urban nexus," will necessarily be context specific. In addition, each city represents its own political economy and political ecology. Integrating governance systems, breaking down silos, and developing cross-cutting policies and institutional responses is fundamentally a political process requiring leadership that understands the need for and is committed to change.

It needs to be underlined that cross-sectoral governance also addresses response to growing risks and uncertainties, with a focus on stronger networks across the private sector, levels of governments, and bureaucratic structures, as well as informal networks. Cross-sectoral and planning ministries also have a key role to play in supporting cities in their nexus approaches. The translation of collaborative and coherent policies and enabling mechanisms into action could pave the way toward resource-efficient, inclusive, and sustainable cities.

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Section II
Operationalizing the Nexus

6

Modeling the Water-Energy-Food Nexus: A 7-Question Guideline

Bassel Daher[1], Rabi H. Mohtar[1,2], Sang-Hyun Lee[1], and Amjad Assi[1]

ABSTRACT

Water, energy, and food resource systems are under increasing stress. As we prepare to move toward more sustainable resource allocation and management strategies, it is critical that we quantify and model the interconnections that exist between these sectors. Such action will help guide decision making and planning for the future of these resources and related strategies. While there is no single cookbook method for "modeling the nexus," this chapter provides a list of seven guiding questions to help conceptualize a nexus case, model it, and then assess it. The 7-Question nexus modeling guideline is demonstrated using three case studies that represent a wide spectrum of critical questions, involving stakeholders, at different scales.

6.1. INTRODUCTION

In a nonstationary world, with intertwined resource systems, uncertain externalities, and high future stakes, it is essential that we better understand the existing interconnections across different resource systems and integrate these interconnections into the decision-making process for their allocations. This will improve our ability to develop long-term, sustainable resource allocation strategies and enable us to move away from reactive, short-term tactics. Water, energy, and food securities are major constituents of a healthy economy; the ability to understand how the three resource systems interact, and the interdependencies between them, will be crucial to the development of such an economy. Different players govern and impact these resource systems, each at a different scale. To a large extent, water, energy, and food are governed and planned for from within silos: this is not synchronous with the reality of the interconnectedness that exists between them. Our ability to understand each of these resource systems, how they interact, and the trade-offs associated with various resource allocation pathways offers an important tool for planning future development. Additionally, there is a need to approach ongoing and projected resource challenges through developing solutions that recognize not only the interconnectedness between resources, but also that each is multifaceted (biophysical and socio-economic), cross sectoral, and cross disciplinary, across different scales. Decision-makers currently lack the proper tools to assess the implications of different resource allocation strategies; modeling those interactions and communicating them through proper assessment and communication tools can be a key to facilitating that process. The main goal of this chapter is to demonstrate that there is no one-size-fits-all model to address water-energy-food (WEF)-related issues. While "modeling nexus issues" follows a common, guiding, holistic, and cross-sectoral approach, localizing and contextualizing the issue in hand will be a key to assess trade-offs at a given scale [*Mohtar et al.*, 2015]. Thus, this chapter outlines a

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list of guiding questions that facilitate conceiving and modeling a "nexus issue." After that, the WEF nexus modeling platform is introduced, and then three different case studies are demonstrated. The cases studies address three critical perspectives: water security focus, energy security focus, and food security focus, at different scales (national, state, and international levels). They highlight how building on a common platform and nexus philosophy, three different models are created to respond to different questions.

6.2. HOW DO WE "MODEL THE NEXUS"? NO COOKBOOK METHOD: A 7Q GUIDELINE

There is "no cookbook" method to model a "nexus challenge": each has its own complexities at the level of resources, involved stakeholders, scale, and data needs, among others. As we work toward "modeling the nexus" for the specific case in hand, several questions need to be answered (Figure 6.1). These questions will guide conceptualization of the needed framework, quantify existing interlinkages between resources, develop scenarios, and assess trade-offs, in order to better guide decision making. The following list summarizes seven key questions (7Q) that need to be asked, several of which need to be addressed concurrently.

1. ***What is the critical question?*** It is important to identify what is driving the study: is it water scarcity, food insecurity, economic development, or other factors? The central question around which the interconnections and system of systems will be framed is a starting point and a building block.

2. ***Who are the players/stakeholders?*** Defining the critical question comes hand in hand with identifying the stakeholders, the beneficiaries of addressing those questions, as well as other players connected to the systems being considered. Stakeholders need to be involved and accounted for in the process and be part of any prescribed solution. It is important that we understand the role of policy, of the private sector, the public sector, as well as that of civil society. These players do interact, and understanding that interaction is critical to evaluating the feasibility and effectiveness of any proposed solutions.

3. ***At what scale?*** This is the critical question to be addressed at farm, city, state, national, regional, global, or some other level. Identifying the scale has a major impact on how the model is created, who the stakeholders are, and what data are needed. The question also helps identify how scenarios might be assessed.

4. ***How is the system of systems defined?*** It is important to define the systems based on the critical question/s identified. The more components the model includes, the

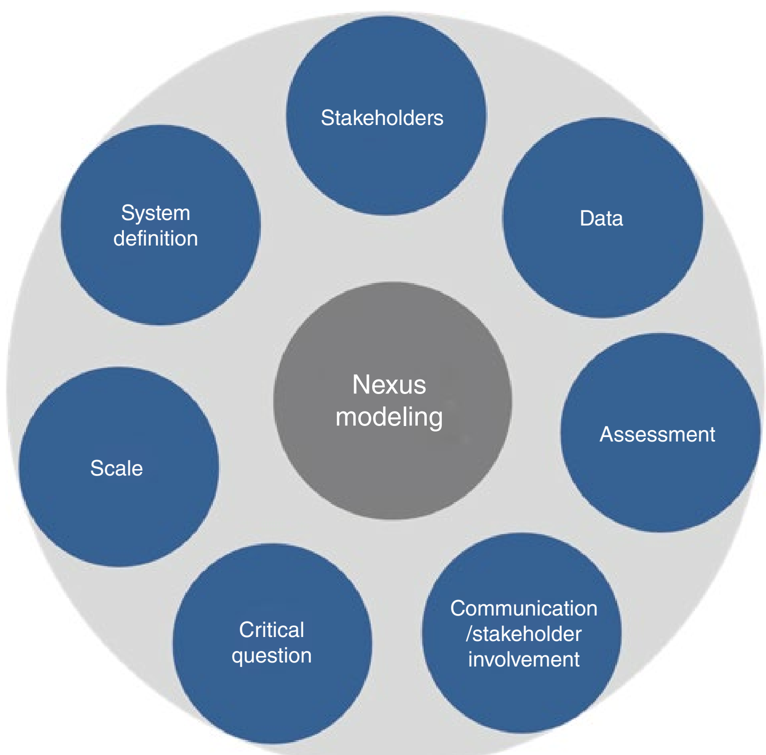

Figure 6.1 7-Question guideline for modeling nexus issues.

more complex it will be to create and manage. Simplify the system as much as possible, without losing the key interactions of interest. Our understanding of how resource systems are interconnected may be the result of a specific methodology or approach that helps capture our understanding of more generic processes and interactions. Having said that, the level of urgency into looking at these interlinkages may vary from one country to another depending on local characteristics.

5. ***What do we want to assess?*** How a scenario is assessed is an important step that allows the modeler to identify outputs that need to be quantified, and this is highly dependent on the stakeholders and the availability of data.

6. ***What data are needed?*** Depending on the end use of the analysis, data resolution and complexity can be determined. If we are looking at quick assessment to better understand certain trends, a coarser level of data may be sufficient. This is particularly useful in the absence of capacity, resources, and time. If more specific interlinkages are of particular importance, more granular data may be needed.

7. ***How do we communicate it? Where do we involve the decision-maker in the process?*** The point at which a decision-maker becomes involved is critical. The model should be presented so that unnecessary complexities are eliminated: such complexities should be addressed within the model, but should appear "transparent" to the stakeholder. The model should not take over the decision-maker's authority or make decisions on their behalf; rather, it should be able to assess possible scenarios and highlight the trade-offs associated with each. These trade-offs would then be presented to the decision-maker, who would prioritize them and make choices based on simplified results.

6.3. MODELING THE WEF NEXUS

6.3.1. WEF Nexus Platform

Many available models cover different aspects of the nexus. Some focus on answering water-specific questions; others take a more energy-centric approach; while some seek to answer food-security-related questions. A review of existing models, the areas they cover, and the types of inputs required and outputs delivered can be found in *Daher and Mohtar* [2015], *IRENA* [2015], and *FAO* [2014]. Following the guiding questions introduced in Figure 6.1, it is possible to frame the pieces that constitute the desired model. A model is both an assessment tool and a communication tool: it should help produce the required analytics to capture the consequences of different trends or practices that feed into a larger platform.

Two main pieces constitute the platform (Figure 6.2) as presented by *Mohtar and Daher* [2016]. One is the "nexus

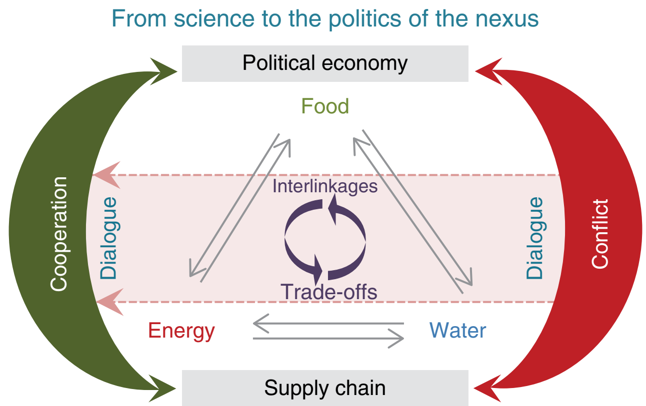

Figure 6.2 Water-energy-food nexus platform – Analytics and stakeholder dialogue. Source: *Mohtar and Daher* [2016]. Reproduced with permission of Taylor and Francis.

analytics," where interlinkages among resource systems are quantified and trade-offs assessed for an identified hot spot. These analytics are needed to facilitate a dialogue among stakeholders. The platform does not make decisions for the stakeholders; it allows them to have the necessary data, trends, and challenges that enable them to understand potential outcomes of possible resource allocation decisions.

6.3.2. Model Structure: Exploring the WEF Nexus Tool 2.0

The conceptual generic structure for the WEF assessment tool was conceived through the development of the WEF Nexus Tool 2.0 [*Daher and Mohtar*, 2015], which outlines the main elements and stages of a nexus assessment. This tool is not rigid, but is inspired by a strong nexus philosophy that considers the interconnectedness of systems, the need for holistic assessment, and stakeholder involvement. The tool is fluid in the sense that it takes on different shapes and sizes depending on the specifics of the study at hand; this will be further demonstrated in the following case studies.

Data need to be collected for quantifying the interlinkages among the different resource systems. The data depend on the scale in which scenarios will be created, and the way by which the modeler decides to construct and assess the scenario itself. Defining the scenario components will reflect the degrees of freedom that the designed model provides to a user. Do we want to change different water sources or energy sources? Do we want to make agriculture-related decisions? Which question should be asked first? Are those questions independent or does one feed into another? After addressing these questions, the scenario assessment components must be identified. How do we plan to assess a scenario? Are certain outputs more important than others? Do we want to know what water requirement is associated with a given scenario? Is it something the decision-maker needs to be alerted to? After deciding that and holistically assessing different scenarios through a list of identified, quantifiable outputs, the feasibility and trade-offs among different scenarios need to be highlighted. In what format should the trade-offs be presented to the decision-makers? What information needs to be included and what is of less significance? The presented WEF Nexus Tool (Figure 6.3) does not decide which assessed scenario is the best for adoption; rather it provides an overview of the list of resource requirements associated with a developed resource allocation scenario. It highlights areas in which a given scenario might fall short of being feasible due to local resource availability or externalities. The decision-maker's input is then captured through a prioritization process, which reflects the relative importance of reducing each of the resource requirements needed for a scenario. Only after a combination of holistic assessments regarding localized resource needs, and with a mechanism to capture the priorities of the decision-makers, the WEF Nexus Tool will be able to identify the feasibility of the given scenario. If deemed satisfactory, the scenario could be further studied and discussed among different stakeholders; otherwise, a different variation of the scenario could be assessed through the same process. More information on the platform and WEF Nexus Tool can be found on www.wefnexustool.org.

6.4. CASE STUDIES: ANALYZING WEF NEXUS TRADE-OFFS

In this section, three case studies will be demonstrated in the context of the presented water-energy-food nexus platform and 7Q modeling guideline. The case studies were chosen to cover a wide spectrum of scales, stakeholders, and critical questions.

6.4.1. Case Study I: Food Security in the Gulf State of Qatar

The state of Qatar, an arid country known for its abundance of natural gas, water scarcity, and harsh environmental conditions, imports more than 90% of the food it consumes. In the past few years, driven by national security concerns, the country began developing a food security master plan, which brought to light that while there are risks associated with high reliance on imported food, other challenges arise when considering the resources needed for increasing local food production.

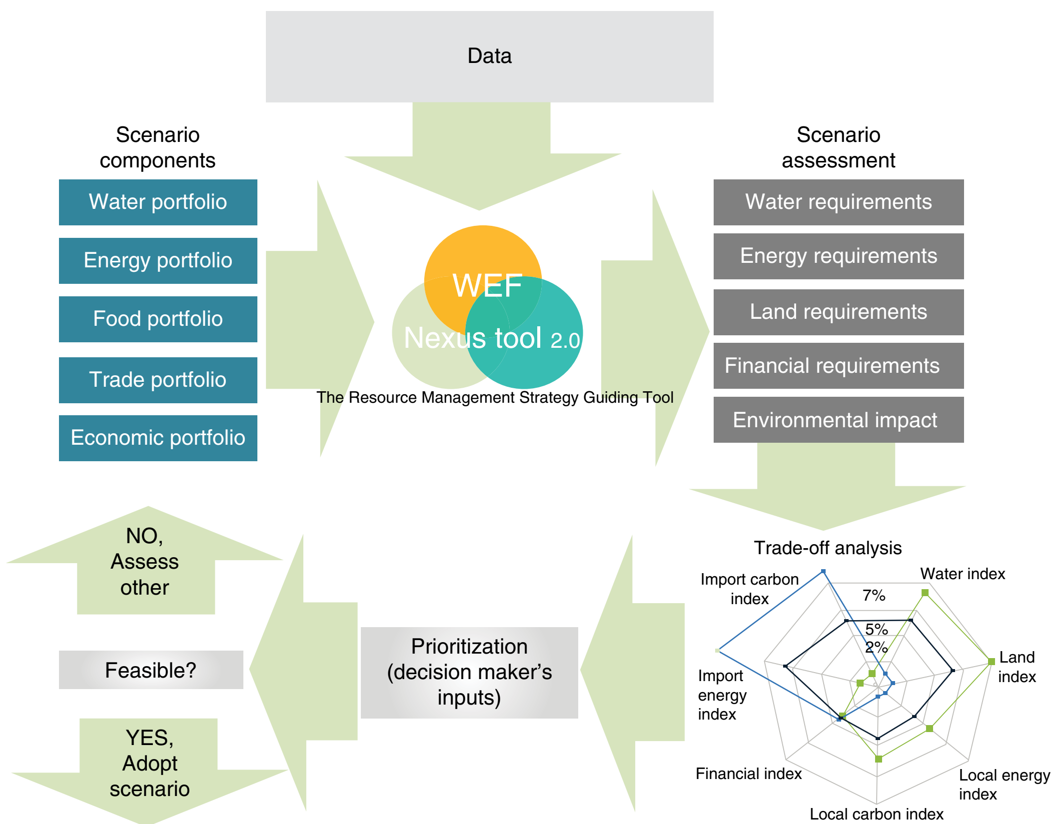

Figure 6.3 Overall generic modeling approach.

According to the 7Q modeling guideline, the following questions are addressed.

1. **What is the critical question?**

In response to the new food security master plan, what is an appropriate level of local food production in Qatar?

2. **Who are the players/stakeholders?**

The Qatar National Food Security Program is the entity given the responsibility of putting together the food security master plan and, hence, the primary stakeholder/beneficiary of the tool. The program, which has been transformed to an interministerial committee, does not exist anymore in its former capacity since the past years. This also gives an idea of the dynamic nature of involved stakeholders in some cases, and the need to evolve with the needed framing and analysis accordingly. Furthermore, other players who also play a role that must be reflected in developing the strategy and scenarios would include the ministries of environment, finance, water, and energy.

3. **At what scale?**

This case study covers the entire state of Qatar and looks at improving the level of food security and associated costs from a national perspective.

4. **How are we defining our system of systems?**

In this case study, the framework was food-centric (Figure 6.4). The first building block for a scenario constituted a new level and choice of local food production. After that, different sources of water for growing the food were included, each with its specific financial, energy, and carbon footprint tag; likewise, different sources of energy, each with a different carbon tag, were also included. Energy is an input necessary for securing water (pumping, treating, desalinating) and for different food production processes (tillage, harvesting, fertilizer production, and local transport).

5. **What do we want to assess?**

A scenario consisted of choosing the following:

(i) Food: type, amount of food to be produced
(ii) Agricultural practice: type of agricultural practice per product (open field vs. greenhouse)
(iii) Water: sources of water
(iv) Energy: sources of energy
(v) Trade: countries of import and export

The tool in turn assessed the following for each scenario:

(i) Water requirement (m^3)
(ii) Local energy requirement (kJ)
(iii) Local carbon emission (ton CO_2)

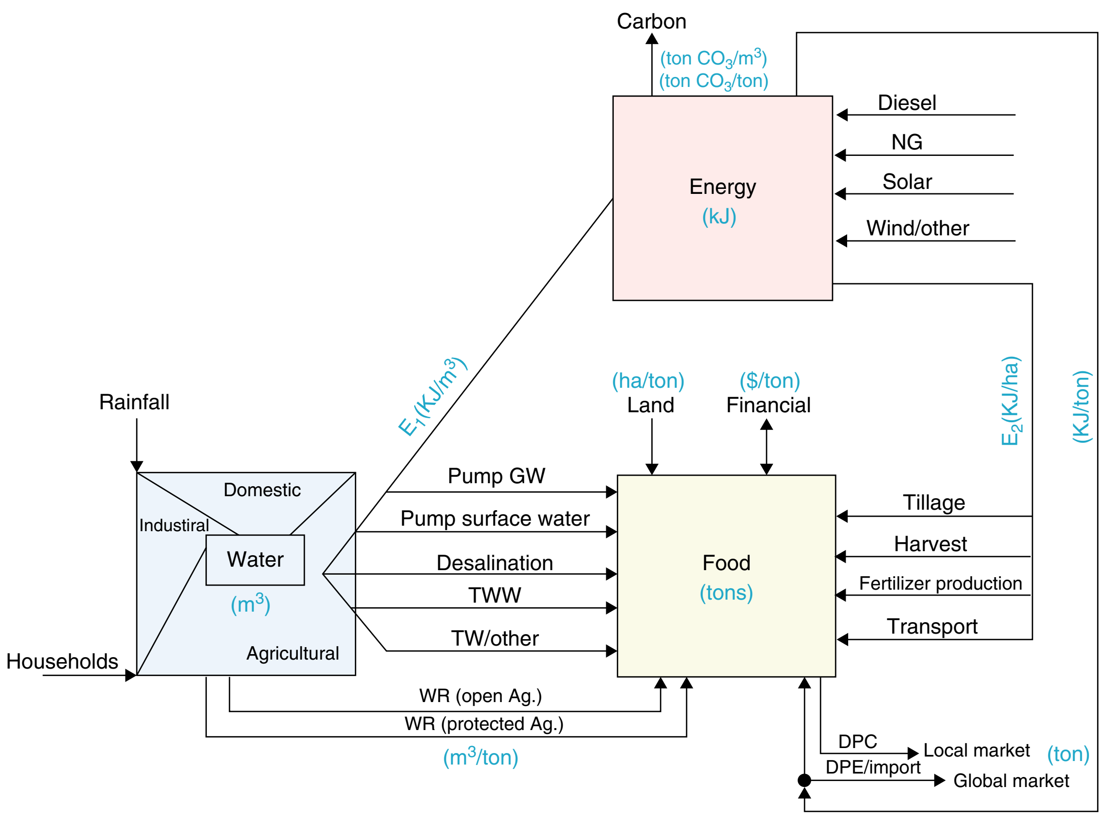

Figure 6.4 Diagram demonstrating the water-energy-food nexus framework. Source: *Daher and Mohtar* [2015]. Reproduced with permission of Taylor and Francis.

(iv) Land requirement (ha)
(v) Financial requirement (QAR)
(vi) Energy consumption through import (kJ)
(vii) Carbon emissions through import (ton CO_2)

6. **What kind of data is needed?**

Among the data needed was yield per food product (ton/ha); water requirement per food product (m^3/ton); annual rainfall (mm); energy requirement for water (kJ/m^3); energy requirement for agricultural production (kJ/ha); carbon footprint (ton CO_2/kJ); market price ($/ton).

7. **How do we communicate it? Where do we involve the decision-maker in the process?**

In 2012, scenarios of 50, 80, and 100% self-sufficiency of eight chosen locally produced food products were explored and assessed [*Mohtar and Daher*, 2014]. In spite of the awareness of how resource demanding such levels of self-sufficiency could be, the interest to investigate higher levels of locally produced foods stems from a national security perspective. A preliminary assessment by WEF Nexus Tool 2.0 framework showed that a 10% increase in self-sufficiency of a few food products grown locally helped highlight the water, energy, carbon, financial costs, and risks associated with local food production (Figure 6.5). This information, when shared with local stakeholders, contributed to a shift in the overall narrative of what can be done and what the trade-offs are. The complete case study could be found in *Daher and Mohtar* [2015].

6.4.2. Case Study II: Renewable Energy Deployment

The world has decided to move forward with phasing out fossil fuels; most recently, that commitment was relayed through the historic Paris Climate Agreement in December 2015. Changes within the energy system will affect other, interconnected, resource systems. As different countries explore possible renewable energy options, it is important to understand the implications associated with each and the extent to which one affects the other systems.

1. **What is the critical question?**

How can we assess different renewable energy deployment options through quantification of the impact of different national energy mix possibilities?

2. **Who are the players/stakeholders?**

Ministries of Energy, Ministries of Environment, International Energy Agencies, and International Climate Change Agencies that are interested in understanding the implications of shifts in the energy mix.

3. **At what scale?**

The scale at which the scenario assessment is made is national. Yet, there is also interest in the aggregate collective global picture as a result of shifts across different national boundaries.

4. **How are we defining our system of systems?**

Using the same framework and understanding of resource interactions, the building block is no longer food as the previous case study, but rather energy. The central piece of the framework is the well-known International Energy Agency (IEA) energy balance sheet. Such sheets have been consistently reported by the IEA for different countries over the years. The sheet provides a summary of production, import, export, and consumption for different types of energy sources. The model developed in this case allows a user to make changes to a base year energy mix, and then assesses the implications of those changes. Parallel sheets were conceptually developed [*IRENA*, 2015] to allow us to make these assessments (Figure 6.6). These included a table for "water for energy," "land for energy," "emissions for energy," and "cost of energy."

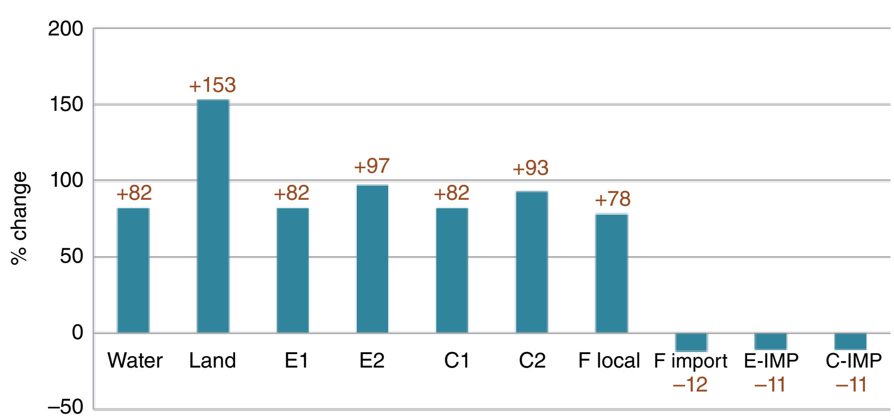

Figure 6.5 Resource requirement for a 2010 scenario (input data from the Qatar National Food Security Programme, QNFSP) and percentage change in the resource requirements as a result of a 10% increment in self-sufficiency. Source: *Daher and Mohtar* [2015]. Reproduced with permission of Taylor and Francis.

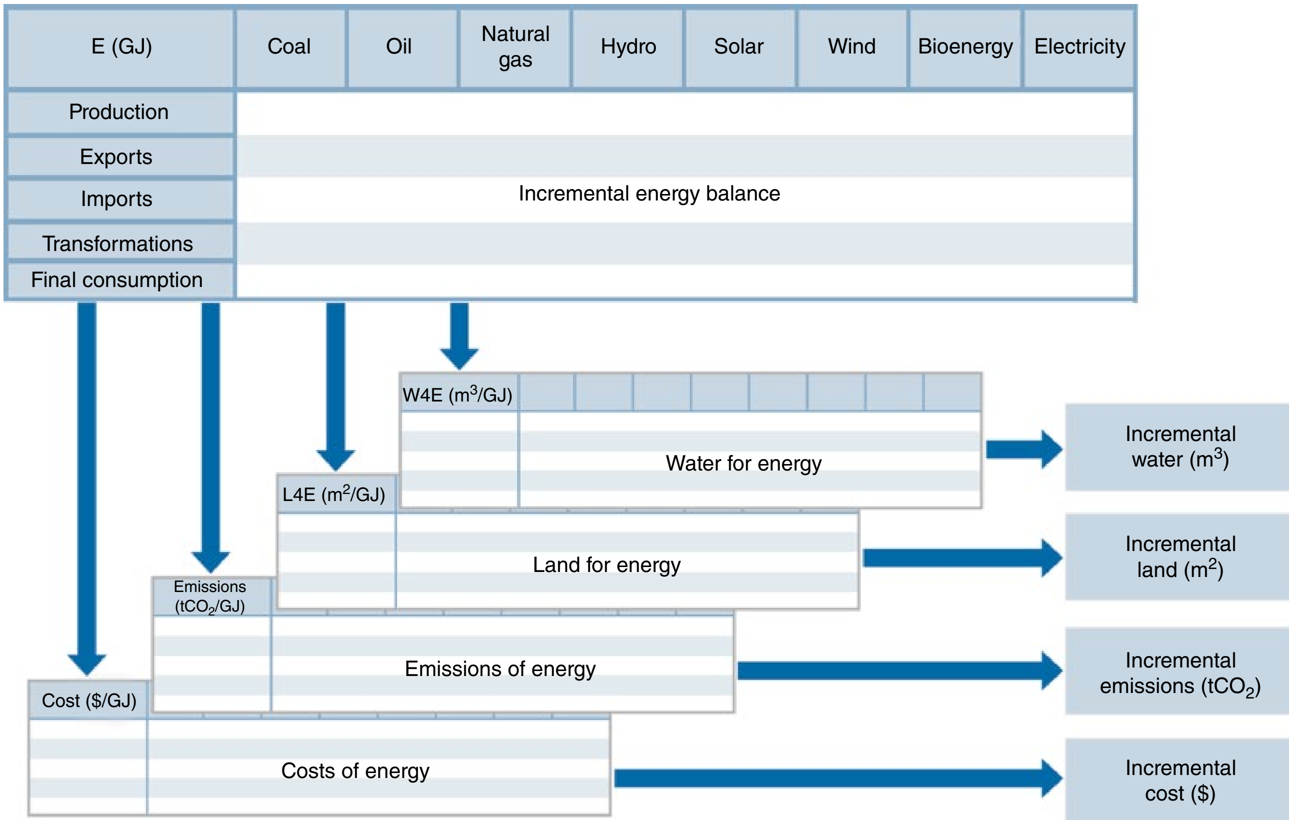

Figure 6.6 Estimation of the water, land, emissions, and cost implications of the assessed energy policy [*IRENA* 2015].

5. **What do we want to assess?**

As stakeholders aim to investigate the implications of different shifts in energy mixes, this model allows them to assess the water needs, land needs, emissions, and costs associated with possible changes. Such a holistic overview of resource needs provides a foundation for a trade-offs discussion and dialogue among involved stakeholders.

6. **What kind of data is needed?**

Among the list of needed data are the IEA reporting data on national energy mixes; water requirements for different energy options; land requirements for different energy options; emissions associated with each energy source; and the cost of implementing each of the new energy sources.

7. **How do we communicate it? Where do we involve the decision-maker in the process?**

Similar to the first case study, the holistic assessment of the various shift scenarios needs to be provided; after which local or national resource constraints and strategies could be incorporated to filter out unfeasible scenarios.

6.4.3. Case Study III: Water Scarcity in Texas

The state of Texas expects to face a 40% gap in water availability by the year 2060 to satisfy growing demands [*TWDB*, 2012]. It is planned to cover 60% of the gap by conventional water sources, 24% from conservation, and 16% from nonconventional water supply reuse and desalination [*Arroyo*, 2011]. The state of Texas has the fastest growing cities in the United States, accompanied by the boom in shale gas production through hydraulic fracturing, and the growth in agricultural activities in different regions of the state. Understanding the growth of these burgeoning water-thirsty sectors, the trade-offs associated with limiting one in favor of the other, and the implications for social, economic, and environmental indicators will be of particular importance to the plan.

1. **What is the critical question?**

How could we better allocate water resources to help bridge the projected 40% water gap in the state of Texas by the year 2060?

2. **Who are the players/stakeholders?**

A main stakeholder is the Texas Development Water Board. According to their 5 year plan report, planning groups for each of the 16 planning zones across the state consist of representatives of the general public, county, municipalities, industry, agriculture, environment, small businesses, electric-generating utilities, river authorities, water districts, and water

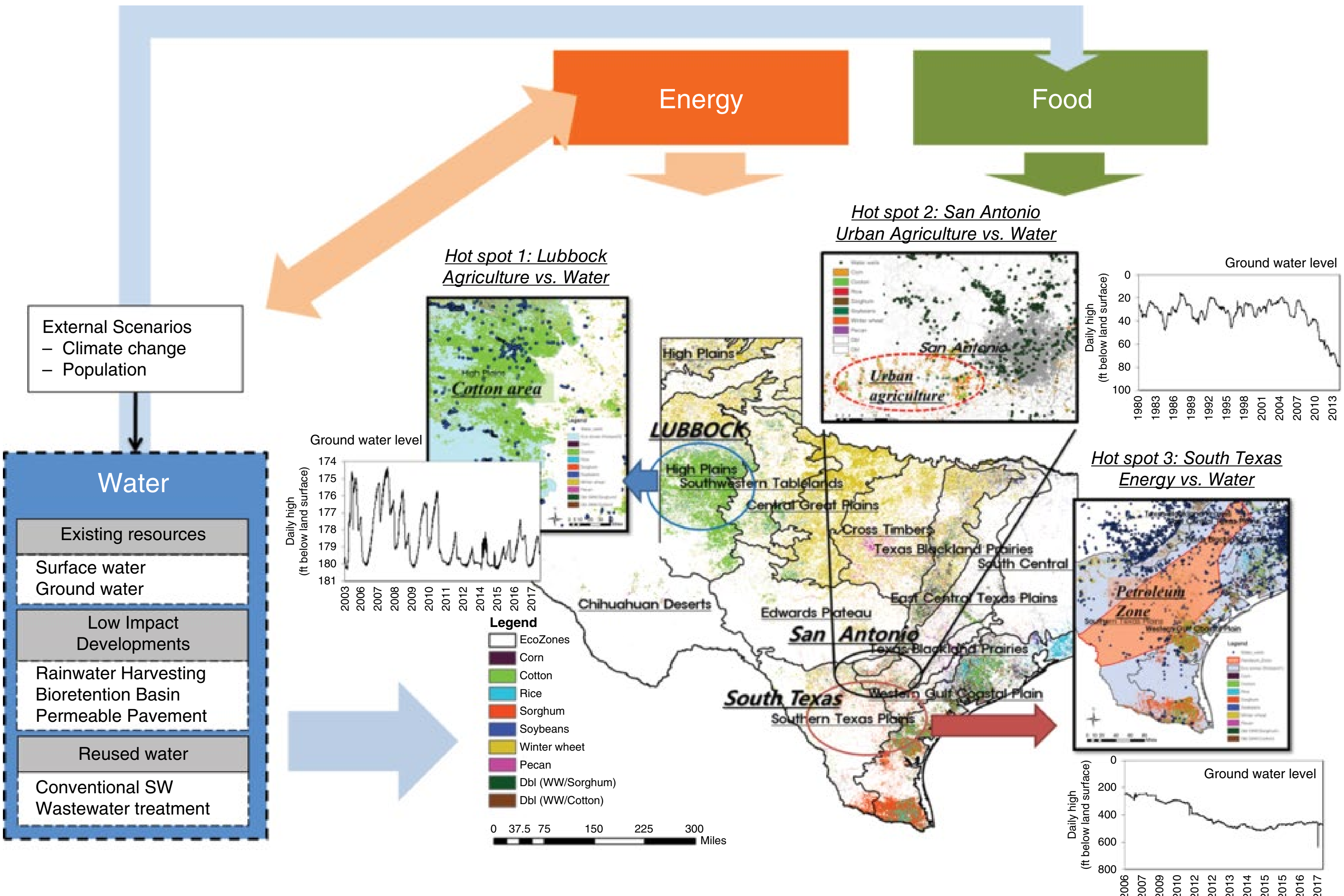

Figure 6.7 Water-energy-food nexus based on water management in various hot spots. (*See insert for color representation of the figure.*)

utilities [*TWDB*, 2016]. All these stakeholders are voting members and have a say in the development of the state water plan.

3. **At what scale?**

State. The threat of water scarcity is a state issue, yet addressing it might take different forms, depending upon each region and its characteristics (practices and resources). Texas is a large state that includes great variability in resource distribution and resource demand hot spots.

4. **How are we defining our system of systems?**

Different hot spot areas in which projected resource demands and resource availability are in conflict must be identified (Figure 6.7). In this case study, particular importance should be given to identifying the spatial and temporal distribution of demand and availability. Thus, the building block of this model is a map representing the distribution of resource supplies and the demands on them.

Each hot spot would be treated as a separate resource allocation case study in which the competition over different sources of water could be analyzed. Different water sources require different amounts of energy. Energy, in turn, could come from different sources (oil or gas or other renewable energy sources) which are also water consumers. Different environmental impacts are also attributed to the use of different sources of energy (emissions, soils, and water degradation). In areas where irrigated agriculture is growing, more water will be needed; the ability to assess the different costs associated with the use of different sources is of great importance.

5. **What do we want to assess?**

Based on the characteristics of the hot spot and of the involved stakeholders, different outputs could be of particular interest. For example, the San Antonio Region is a hot spot: the city is projected to grow in the coming decade, as is the hydraulic fracturing industry and cotton production. The assessment must include scenarios of growth in these different areas and over different times of the year, for each of the three water-demanding activities. The scenario outputs will include a list of social, economic, and environmental indicators that will need to be compared.

6. **What kind of data is needed?**

Among the data that need to be collected for this case study include water resources (type, quantity, spatiotemporal distributions); energy sources; agricultural activities; emissions data; and economic and social indicators over time, among others.

7. **How do we communicate it? Where do we involve the decision-maker in the process?**

The effect on different sustainability indictors could be shared, with different strategies for the growth of conflicting sectors in a given hot spot. A decision-maker would be able to understand the impact of a specific strategy on different resource systems and indicators. The WEF nexus perspective can help bridge the overall water gap in Texas. However, this requires holistic but localized, system level solutions that take into account impacts on energy, food, economics, carbon, and social indicators. In addition, the nexus variables might depend on spatial and temporal characteristics of individual hot spots given by location, temporal resource availability and demand, and climate change. Therefore, spatiotemporal water management of each hot spot is required to solve the water scarcity problem in Texas.

6.5. SUMMARY, CONCLUSIONS, AND FUTURE POTENTIAL OF THE NEXUS MODELING

"WEF nexus" is not a magical term; it is a philosophy that guides the navigation of a holistic resource-modeling platform that enables decision-makers to build their integrative resource plans on the basis of specific, identified needs and interests. These decision-makers vary in scope and capacity: they could be making decisions at small associations, or at local, regional, national, or international levels. So do their interests; and the complexity of their critical questions could differ. The challenge of the WEF nexus modeling philosophy is providing those interested decision-makers with clear, simple, yet comprehensive answers. Consequently, it is unrealistic to expect a single modeling approach to fit all interests, at different scales. Instead, modeling approaches of WEF nexus issues should be built case by case, but guided by the same philosophy. In this chapter, the authors introduced their WEF nexus modeling philosophy through a 7-Question approach. These questions serve as a guideline to help develop customized models that produce the needed analytics to facilitate dialogue among involved stakeholders. The strength of the proposed framework lies in its dynamic and easily modifiable structure, while considering inputs from scientific spheres and decision-makers. Some challenges remain in the availability and compatibility of data sets. The different tools that are useful within the context of this WEF platform require continuous development so that they continue to capture needed interconnections and trade-offs. In addition to accounting for physical resource interactions, it is also important to capture the interactions among the different players and stakeholders governing these resources.

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7

Water-Energy-Food Nexus: Selected Tools and Models in Practice

Victor R. Shinde

ABSTRACT

In order to better manage the water, energy, and food sectors it is first important to understand the linkages between the three, and subsequently adopt an integrated approach of management. There have been a number of tools developed to assess and implement the water, energy, food nexus approach of management. This chapter describes some of these tools and models developed by leading international organizations and agencies. The tools discussed are (i) Water-Energy-Food Nexus Rapid Appraisal Tool, *developed by FAO*; (ii) Water-Energy-Food Nexus Tool 2.0, *developed by Bassel T. Daher and Rabi H. Mohtar*; (iii) Integrated WEAP and LEAP Tool, *developed by Stockholm Environment Institute*; (iv) Foreseer Tool, *developed by University of Cambridge, UK*; and (v) IRENA's Proposed Preliminary Nexus Assessment Tool, *developed by the International Renewable Energy Agency.* Each tool is elaborately discussed, detailing its structures, inputs required, outputs produced, and constraints under which it was developed. A comparative analysis of the tools is provided toward the end of the chapter to summarize the main features of the tools.

7.1. INTRODUCTION

The resource nexus of water, energy, and food is deeply intertwined and highly complex. Impacts of any one of these sectors will cause direct and indirect repercussions in the others. The demand for each of these resources has grown over the years, and this trend is expected to continue in the future as well, raising serious questions on the sustainable exploitation of these resources. Rapid economic growth, expanding population, and socioeconomic development are increasing the demand for energy, water, and food. An escalation in the demand in any sector will have a cascading effect on the stability of the other sectors, thereby affecting the security of supplies across all sectors.

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The world is already reaching the sustainable limit of resource availability, and is at risk of exceeding planetary boundaries. Under the circumstances, there is a strong likelihood that water security, energy security, and food security will become more elusive. Traditionally the management of these resources followed a "silos" or compartmentalized approach. Now, it is becoming increasingly evident that development strategies and policies cannot be formulated for individual sectors alone. These must cut across the different sectors to manage trade-offs holistically. If water, energy, and food security are to be simultaneously achieved, decision-makers need to expand the scope of thought to consider the influences of all three sectors.

In order to better manage the water, energy, and food sectors it is first important to understand the linkages between the three, and subsequently adopt an integrated approach to develop tools to govern and manage the resources. Adopting a nexus approach to sector management involves analyzing cross-sectoral interactions to facilitate integrated

Water-Energy-Food Nexus: Principles and Practices, Geophysical Monograph 229, First Edition.
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planning and decision making. Such an approach encompasses the use of a vast array of quantitative and qualitative decision support tools and methodologies depending on the purpose of the analysis, access to data, and availability of technical capacity [*SEI*, 2013]. *Endo et al.* [2015] provide a review of 37 projects that have used the water-energy-food nexus approach.

There have been a number of tools developed to assess and adopt the water-energy-food nexus approach of management. While most of these tools are conceptual in nature, rapid strides made in this regard suggest good potential for upscaling. *IRENA* [2015] carried out a review of some of the tools used worldwide, studying the various inputs, outputs, or analytical characteristics of these tools. For all tools, the inputs are primarily needed to characterize the systems under study and their context. These inputs could be in the form of data to characterize the system or even policy-related interventions that will influence the system as a whole. In terms of outputs, many tools focus on a single element of the nexus (e.g., only energy). A few of these tools represent two or more elements, and others even add further components such as greenhouse gas (GHG) emissions. The underlying analytical characteristics of the tools also differ in terms of the following:

1. Level of accessibility to a wide number of users (e.g., from free online tools to costly software packages)
2. Flexibility to be applied to different contexts (e.g., to various countries)
3. Level at which the tools are defined (e.g., while some tools are defined at a national level, others focus on the subnational or even local levels, for instance considering a single watershed)
4. Comprehensiveness and degree of complexity

While models and tools to implement the water-energy-food nexus have their limitations and constraints, these are a powerful way to help decision-makers arrive at judicious decisions in managing the three sectors. This chapter discusses some of these tools.

7.2. WATER-ENERGY-FOOD (WEF) NEXUS MANAGEMENT TOOLS

7.2.1. WEF Nexus Rapid Appraisal Tool

This tool has been developed by the Food and Agricultural Organization of the United Nations [*FAO*, 2014]. The tool uses a WEF nexus assessment approach in order to do the following:

1. Understand the interactions between water, energy, and food systems in a particular context
2. Evaluate the performance of a technical or policy intervention in the given context

The structure of the WEF Nexus Rapid Appraisal Tool has three distinct components as presented in Figure 7.1.

Context analysis: The first component, "context analysis," focuses on using a systems approach to develop a

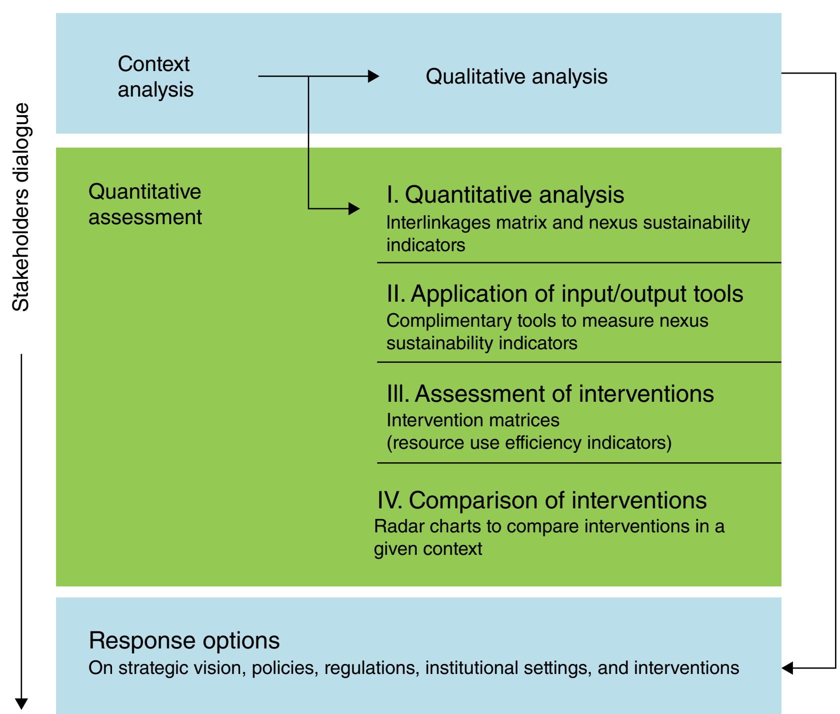

Figure 7.1 Components of FAO's WEF nexus assessment approach [*FAO*, 2014].

site-specific understanding of the issues surrounding water, energy, and food securities. There are a number of aspects that are considered to arrive at this understanding. Here are some examples:

1. The current state and pressures on natural and human resource systems.
2. Expected demands, trends, and drivers on resource systems.
3. Interactions between water, energy, and food systems.
4. Different sectoral goals, policies, and strategies with regard to water, energy, and food; this includes an analysis of the degree of coordination and coherence of policies, as well as the extent of the regulation of uses.
5. Planned investments, acquisitions, reforms, and large-scale infrastructure.
6. Key stakeholders, decision-makers, and user groups.

While it is possible to carry out the context analysis in a qualitative manner (e.g., through experts' opinion or multi-stakeholder consultation) these are strengthened if they rely on a quantitative assessment by using appropriate sustainability indicators.

***Quantitative assessment*:** The second component, "quantitative assessment," focuses on evaluating the performance of technical or policy interventions. Specific interventions are identified and discussed and their nexus links are quantified in two ways. First, the intervention itself is analyzed. Then, the intervention is analyzed against the context status in order to better analyze the appropriateness of different interventions according to the context in which they are implemented. For example, a wastewater treatment plant may have the same "nexus performance" per se, but its appropriateness will be very different in different contexts. The overall quantitative assessment is a four-step procedure.

Step 1: Context quantitative analysis to determine the sustainability of the context: This involves the collection and analysis of data to identify and assess the interlinkages of water, energy, and food systems. The objective is to investigate which environmental and social resources are under pressure and how these are interlinked. A key part of this analysis is to establish meaningful nexus sustainability indicators, for which data on both the status of the ecosystem resource and the socio-economic aspects are needed.

Step 2: Application of input/output tools to quantify impacts and draw scenarios: This involves the development of possible scenarios to examine the effects of interventions (and current trends, i.e., business as usual) on the natural environment and the society. The data required for developing these scenarios would ideally be available from existing data sets. If not, then the appropriate modeling tools will need to be employed to generate the required data.

Step 3: Assessment of (the performance of specific) interventions: This step involves assessing the various interventions in terms of their performance, that is, how efficiently the environment and human resource bases are used. The efficiency of water, energy, land, and human time use can vary before and after an intervention, as well as among different interventions.

Step 4: Comparison of interventions: In this step, the different intervention options are compared using the nexus sustainability indicators, and other relevant criteria. Given that the indicators are quantifiable, pictorial representations of the performance of each intervention can be made for ease of visualization.

***Response options*:** This component essentially focuses on engaging different stakeholders in an open and participatory policy dialogue to build consensus on specific policy issues related to effects of interventions, and strategizing the way forward.

***Stakeholder dialogue*:** This is a cross-cutting component applicable at each stage of the framework. Stakeholder dialogues are crucial for an intervention to have any long-term impacts. It is a continuous process that brings together the different working areas through a participatory process of engaging with all relevant stakeholders and experts. The dialogues have to be designed for a specific context (regional, national, local, or basin level) and problem, for example, to evaluate a national policy on water, energy, and food systems, or to choose among specific possible project interventions.

7.2.2. Water-Energy-Food Nexus Tool 2.0

This tool is developed by *Daher and Mohtar* [2015], and the interface for it was later created at the Qatar Environment and Energy Research Institute. The tool has been applied to a case study focusing on Qatar, a hyper-arid Gulf country, and can be used for similar geographic areas. The tool can be used to create different scenarios, with varying food self-sufficiencies, water sources, energy sources, and countries of import. The tool is based on a conceptual scenario-based framework with food as the entry point, and accounts for nationally consumed food products. Some of these products are domestically produced and consumed (DPC), while others are imported (IMP). Products could also be domestically produced and exported (DPE). Based on an identified food profile, and national water and energy portfolios, the local feasibility of any proposed scenario can be assessed in line with the systems' interconnections. This framework forms the premise for the WEF Nexus Tool 2.0 structure (Figure 7.2). The tool requires the user to create different scenarios by choosing different values of the following:

1. ***Percentage of self-sufficiency of food products*** (%SS): Users can choose a combination of different crops, such as %SS of tomato 50% and %SS of cucumber 20%.

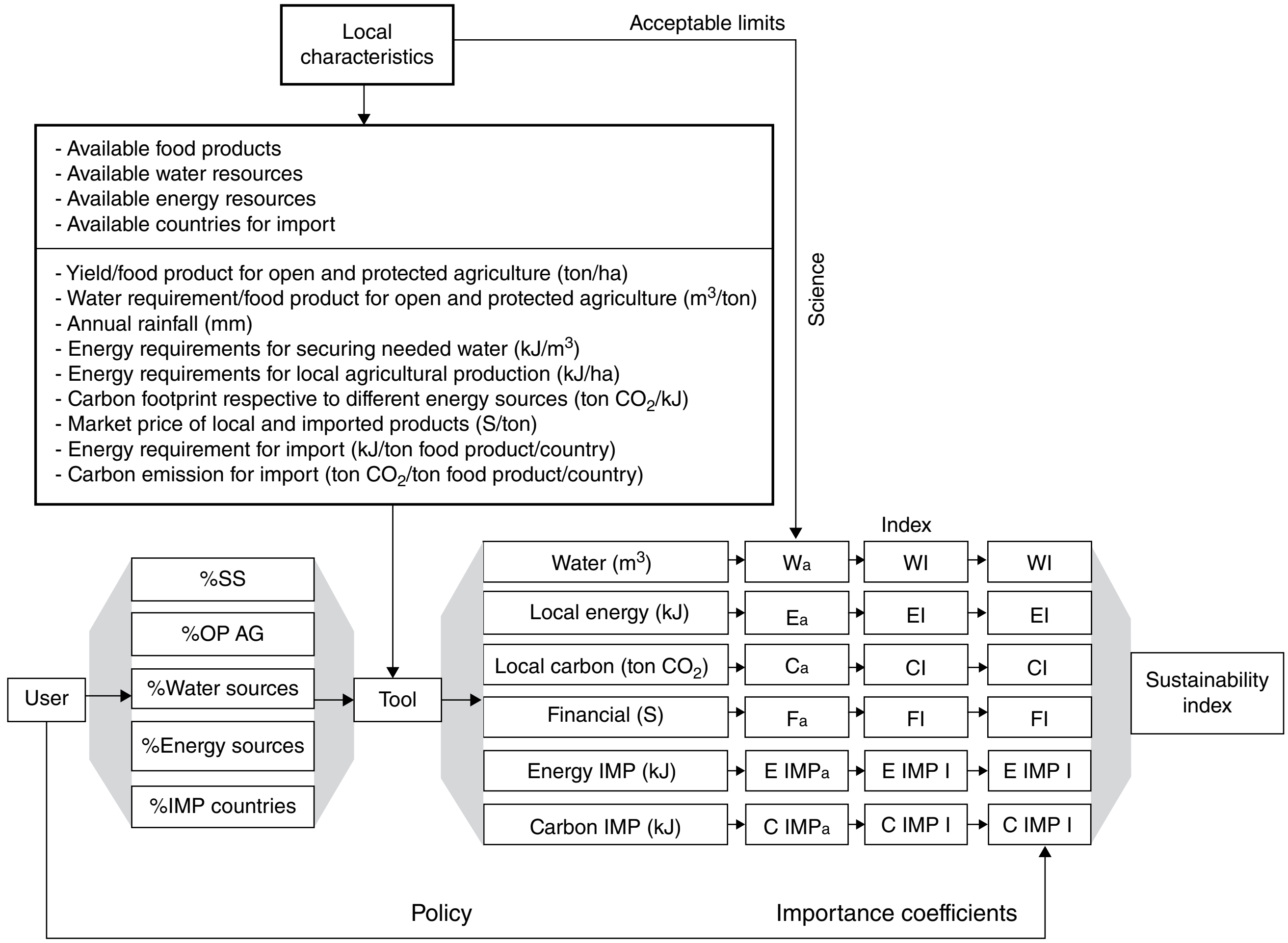

Figure 7.2 Water-Energy-Food Nexus Tool 2.0 structure and the calculating sustainability index. Source: *Daher and Mohtar* [2015]. Reproduced with permission of Taylor and Francis.

"Self-sufficiency" is determined as the ratio of a specific food product produced locally to its total consumption.

2. ***Percentage of food products grown in open agriculture conditions*** (%OP AG): For each crop, users are required to enter the percentage of crops grown in open agriculture conditions as well as in protected agriculture conditions such as greenhouses.

3. ***Percentage of the different water sources*** (%water sources): Users are required to choose a combination of different water sources such as groundwater, rivers, desalination, and lakes.

4. ***Percentage of energy sources*** (%energy sources): Users are required to choose a combination of different energy sources such as fuel oil, wind, natural gas, and solar.

5. ***Percentage of the imported food products from different countries*** (%IMP countries). For each crop, users are required to enter the percentage of import and the country from which the import is made. For example, 30% of imported tomatoes from Jordan and 70% from Lebanon.

The tool also requires the user to provide contextual information in the form of "local characteristics." This includes yields for different food products (ton/ha), water requirements (m^3/ton), energy needs (kJ/ha or kJ/m^3), and other items, as listed in Figure 7.2.

Based on the information supplied by the user, the tool provides an output which includes the following:

1. Total water requirement for the scenario W (m^3)
2. Total land requirement L (ha), based on local production and yields
3. Local energy requirement E (kJ), split between energy needed for securing the required water (E1) and energy for local food production (E2)
4. Local carbon footprint C = (C1 + C2) (ton CO_2)
5. Financial cost F (US$)
6. Energy consumed through import EIMP (kJ)
7. Carbon emission through import CIMP (ton CO_2)

A unique feature of this tool is that it provides the option of exploring the sustainability of the different scenarios created by the user, through a "sustainability index" of each of the proposed scenarios. The sustainability index is calculated in two simple steps. In the first step, the "resources indices" are developed, which throws light on the amount of resources required by a scenario in terms of total available resources. For example, water index (WI) is the ratio of the amount of water required (Wi) by the scenario to the total allowable water availability (Wa). Similarly, the resources indices of land, energy, carbon, finances, imported energy, and imported carbon are calculated. The second step involves the determination of the "importance coefficient" by identifying the relative importance of reducing each one of the resource requirements (water, energy, carbon, land, financial). This is done by the relevant stakeholders assigning an importance coefficient to each resource requirement, depending upon what their policies and strategies determine to be the most important to be minimized. The higher the importance coefficient, the more critical it is to adopt a scenario with a lower respective resource requirement. The sustainability index of each proposed scenario is calculated as a summation of the products of the "resource indices" and their assigned "importance coefficients."

$$
\begin{aligned}
\mathrm{S.I.}_{\mathrm{i}} = [&\mathrm{WI_i}(100-\mathrm{I_W}) + \mathrm{LI_i}(100-\mathrm{I_L}) + \mathrm{EI_i}(100-\mathrm{I_E}) \\
&+\mathrm{CI_i}(100-\mathrm{I_C}) \\
&+\mathrm{FI_i}(100-\mathrm{I_F}) + \mathrm{E_{IMP}I_i}(100-\mathrm{I_{EIMP}}) \\
&+\mathrm{C_{IMP}I_i}(100-\mathrm{I_{CIMP}})]\times 100 \\
&\mathrm{I_W}+\mathrm{I_L}+\mathrm{I_E}+\mathrm{I_C}+\mathrm{I_F}+\mathrm{I_{EIMO}}+\mathrm{I_{CIMP}} = 100
\end{aligned}
$$

7.2.3. Integrated WEAP and LEAP Model

The Water Evaluation and Planning (WEAP) model is a widely used model developed by the Stockholm Environment Institute [*SEI*, 2013]. The primary function of the model is to examine the balance between water demand and supply at different spatial and temporal scales. WEAP is capable of simulating real-time situations in terms of policies, plans, and priorities to model both the water demand and its main drivers. The model has been used to explore, and evaluate, various water management measures, from conservation to wastewater reuse, and to plan for adaptation to climate change.

The Long-range Energy Alternatives Planning (LEAP) system is a model for integrated energy and climate change mitigation planning. A number of countries use LEAP for conducting their climate change mitigation assessments and creating Low Emission Development Strategies (LEDs). In addition, LEAP has also been used by countries to develop climate strategies and build scenarios for a global energy assessment.

WEAP and LEAP can individually address aspects of water and energy planning; however, they were not designed to have synergies with each other. For instance, LEAP can model hydropower but it does not look into water scarcity as a possible constraint. Similarly, although WEAP can examine the change in hydropower potential under different water supply and demand scenarios, it cannot explain how hydropower fits within a larger energy system.

SEI has now integrated WEAP and LEAP to address these limitations. Each still remains a separate tool, but they have a common "wizard" that connects them. Thus, WEAP and LEAP can now exchange key model parameters and results, and can represent evolving conditions in both water and energy systems simultaneously. Using this integrated model, planners can examine the impact of individual water or energy management choices on both the water and energy systems. It is now easier to comprehend the trade-offs between choices that would not have been possible when looking at either system alone. For example, planners can evaluate outcomes of any specific policy against two objectives, that is, to supply enough water for all and to reduce GHG emissions. If one approach leads to unacceptable results, alternative policies and measures can be explored.

7.2.4. Foreseer Tool: Developed by University of Cambridge, UK

The Foreseer Tool has been developed by the University of Cambridge [*Allwood et al.*, 2012]. The tool is used to investigate the influence of future demand scenarios of requirements for energy, water, and land resources. The tool comprises of a set of physical models for energy, water, and land which are interconnected. It also considers the technologies that transform these resources into final services (e.g., housing, food, transport, and goods). The tool allows the user to generate different scenarios of natural resource supply and use, and, apart from the final services, also calculates GHG emissions and other measures of stress, such as groundwater depletion. Figure 7.3 presents the conceptual model of the Foreseer Tool.

The Foreseer Tool uses a set of Sankey diagrams to visualize future scenarios of energy, water, and land situations. The diagram depicts the flow from the basic resource (e.g., coal, surface water, and forested land) through transformations (e.g., fuel refining and desalination) to final services (e.g., sustenance, hygiene, and transportation). The user can explore various future scenarios by choosing different parameters such as estimated population growth, climate change scenarios, and others. The inputs to the Foreseer Tool include forecasts of demand for final services and technology scenarios to predict how technology performance and selection (e.g., between electric and petrol cars) may evolve over time. The tool also allows for sensitivity analysis to predict the value of technology.

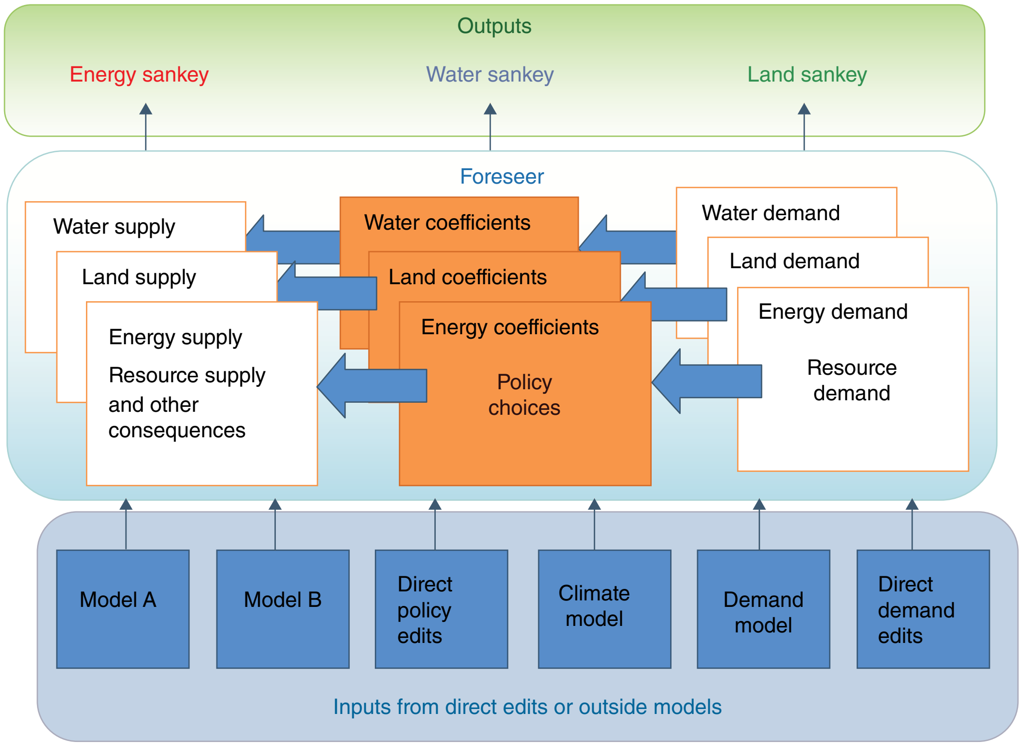

Figure 7.3 Conceptual model of the Foreseer Tool. Source: *Allwood et al.* [2012]. Reproduced with permission University of Cambridge.

The Foreseer Tool requires four categories of data for current and future resource pathways.

Energy: current primary energy sources, energy allocation and end use conversion devices, passive systems, final services, future energy mix, and future demand.

Land: potential vegetation and current land use, soil types, crop types and yield, imported food and fiber, future land use/land use change scenarios, future food and biomass demand, and change in diet.

Water: renewable (surface and groundwater) sources and stocks, precipitation, evapotranspiration, pretreatment distribution for use, treated water, virtual water, services, desalination and post-use treatment, future demand, climate change/variability, and sinks.

Socioeconomic: population growth, future policy direction, and local and international regulations.

7.2.5. IRENA's Preliminary Nexus Assessment Tool

This tool is a conceptual framework developed by the International Renewable Energy Agency [*IRENA*, 2015] and is theoretically similar to the Water-Energy-Food Nexus Tool 2.0. This tool uses energy as the entry point. The framework uses a country's energy balance as the main input to develop various scenarios. The scenarios are developed by modifying the energy balance associated with different policy choices (e.g., a greater use of renewable energy), and to analyze the resulting nexus impacts. Energy balance data are quite easy to find and most countries compile these as part of their national energy statistics. Furthermore, the International Energy Association (IEA) also gathers this information in a standardized and widely accepted format on a regular basis [*IEA*, 2014].

The first step in the use of the proposed tool is baselining, that is, to establish a baseline energy balance. The baseline energy balance could represent the current energy scenario that is the year in which the analysis is carried out or a reference case in the future (e.g., 2030), based on energy forecasting/modeling exercise.

The second step is to provide an alternative energy balance. This involves developing different policy scenarios that will then be analyzed from a nexus perspective. For example, a policy scenario could be to put stronger emphasis on renewable energy. The alternative energy balance should reflect changes in the energy types (e.g., increased use of wind energy, if the policy promotes renewables) and should be consistent with the baseline energy balance with respect to the energy policies that have not changed (e.g., if energy efficiency remains the same, total final consumption of energy should be the same in both energy balances). The tool would then estimate the incremental energy balance by simply subtracting the alternative and the baseline energy balances. The incremental energy balance would represent the changes in the energy situation due to the analyzed policy.

The third step is to estimate the water, land, emissions, and cost implications of the incremental energy balance. The tool would multiply the incremental energy balance by certain data matrices. The data matrices represent, for each type of energy (columns of the energy balance) and for each stage of the energy supply chain (rows of the energy balance), the amount of water or land required per energy unit, the amount of emissions produced in each of those stages per energy unit, or the unitary cost incurred. This is illustrated in Figure 7.4, where each of these data matrices are respectively called Water for Energy, Land for Energy, Emissions of Energy, and Costs of Energy. The result of this step would be the basic incremental use of water or land resources (e.g., volume of water, area of land), the incremental costs, or the incremental emissions produced by the analyzed energy policy, all else being equal.

The final step is to assess whether the incremental use of resources or emissions are acceptable. This will essentially involve the consideration of context-specific information. A policy could have the same nexus performance in two different contexts, but be acceptable in only one of them [*FAO*, 2014]. For instance, the same renewable energy policy (e.g., promoting large-scale solar photovoltaic (PV) effect), applied to two different arid countries, could yield the same results in terms of water and land (e.g., savings of cooling water for thermal generation and additional land needed). However, such results may not be acceptable in one of the two countries (e.g., if a political decision has been made to prioritize land use for food production over other uses such as power generation).

In order to evaluate the acceptability of the analyzed policy, policy-makers can first identify the acceptable increments in water, land, emissions, and costs. These acceptable levels can then be compared to those generated by the alternative energy balance (baseline + incremental), thereby resulting in four partial indexes (Water Index (WI), Land Index (LI), Cost Index (CI), and Emissions Index (EI)), all of which are expressed in per unit (p.u.) terms. Figure 7.5 explains these calculations. If any of these indices takes a value greater than 1, it means that the acceptable limit has been exceeded, and the opposite occurs if the index is smaller than 1. Finally, the four partial indexes can be aggregated into an "overall index" according to the policy importance that each of the four aspects has in the specific country, as indicated by the policy-maker.

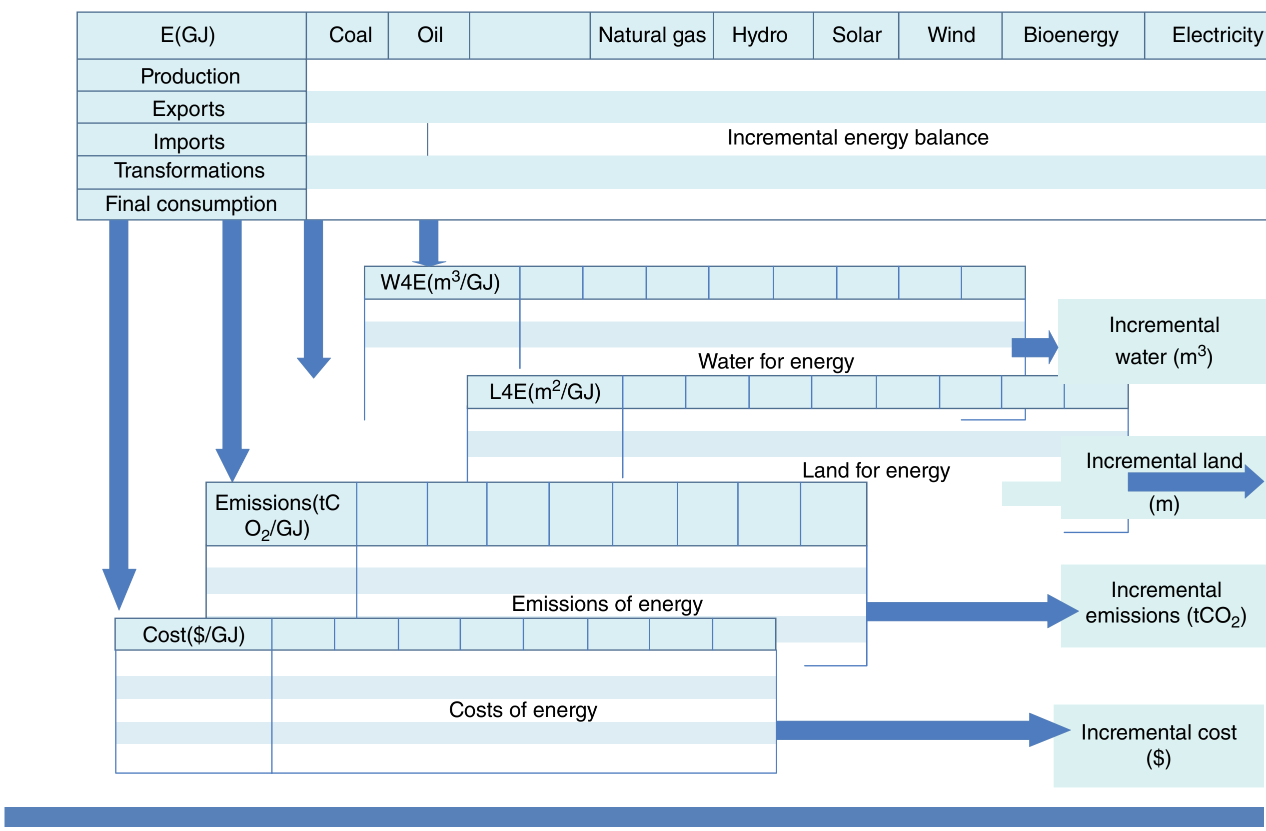

Figure 7.4 Estimation of the water, land, emissions, and cost implications of the assessed energy policy. Source: *IRENA* [2015].

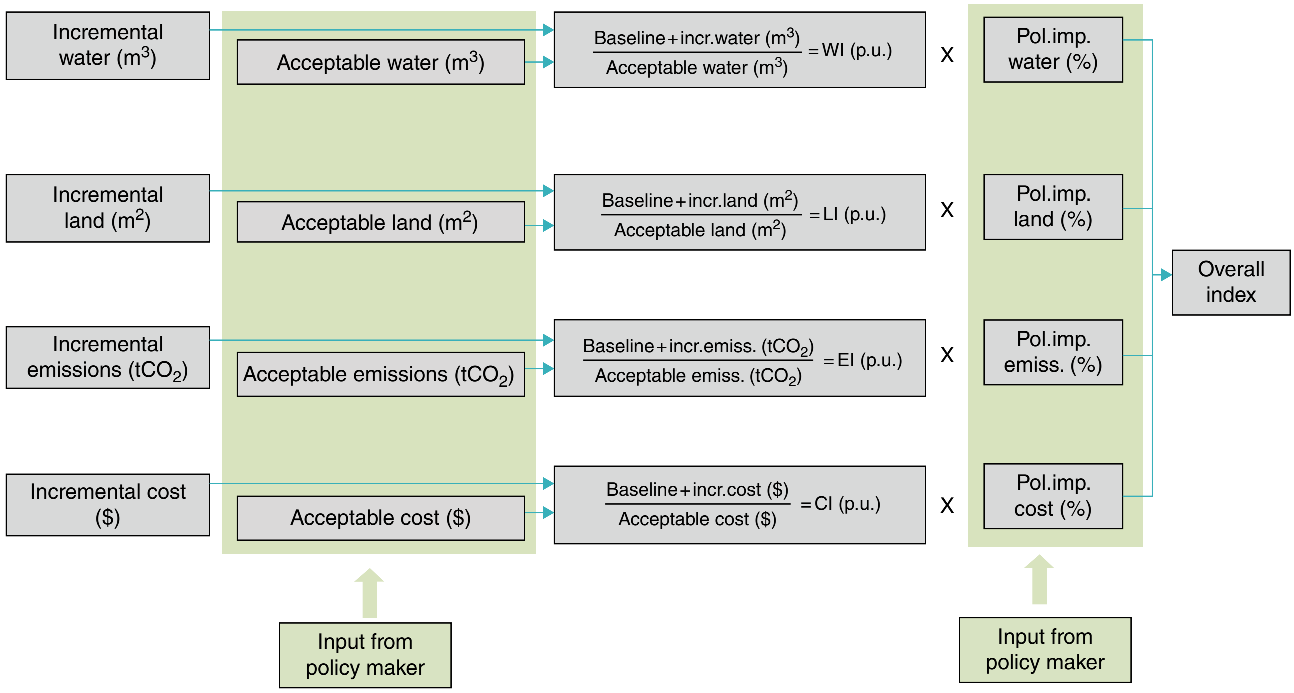

Figure 7.5 Use of policy inputs to estimate the water, land, emissions, and cost implications of the analyzed energy policies and to aggregate them into a context-specific overall index. Source: *IRENA* [2015].

7.3. COMPARATIVE ANALYSIS OF THE WEF NEXUS TOOLS

Table 7.1 presents a comparative analysis of the WEF nexus tools discussed in the preceding section. The table summarizes the data requirements for each tool and the output products that can be obtained. It also gives an indication of the scale at which the tools could be used and their potential for application in different geographic regions. As seen, all the tools require substantial data, which at times can be challenging to procure. More on the data issues will be discussed in the next section. Although the outputs of the various tools depend on the context in which they are used, they provide crucial information that decision-makers look for. The tools are mostly designed to capture the national/basin-scale scenario. This works well because policies and development plans are made at this scale, and these tools can provide vital output to these plans. Also, because boundaries are well defined at the national/basin scale, data procurement becomes less arduous. Most tools also have good potential for application in diverse regions so long as the required data are available.

7.4. THE WAY FORWARD

Tools for quantifying, and implementing, the water-energy-food nexus have been growing steadily over the years, although large-scale implementation is still non-evident. This, in all likelihood, has more to do with political and governance implications than with technical limitations (which are undoubtedly there). The primary concern from the technical point of view is with data availability. While it is relatively straightforward to obtain national data for energy, water presents greater challenges, as reported by the UN World Water Development Report [*UN Water*, 2014]. Data availability on water and energy becomes even more challenging when considering the water-energy nexus perspective. For example, there could be adequate data available on water consumption and on electricity generation; however, data on water consumption for electricity generation is limited. Also, the lack of information on the cooling technologies used in power generation, which influence water use estimations as much as the generation technology itself [*Halstead et al.*, 2014], remains a key challenge. These challenges make it difficult to develop effective indicators for water-energy-food nexus interventions.

There are, however, efforts being made in addressing the data availability issues on the water-energy nexus. For example, *Spang et al.* [2014] and the *IEA* [2012] present updated international comparisons of water use for both primary energy production and power generation. Data for energy use for water production and supply are now more easily available (e.g., Global Water Intelligence, 2010 provides data on energy use in desalination). Governments are also taking significant measures in this regard, For example, in California, a

Table 7.1 Comparative analysis of selected WEF nexus tools/methodologies

Tool/Methodology	Entry point	Input required	Output provided	Scale	Potential for application in different regions
Water-Energy-Food Nexus Rapid Appraisal Tool	Food	Context-specific information such as demand, trends, and policies Data mostly acquired from existing data sets	Depends upon the type of intervention but can provide coarse-scale outputs such as energy consumption, water consumption, and crop yield	Mostly national	Good
Water-Energy-Food Nexus Tool 2.0	Food	Data on types and characteristics of food, water, and energy systems Context-specific policy and regulations	Water, land, and energy requirements and trade-offs for various scenarios/ interventions Financial outputs and carbon emissions for various interventions Sustainability index for different scenarios	Mostly national	Developed for Middle East countries. Can be replicated but requires quite specific data
Integrated WEAP and LEAP model	Water and energy	Data intensive For WEAP data requirements include maps of basin, water demand, transmission, hydrology, morphology, waste water, policy For LEAP data requirement is for demographic, economic, general energy, transformation, environmental, and fuels	For different hydrologic and policy scenarios the WEAP outputs include water demand and supply; runoff and flow regimes; pollution generation and water quality; and storage and other parameters LEAP outputs include energy balance and energy flow diagrams	National, basin	Good potential for generalization but quite data intensive
Foreseer Tool: developed by University of Cambridge, UK		Energy sources and systems; land use type and food characteristics Water sources, systems, and demands; socioeconomic and policy-related information	In response to use-defined scenarios the outputs are natural resource supply, transformation, and use; greenhouse gas emissions and other measures of stress (e.g., groundwater depletion)	National	Good
IRENA's Preliminary Nexus Assessment Tool	Energy	Energy balance; data on water and food resources, types, and systems Policy and regulation	Water, energy, and food requirements for various scenarios Costs associated with different scenarios Acceptability of different policies through index-based approach	National	Excellent potential for generalization

bill was unanimously approved that requires oil companies to report how much water they use in drilling operations and from which source of water [*California Legislative Information*, 2014].

Water-energy-food nexus tools are a useful way to quantify and manage the nexus between the three vital sectors. However, as highlighted in Table 7.1, each of the tools (and there are several others as well) has its own data requirements, contextual applications, and operating conditions. The choice of using an appropriate tool will be dictated by these factors.

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8

Governing for the Nexus: Empirical, Theoretical, and Normative Dimensions

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ABSTRACT

While research into the nexus has expanded significantly, few studies have sought to theorize its governance. By adopting a policy instruments perspective, this chapter therefore initially examines how the nexus is emerging at different scales and national contexts worldwide. Empirical evidence of policy instrument innovation is then analyzed using conventional governance theories to argue that the holistic nature of the nexus concept requires new theorizing to interpret this emerging reality. Normative suggestions for theorizing future nexus governance are also forwarded.

8.1. INTRODUCTION

Research into governing the nexus requires engagement with two terms: *nexus* and *governance*. The nexus itself has emerged in the last few years as a rather diffuse concept that seeks to better integrate different sectoral components in the management of environmental resources in order to support synergies and reduce conflicts between them [*Benson et al.*, 2015; *Gain et al.*, 2015]. Nexus thinking stems from the recognition of inextricable linkages between water resources, food production, and energy generation and use but also interrelated sectors such as climate mitigation and biodiversity protection. Development of the nexus concept is consequently coalescing around guiding principles to achieve such linkages [*Allan et al.*, 2015]. The World Economic Forum, for example, provides a normative blueprint for its vision of a water, energy, food (WEF), and climate nexus, which encompasses resource security on a global scale [*WEF*, 2011; *Leese and Meisch*, 2015]. The WEF nexus consequently narrows down the consideration of intersectoral linkages to dimensions that are of prominent interest for both developed and developing countries. The nexus has also become a policy discourse, or set of policy discourses, that incorporates these principles at different institutional scales. For United Nations agencies, the nexus is now forming the basis of international dialogues on development policy strategy [e.g., *UN-Water*, 2014]. More importantly, ensuring water, energy, and food securities within the nexus approach has been recognized as a priority in the sustainable development goals (SDGs) by the United Nations [*UN-SDSN*, 2014]. After the phasing out of the millennium development goals (MDGs) in 2015, the United Nations Rio+20 Summit 2012 in Brazil committed itself to establishing the SDGs to guide global development for achieving sustainability [*Glaser*, 2012]. Finally, these nexus discourses are now informing specific governance solutions to integrating such components at multiple scales and national contexts worldwide [see, e.g., *Gulati et al.*, 2013; *Meza et al.*, 2015; *Middleton et al.*, 2015].

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The rapid development of policy innovations raises questions over the nature of "nexus governance," how it can be explained theoretically, and what specific forms of governing it should (normatively) take.

Answering these questions relies on an effective definition of governance, which also remains an essentially contested concept, generating multiple and often conflicting meanings evident across a burgeoning literature. While the term governance pre-dates modern political systems, in more recent decades it has come to denote shifts in state-society relations, away from centralized government decision making toward power sharing with a multiplicity of actors at different levels, from the global to the local [*Pierre and Peters*, 2000]. Such processes have been driven by wider forces including, inter alia, neoliberal demands for deregulation and smaller government, new public management reforms, regionalization (including Europeanization), internationalization of politics via "global governance," and increasing demands for multi-stakeholder collaboration [see *Bevir*, 2009]. For states, achieving their political objectives under such changing contexts is therefore increasingly reliant on steering or coordinating policy through governance modes such as hierarchies of institutional levels, private markets, networks of actors, and also communities [*Pierre and Peters*, 2000]. Steering or coordinating in this way has also necessitated developing and utilizing innovative policy instruments to promote action, whereby regulation (associated with traditional forms of government) is being supplemented (rather than supplanted) with mechanisms such as market-based instruments (MBIs), provision of best practice information, voluntary agreements with or between non-state actors such as businesses, and the establishment of specific institutional organizations [*Jordan et al.*, 2012; *Wurzel et al.*, 2013].

With regard to the environment, governance can be understood to mean "the processes [steering or coordinating] through which different actors govern the environment" and the structures established for this purpose [*Benson and Jordan*, 2016]. Governing environmental resources now can involve multiple actors, both state and non-state, such as government environmental agencies, businesses, nongovernmental organizations (NGOs), regional bodies such as the European Union (EU), global environmental regimes, and, most saliently, civil society. For example, EU member states derive much of their national environmental policy from the European level but are responsible for implementing it within their sovereign territory, that is, multilevel governance [*Benson and Jordan*, 2007]. While hierarchical modalities for environmental governing still remain dominant globally, inter- and intra-national environmental networks have become important mechanisms for coordinating state environmental policy objectives, particularly within the EU [see *Adelle et al.*, 2015]. Some environmental policy networks exist "beyond the state," involving nongovernmental actors in governing specific environmental issues across transnational spaces [e.g., *Bulkeley et al.*, 2014]. Meanwhile, market-based steering has increased via ecological modernization and techno-centric approaches to environmental governance that have emerged alongside greater multi-actor collaboration [*Benson and Jordan*, 2016]. Regulatory approaches to environmental governance, synonymous with traditional "command and control" legal mechanisms, have come to be supported by a plethora of "new" environmental policy instruments such as green taxes, emissions trading, corporate sustainability reporting, eco-labeling of products, environmental management systems, and consumer advice [*Wurzel et al.*, 2013].

When taken together, these two concepts infer that "nexus governance," or what we refer to as governing for the nexus, could be understood as the different patterns of governing by which political actors seek to achieve nexus objectives for sectoral integration, thereby enhancing synergies between water, energy, and food production, and reducing conflicts. Such governing logically necessitates consideration of how steering and coordinating the nexus occurs through different scales, actor types, governance modes, and, critically, the instrumental means employed to achieve such objectives. Governing the nexus, we argue, consequently raises *empirical* (how is such governance achieved?), *theoretical* (how can we interpret such governance?), and *normative* (what form should nexus governance take?) questions. In respect of the latter, the United Nations has argued that a

> … nexus approach to sectoral management, through enhanced dialogue, collaboration and coordination, is needed to ensure that co-benefits and trade-offs are considered and that appropriate safeguards are put in place. [*UN-Water*, 2014]

However, very few studies to date have examined nexus governance specifically, with almost no theoretical analysis evident in the literature [see, e.g., *Scott et al.*, 2011; *Kurian and Ardakanian*, 2014; *Halbe et al.*, 2015], thus representing a significant gap in the literature.

In seeking answers to these questions, this chapter is structured as follows. First, it examines how, in various political contexts, the nexus is being governed in practice, with an emphasis on different policy instruments as a signifier of governance. A policy instruments perspective also potentially allows insight into the actors and modes involved in environmental governing [*Jordan et al.*, 2012]. Of interest is just how far integrated approaches to management, which involve coordination, collaboration, and dialogue to produce co-benefits, have developed. A literature review of various "nexus"-type policy instruments is employed to determine the extent of emergent governance. However, the cases employed are necessarily only illustrative and by no means exhaustive.

Second, it discusses some potential theoretical approaches to explaining nexus governance in this emerging area of research. While theories of governance abound [e.g., *Bevir*, 2009], here we explore four approaches with potential significance to nexus research, namely (i) global governance; (ii) regulatory governance; (iii) market governance; and (iv) collaborative governance. One argument is that existing governance theory fails to capture all aspects of nexus governing: as a holistic concept, it requires more holistic theorizing. Finally, the chapter draws upon contemporary nexus debates to forward the argument that a wider dialogue is needed on both theorizing nexus governance and the normative aspects of "good" nexus governance in terms of how it could, or indeed should, be framed in the future.

8.2. GOVERNING IN PRACTICE: A POLICY INSTRUMENTS PERSPECTIVE

Recent years have seen the emergence of a polycentric landscape of nexus-type innovative policy solutions, from the global to the local. Here, we define a nexus policy instrument as an example of a regulatory, market-based or fiscal, informational or institutional policy mechanism that provides co-benefits (and reduces conflicts) between water-energy-food and associated sectors while increasing dialogue, collaboration, and coordination. Examination of emergent policy responses reveals a complex pattern of multilevel innovations which can be examined according to instrument type. One evident feature is that policy instruments promoting integration between sectors such as Integrated Water Resources Management (IWRM) [*Gain et al.*, 2013] pre-date current debates over the nexus; hence, precise classification of "nexus governance" can be problematic in practice. Another feature apparent from the survey is the limited existence of genuinely integrated instruments that address water, food, and energy concerns holistically, although many policies attempt to link some of these components: primarily energy and water, or food and water. This feature reflects the varying and often overlapping conceptualizations of the nexus itself in the academic literature and the lack of an agreed definition of this term [see *Benson et al.*, 2015]. We therefore categorize these approaches broadly into instruments for water-food-energy; water-energy-climate; water-food; and water-energy.

8.2.1. Water-Food-Energy

Perhaps the most high-profile instruments globally are those that seek to diffuse norms around the water-food-energy nexus, that is, informational instruments. Most notably, the WEF model for the nexus contains several key features, primarily its focus on implementation via business actors, thereby reflecting the main constituency of the forum [*WEF*, 2011; *Benson et al.*, 2015]. Nexus thinking has also permeated United Nations agency normative guidance. The United Nations Economic Commission for Europe (UNECE), for example, has become an active promoter of the water-food-energy-ecosystems nexus, with an emphasis on reconciling water resource use with other sectoral priorities, particularly in river basins [*UNECE*, 2015]. UN-Water also actively supports the water-food-energy nexus through its interagency approach to coordinating action on water development [*UN-Water*, 2014]. Meanwhile, the IUCN and International Water Association (IWA) have established a Nexus Dialogue on Water Infrastructure Solutions that provides a platform for information dissemination on the water nexus, including a section on best practice case studies [*IUCN/IWA*, 2015]. That said, seemingly few governments offer specific advice for implementing the nexus. The German government has supported research and knowledge dissemination of nexus information via the GIZ Water, Energy & Food Security Resource Platform. Launched at the Bonn2011 World Water Forum Nexus Conference, the platform aims to promote greater understanding of water, energy, and food security interactions while providing online access to nexus information [*GIZ*, 2015a]. Various NGOs and think tanks are also disseminating nexus knowledge, including the Stockholm Environment Institute, the World Wildlife Fund (WWF), and the International Food Policy Research Institute.

While few national-level policy instruments that seek to integrate these norms are evident, some attempts to institutionalize nexus thinking within IWRM at river basin scales are currently occurring [see *Foran*, 2015; *Karlberg et al.*, 2015; *Kibaroglu and Gürsoy*, 2015; *Mayora et al.*, 2015; *Giupponi and Gain*, 2016]. International River Basin Commissions represent large-scale institutions that promote integrated thinking across the water, energy, and food domains. For example, water-food-energy-ecosystems assessments were undertaken for selected river basins by parties to the UNECE Water Convention [*UNECE*, 2015]. The UNECE describes how a pilot project was developed for the Alazani/Ganikh Basin in Azerbaijan and Georgia "to identify integrated cross-sector solutions where through joint action additional benefits can be achieved by both riparian countries" [*UNECE*, 2015]. Subsequent assessments were scheduled for the Isonzo/Soca, Narva, Niger, Mekong, and North-West Sahara Aquifer, and Sava and Syr Darya river basins. The Inner Niger Delta, Mali, also provides another example of how IWRM can structure nexus-type coordination between water allocations, food production, and ecosystem protection [*GIZ*, 2015b]. The Government of Mali is working with several neighboring states under the auspices of the Niger Basin Authority to promote cooperation in energy production, agriculture, transport, forestry, and industry. An international regime (the Niger Basin Water Charter) became operational in 2010 to coordinate the access of parties to water resources. Another widely known example of a multifunction intergovernmental body is the Mekong River Commission. Governed by a committee comprised of representatives of four governments (Vietnam, Cambodia, Laos, and Thailand), the Commission adopts an IWRM approach to managing transboundary water resources [*Foran*, 2015]. Specific programs have been introduced for agriculture and irrigation, hydropower, flood management, climate adaptation, fisheries, environmental quality, and navigation. Other "agency"-type multipurpose collaborative institutions have been established in the United States and other states. The Chesapeake Bay Program, established in 1983, is a multi-actor partnership established under an agreement between the US federal government and the states. The program coordinates actions for restoring the estuary and its watershed that include improving water quality, habitat restoration, fisheries management, renewable energy production, and land conservation measures [*Chesapeake Bay Commission*, 2015].

8.2.2. Water-Energy-Climate

At national level, water, energy, and climate dimensions are linked by a variety of statutes and management approaches, that is, regulations. These include management plans for achieving environmentally sound low flows in France or the Water Protection Law 1991 in Switzerland, which require the environmental improvement of hydropower and set minimum flow requirements for rivers impacted by all types of reservoirs. In the United States, California's ongoing drought has led state legislators to adopt several regulatory measures linking water, energy, and climate. In updating the statewide Scoping Plan, adopted to implement the California Global Warming Solutions Act AB32 (2006), the government Air Resources Board has introduced strategies for the water and agricultural sectors both to increase energy efficiency and to reduce climate emissions [*ARB*, 2014]. Meanwhile, the California Integrated Regional Water Management Planning Act (as amended in 2008) requires the integration of water supply and flood protection with reducing energy consumption from water distribution in order to limit greenhouse gas emissions.

Examples of regulatory measures established by quasi-governmental agencies are also evident in linking water, energy, and climate policy. For example, in California, the Sonoma County Water Agency, created as a separate legal entity to act as a water supplier under state law, has adopted a policy that aims to provide "carbon-free water" [*Sonoma County Water Agency*, 2015]. As a large user of energy for water supply, the agency has committed to implementing programs that will achieve carbon neutrality for its operations. Similarly, the San Antonio Water System (SAWS), a publicly owned utility, is widely recognized for its innovative water conservation initiatives [*SAWS*, 2015]. By reducing energy use for water distribution, recycling waste water, and generating biogas from sewage, SAWS provides an interesting example of a quasi-public agency that utilizes its administrative responsibilities to promote nexus solutions.

8.2.3. Water-Food

Some regulatory approaches seek to specifically bridge the nexus between food production and water. For example, in Europe, the very influential EU Common Agricultural Policy requires, since 2005 via "cross-compliance," the meeting of "basic standards concerning the environment, food safety, animal and plant health and animal welfare, as well as the requirement of maintaining land in good agricultural and environmental condition" [*European Commission*, 2015]. Cross-compliance is linked to direct payments from the EU to farmers and so could also be considered a form of fiscal instrument. Regarding the linking of water and food, the Rural Development Programme (RDP) of the EU Common Agricultural Policy had historically promoted environment-friendly practices in agriculture primarily via a compensation scheme (e.g., for lost income). While the scheme focused on funding biodiversity enhancing agricultural land use change, current developments have seen a greater number of subsidy measures aiming for water protection. The 2014–2020 program (i.e., through the so-called agri-environment-climate schemes) now also includes climate dimensions both in terms of mitigation and adaptation targets.

While few similar regulatory approaches seemingly exist at the international or national level, they are more visible at the subnational level. In California, in the United States, the Water Conservation Act 2009 (Senate Bill ×7-7) requires all water suppliers to increase their water use efficiency, specifically for urban and agricultural sources [*CA.GOV*, 2015]. Per capita urban water use must be cut by 20% by 2020 (potentially also leading to reduction in energy use), while agricultural water suppliers must prepare water management plans and introduce pricing and efficiency measures. Failure to meet these requirements results in water suppliers becoming ineligible for state water grants and loans.

A shift toward locally collaborative, integrated forms of management globally has also led to nexus institutional (or organizational) forms, which integrate food production and water protection, emerging beyond direct government control. In South East Queensland (SEQ), Australia, the Healthy Waterways (HW) was established as an NGO to counter chronic pollution of the Brisbane River and Moreton Bay [*Smith et al.*, 2015a]. The HW, an environmental not-for-profit NGO, coordinates the actions of many actors in water management, most notably Brisbane City Council but also state agencies, industry, farmers, and epistemic communities. Although water quality and biodiversity were a critical concern of the HW, it is also now involved in aspects of land management via its Water by Design and Healthy Country programs. The former aims to support the sustainability of SEQ's water and urban development, while the latter aims at reducing rural diffuse pollution by, for example, reducing nutrient and sediment runoff from agricultural land. Indeed, many such catchment partnerships exist in Australia, funded by federal government initiatives such as Landcare or the National Heritage Trust/Caring for Our Country that support multifunctional collaborative resource management. Landcare Australia currently lists a membership of 4000 community groups, including many farmers, engaged in farmland and habitat restoration, rehabilitation of waterways, coastal protection, afforestation, and urban improvement [*Landcare Australia*, 2015].

The United Kingdom also provides some examples of innovative emergent institutions promoting integration across water and food dimensions within the voluntary or not-for-profit sector [*Cook and Inman*, 2012]. For example, *Benson et al.* [2013] note the recent expansion of local catchment partnerships, whose multifunctionality can include water quality management, habitat restoration, and working with local farmers on land management to generate environmental co-benefits. One interesting example is the Westcountry Rivers Trust [*Cook et al.*, 2014], a registered charity combining a collaborative approach to working with local farmers to improve river water quality but also to restore habitats and seek out new economic opportunities for land management. Integral to this approach is an MBI (Payments for Environmental Services (PES)) whereby farmers are financially supported by commercial partners for producing environmental goods such as clean drinking water and leisure opportunities, thereby ensuring the coproduction of benefits [*Cook et al.*, 2014].

A growing number of stand-alone schemes focused on promoting payments for ecosystem services for water protection and agricultural land management also exist in other countries. In Lower Saxony, Germany, the state (land) government recognized that rising nitrate levels in groundwater threatened its ability to meet water quality objectives of the EU Water Framework and Drinking Water Directives [*Smith et al.*, 2015b]. It adopted a water abstraction levy, or "water penny," under which consumers pay a small charge to water suppliers. Revenue raised is transferred to the state government with 40% hypothecated for source water protection and sustainable land use [*Aue and Klassen*, 2005]. Cooperative partnerships have been developed with farmers, with funding employed to support organic farming, afforestation, and land purchases to protect groundwater resources. Unlike the RDP scheme where subsidies are provided for land management, the PES approach focuses on providing direct economic incentives for the provision of integrated ecosystem services.

8.2.4. Water-Energy

Interesting types of nexus-relevant regulatory instruments now exist for linking the water and energy fields. For example, in the United States, 10 states (Texas, Arizona, California, Nevada, Colorado, Connecticut, Washington, South Dakota, Wisconsin, and West Virginia) are now adopting statutes for better integrating water and energy dimensions. Other US states, such as Ohio and Illinois, have signed The Great Lakes-St. Lawrence River Basin Water Resources Compact, a legal agreement that compels state governments to adopt "Environmentally Sound and Economically Feasible Water Conservation Measures" and consider their effects on energy generation [*Library of Congress*, 2008, sec. 4.2 - 4]. It is, however, Nevada, Arizona, and California that are taking the lead in regulating water use in electricity generation. *Berry and Berry* [2014, p. 323] describe how policy innovation can be driven by internal political determinants, including "problem severity." For these states, water scarcity linked to energy generation is a significant issue, leading to state laws that regulate its usage. Water-stressed Arizona adopted legislative authorization as far back as 1999. State Statute 45-156 stipulates that an application for appropriation of water for electricity generation within the state must receive official approval via a legislative act. Nevada has also introduced a statute compelling the state engineer to approve water use for generating energy exported beyond the state (Statute 533.372).

Regarding the linking of water and energy dimensions, an interesting MBI is the green-hydropower certification scheme in Switzerland. Developed in the early 2000s, the scheme assesses the sustainability of hydropower against 45 scientifically defined criteria which allow a comparable certification of different power plants, regardless of their age, size, or how they are built or operated [*Wüstenhagen et al.*, 2003]. It is associated with an eco-investment, financed by a fixed markup on every kilowatt-hour sold as green hydropower. On an annual basis, this surcharge must be reinvested in the river system in which the plant is located in the form of river restoration measures adapted to the demands of the individual river system. The utilization of the eco-investments needs to be based on a catchment analysis and these investments are prioritized by roundtable decisions with local stakeholders and agencies [*Bratrich et al.*, 2004].

8.3. THEORIZING NEXUS GOVERNANCE

Governance has become a widely used term in social sciences but this popularity has resulted in multiple theoretical approaches, each with divergent objects of study [e.g., *Kjaer*, 2005; *Bevir*, 2009; *Chhotray and Stoker*, 2010]. A significant problem identified by *Bevir* [2009, p. vii] is that because the "key concepts of governance derive from diverse disciplines … [they] rely tacitly on different assumptions." To overcome this "language" issue when theorizing nexus governance, we could therefore focus on political science approaches as they can provide guidance on both policy instrument use and processes of steering and coordinating. While it is clearly not possible to examine the entire panoply of governance theory, four major approaches can initially be employed: global governance; regulatory governance; market governance; and collaborative governance (see Table 8.1).

8.3.1. Global Governance

Global governance as both concept and theory has developed significantly in the last two decades, although confusion exists over its meaning [see *Dingwerth and Pattberg*, 2006]. At its most basic, global governance refers to the patterns of governing that emerge from the interactions of different actors at the global level [*Bevir*, 2009]. These patterns have emerged from a situation in which only sovereign states used to conduct international relations to an increasing interdependence between states and non-state actors at the international level in response to globalizing socioeconomic relations [*Kjaer*, 2005]. To coordinate their responses, liberal International Relations (IR) theorists argue that states have therefore created institutions or "regimes" for cooperation such as the United Nations and the World Bank. For *Krasner* [1983, p. 1], such regimes comprise "principles, norms, rules, and decision-making procedures around which actor expectations converge in a given issue-area." The degree to which such regimes can compel states to act remains debatable, with realist scholars in particular arguing that compliance is difficult to ensure under conditions of international anarchy. Challenges have also emerged by those arguing that global governance should be conceived in broader terms "to include systems of rule at all levels of human activity, from the family to the international organization, in which the pursuit of goals through the exercise of control has transnational repercussions" [*Rosenau*, 1995, p. 13]. This view of governance incorporates both state actors and a "plethora of forms of social organization and decision-making … that are neither directed toward the state nor emanate from it" [*Dingwerth and Pattberg*, 2006, p. 191]. As a result, global governance scholars have argued that our analyses should include the actions of multinational corporations (MNC) and NGOs in governing transnationally [*Dingwerth and Pattberg*, 2006). A critical theoretical argument within global governance is consequently the extent to which states, as sovereign actors, are able to exercise enhanced control over transnational issues through global governance, or whether their power is undermined or even supplanted by such interdependencies. *Risse* [2011], for example, provides multiple examples of "governance without a state," whereby governing occurs beyond the control of sovereign governments.

From a global governance perspective, two explanations could therefore be employed to interpret the patterns of nexus policy instruments emerging. Liberal IR scholars [see *Hasenclever et al.*, 1997] would no doubt argue that the expansion in international-level nexus norms represents the preferences of states to coordinate action via cooperative institutions, in response to critical sustainability threats. The nexus emerged more forcefully as a global governance issue after the food security crisis of 2008 in tandem with concerns over rising world energy demand and climate change, providing a rationale for states to coordinate institutional responses on countering these transnational concerns. Nexus thinking also interlinks

Table 8.1 Theoretical interpretations for nexus governance

Governance theory	Object of Study	Empirical explanation for nexus governance	Main actors	Policy instruments
Global governance	• State cooperation • Non-state actions	• The nexus is governed by interstate cooperation via international regimes • The nexus is governed by non-state (business) actors	• States, international organizations • MNCs, NGOs	• Norms, rules, and principles (state steering) • Voluntary instruments (corporate steering)
Collaborative governance	• Collaborative institutions	• The nexus is governed by collaborative institutions at regional or localized scales	• State and non-state actors	• Institutional instruments (collaborative partnerships, multi-actor steering)
Market governance	• Markets	• The nexus is governed through market mechanisms	• Business	• MBIs • Voluntary instruments
Regulatory governance	• Rules	• The nexus is governed by regulation	• Governments	• Regulation (hierarchical and market steering)

strongly with the United Nations MDGs and now the SDGs, which have been broadly supported by many governments. However, liberals would also argue that strong institutions are required to impose cooperation and prevent "defection" [*Hasenclever et al.*, 1997]. The limited and mostly advisory nature of international-level nexus norms, such as those developed by the WEF or UNECE, suggests that cooperation between states on resolving such security concerns is, or will be, merely tacit. The fact that few national governments, it would appear, have introduced nexus-type policies, aside from IWRM, would endorse this point.

A broader conception of global governance would also interpret the emergence of non-state actor responses to the nexus, such as MNC initiatives or NGO nexus informational instruments, as axiomatic of the drift away from state-coordinating power in response to global resource security issues. Indeed, some scholars would argue that such market-based or voluntary initiatives are potentially more effective, as MNCs profoundly influence the distribution of global food, energy, and water resources, and can bypass state-level (in)action. Here, transnational companies are perhaps best placed to govern these interactions in contexts where political and social institutions lack capacity; hence the focus on market-led nexus solutions by the World Economic Forum [*WEF*, 2011]. In this respect, the theory provides normative guidance for future development of nexus governance (see Section IV).

8.3.2. Collaborative Governance

Based on earlier conceptions of network governance and public participation, collaborative public management or collaborative governance has emerged to denote multi-stakeholder decision making between state and non-state actors in institutions primarily, although not exclusively, located at localized scales [*Benson et al.*, 2013]. Collaborative governance theory has developed to encompass such decision making in multiple sectors [e.g., *Agranoff and McGuire*, 2003], although it is mostly associated with environmental management, particularly watershed or catchment management [*Meadowcroft*, 1999; *Wondolleck and Yaffee*, 2000; *Sabatier et al.*, 2005], making it potentially ideal for examining nexus policy implementation. One critical feature of collaborative governance is its shift away from "top-down hierarchical approaches to public policy: a trend that also includes marketization and joined-up government" [*Bevir*, 2009, p. 47]. Supporters of this governance approach argue that it enhances democratic legitimacy and efficiency of policy implementation in response to complex "wicked" problems. However, some scholars have challenged the degree to which environmental governance is becoming more collaborative, while others question its effectiveness, legitimacy, and scope for democratic engagement [*Benson et al.*, 2013].

When applied to the patterns of nexus policy instruments emerging globally, collaborative governance theory can interpret specific intersectoral institutional responses. Although differences exist between IWRM and nexus thinking [see *Benson et al.*, 2015], these institutions are emerging at regional and transnational scales via top-down formalized approaches to embed elements of nexus governance, for example, the Mekong River Commission. Other, less formalized, catchment partnerships and collaborative institutions are also growing in numbers worldwide, for example, the Healthy Waterways partnership and the Westcountry Rivers Trust. Here, the need to collaborate between state and non-state actors is an important prerequisite to developing integrated approaches. In addition, more market-based approaches to governing the nexus such as payments for ecosystems services compel greater interaction with business actors.

8.3.3. Market Governance

One feature of the shift from government to governance is the growing role of markets in the process of governing. As *Bevir* [2009, p. 124] describes, by implication "free" markets would imply no state intervention, or *laissez-faire*, but in reality markets require some institutional-legal frameworks to regulate exchanges, that is, governing *of* markets. These frameworks are supported by institutions such as central banks and regulators, in addition to policy instruments. Regulatory instruments (rules or institutions) can play an important role in protecting property rights and reducing transaction costs [e.g., *Williamson*, 1979]. Governing through markets is also a feature of modern governance, necessitating the use of MBIs such as subsidies and taxes and voluntary industry-led approaches. Such shifts have been detected in environmental governance, with multiple instruments evident worldwide [e.g., *Wurzel et al.*, 2013].

Applied to the nexus, market governance may predict that governing will be achieved by state steering of markets through regulation and market activity via MBIs and voluntary instrumental means. This pattern is certainly evident in the emergence of various instruments globally, most notably funding mechanisms that subsidize nexus approaches, such as payments for ecosystems services. These instruments are particularly evident in generating water and food production co-benefits but other aspects of the nexus such as climate change are being addressed through, for example, carbon offsetting. Also, in some contexts, price-based mechanisms and taxes are being employed to promote co-benefits, although these are most prevalent in climate-energy or water policy. Significant examples include carbon or energy taxes and water-pricing mechanisms that support ecosystems protection via extensive forms of land use.

8.3.4. Regulatory Governance

Regulation is essentially equated with "the coercive power of the state to achieve government goals through the control or alteration of societal … behaviour" [*Howlett*, 2011, p. 83]. Achieving these goals is inherently reliant on public administrations setting and enforcing rules to determine public behavior [*Mitnick*, 1978]. In this respect, administrative rules, which set targets to be attained linked with some form of penalty for non-achievement, have become the fundamental basis of what is known as regulatory governance. Centralized "command and control" regulation became strongly associated with traditional hierarchical government, although, as *Bevir* [2009] discusses, its use came under pressure from the neoliberal de-regulatory agenda in the late twentieth century. Demands to increase the role of markets and non-state actors in governance were met with the rise of the "regulatory state" [*Majone*, 1996; *Bevir*, 2009], whereby new forms of regulatory approaches were introduced by governments, including specific agencies to manage this activity. While typologies abound, regulation can be categorized as either "direct government regulation," which includes legal measures (legal governance) or "indirect government regulation," such as delegated regulation undertaken by nongovernmental or quasi-public bodies [*Howlett*, 2011, pp. 84–92].

On a global scale, national regulation of the nexus is comparatively limited. If we exclude IWRM-type legislation, few examples of "direct" or "indirect" nexus regulations exist at governmental level, while the European Union, often described as the "regulatory state" [*Majone*, 1996], exhibits few genuine nexus-regulatory instruments aside from specific directives and the Common Agricultural Policy (CAP). Regulations are more apparent at subnational level, particularly in the United States, where policy innovation is occurring among state and local governments. A clear factor for innovation is "problem severity" [*Berry and Berry*, 2014, p. 323], with conflicts over water and energy being preeminent. Among several US states, California has consequently adopted several direct legal measures which mandate nexus objectives, most notably to reduce conflicts between water and energy use while promoting greenhouse gas mitigation. Indirect regulatory measures are also apparent, with the Sonoma County Water Agency's "carbon-free water" policy as an interesting example.

8.3.5. Summary of Nexus Governance

Application of preexisting theories of governance can help illuminate the patterns of nexus approaches worldwide but no one theory provides a complete picture (Table 8.1). Rather, different theories explain different parts of how the nexus is governed. Global governance can interpret the development of nexus norms and principles by international-level actors in terms of the needs of states to cooperate to counter critical resource security issues. The growth in NGO and MNC responses to the nexus can also be interpreted as resulting from the expansion of global governance to non-state actors. Market governance could predict the growth of "new modes" of policy instruments in order to coordinate action: a feature certainly evident in the worldwide presence of nexus policy instruments such as subsidies and taxes. Collaborative governance could privilege the growth in partnership forms of nexus governance, which is apparent in the significant presence of collaborative environmental management institutions at different scales. Finally, regulatory governance can explain, to an extent, the rather limited use of regulatory means for both public and quasi-public steering of the nexus. Consequently, a focus on policy instruments shows that governing the nexus involves a mixture or hybrid of "traditional" approaches that are fragmented but gradually merging into a new polycentric governance landscape, providing a rationale for innovative theorizing that better matches this complex empirical reality.

8.4. FRAMING FUTURE GOVERNANCE

Some reflections are possible on both theorizing nexus governance and, hence, making normative recommendations on future governance. As noted earlier, no single theoretical perspective can explain all aspects of emergent nexus governing, suggesting new approaches to theorizing. Here, we could draw on previous analyses to forward some key empirical and normative aspects. *Benson et al.* [2015], when comparing nexus governance to IWRM, suggest four critical features: integration of policy objectives; scales; actors; and institutional and/or instrumental means.

The contours of nexus governance potentially have both empirical (Table 8.2) and normative elements. First, integration is a fundamental component of nexus thinking but only limited discussion exists in the literature on how this feature should be achieved in practice. Questions of policy coordination have traditionally preoccupied students of (environmental and multilevel) governance [e.g., *Jordan and Schout*, 2006]. Related notions of environmental policy integration (EPI) have also been extensively explored both in an empirical, practical sense, at national and EU level, and theoretically as well [*Jordan and Lenschow*, 2010]. But governing the nexus requires much more than EPI, the integration of the environment into other policy sectors, since it implies new ways of policy instrument design that identify sectoral synergies and opportunities for enhancing co-benefits, positive-sum, or

Table 8.2 Features of nexus governance

Governance theory	Object of study	Empirical explanation for nexus governance	Main actors	Policy instruments
Nexus governance	Reducing sectoral conflicts, enhancing synergies (co-benefits, "win-win" outcomes)	Coherence between policy objectives enhances sectoral co-benefits	Multiple at different institutional levels	Multiple

"win-win" outcomes while reducing overlaps and conflicts, that is, policy coherence. Nexus thinking, in this respect, challenges policy making and policy-makers to find innovative Pareto-improving solutions to resource use problems and think further "outside the box" in policy instrument design. Our review highlights some examples of nexus integration for policy evaluation and lesson drawing [*Benson and Jordan*, 2011], although a wider debate on this aspect would be timely.

Such thinking should also permeate policy approaches at multiple vertical "scales" [*Moss and Newig*, 2010] or levels: from the global to the local. Institutional architecture for achieving vertical coordination on nexus practice is, on our evidence, only just emerging, although the United Nation's SDGs may form a more uniform principled approach for national governments to apply. Much scope exists in EU policy design to better integrate food production, water protection, and climate mitigation and adaptation in the CAP, with the RDP appearing to offer some solutions. National governments appear slow to embrace nexus thinking, with little evidence of a diffusion of global norms, although many states now have IWRM policies that help embed an integrated approach to enhancing resource security. But it is at subnational levels that policy innovations appear most advanced. US states such as California are taking a lead nationally in nexus governance, suggesting such contexts can provide "laboratories" for future experimental policy design and learning.

Governing the nexus should, as shown by the empirical section of this chapter, involve multiple actors, both state and non-state, to enhance coherence, collaboration, and dialogue. International organizations and NGOs are already playing an important role in nexus norm development and diffusion. Governmental actors have a particularly significant role to play, given the centrality of the state in environmental governance globally [see *Benson and Jordan*, 2016], but a critical part in implementing nexus thinking should be played by corporate and civil society interests. The previous account of emergent practice shows that governance "beyond the state" may be of increasing importance in the future, as globalization of socioeconomic processes intensifies. Multinational corporations, NGOs, and civil society are very much part of collaborative solutions to global resource use threats, with positive examples emerging from around the world of the opportunities for co-benefits that nexus governance offers.

Finally, effective nexus governance can only be achieved through the use of a full range of policy instruments and institutions, to enhance coordination on nexus objectives across hierarchies, networks, markets, and communities. The nexus, our analysis would suggest, should be governed through multiple instruments and the overall policy "mix" [*Howlett*, 2011] between them will be a critical factor in future nexus governance. New institutions, developed on the basis of reducing sectoral conflicts, will be required to frame dialogue and collaboration. Again, the need for greater knowledge of different approaches and their effectiveness provides an important research agenda.

8.5. SUMMARY

In summing up, our conclusions can return to the introductory questions. Initially we asked how nexus governance is being achieved, with an emphasis on whether coordination, collaboration, and multi-actor dialogues were producing co-benefits. From a policy instruments perspective, it is perhaps evident that a nascent but disjointed landscape of nexus approaches is developing at multiple scales but that there is an emphasis on international-level norm steering and subnational policy responses. Moreover, regulatory responses are limited compared to other forms of instruments, including market-based and institutional approaches. A multilevel architecture for governing the nexus is therefore at a very early stage, with coordination, collaboration, and dialogues detectable, with some co-benefits, particularly for water-energy, apparent, but nexus governance has evidently yet to permeate mainstream policy making and is currently context specific, with some US states leading the way.

We then asked how such governance can be interpreted. Without a dedicated theory, or even a set of common normative principles, for nexus governance empirical analysis was reliant on preexisting notions of global, collaborative, networked, and regulatory governance. When applied to the patterns of instrument use, they each were able to shed theoretical light on different areas of nexus governance, showing that it now involves global cooperation, multi-actor and multilevel relations, coordination across and between markets, networks, and hierarchies, and regulation of socioeconomic processes. However, no one theory appears to capture the complexity of emergent nexus governance hinting at a requirement for innovative theory building.

Finally, in this respect, we can speculate on the form that, normatively, nexus governance should take as it evolves. If, on the basis of the United Nation's observations, a nexus approach should include sectoral management involving dialogue, collaboration, and coordination to identify and enhance co-benefits, our chapter provides some limited examples of current practice for evaluation, learning, and potential "lesson drawing" [*Benson and Jordan*, 2011]. From a theoretical point of view, our analysis also suggests that governing the nexus should aim for cross-sectoral horizontal integration, vertical coordination across all levels to provide policy coherence, engaging state and non-state actors at different levels, and the identification and prioritization of co-benefits in policy instrument design, including specific nexus institutions. Indeed, one area of future debate could be the requisite geo-spatial scale or spatial reference unit for operationalizing nexus governance. IWRM is firmly predicated on the river basin or catchment but our examples might suggest multiple scales are required and hence this issue remains a significant challenge to effectively governing the nexus. Given the limited discussion of nexus governance within the public policy and scientific literatures, such theorizing could productively form the basis of further research, but also normative attempts to determine best practice for governing.

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9

The Role of International Cooperation in Operationalizing the Nexus in Developing Countries: Emerging Lessons of the Nexus Observatory

Kristin Meyer and Mathew Kurian

ABSTRACT

International cooperation constitutes an important means of strengthening nexus understanding and provides the framework for applying nexus principles in practice. Development history shows that a more holistic approach taking account of economic, social, and environmental concerns is necessary for sustainable development. Both the nexus approach to the management of environmental resources and the role of international cooperation are assessed for their mutual benefits. It is argued that holistic assessments of interlinkages and trade-offs between sectors (water, energy, agriculture) and resources (water, soil, waste, ecosystems) provide a platform for increased international and multi-stakeholder cooperation. Similarly, a review of case studies shows that regional and international cooperation promotes mutual learning, dialogue, and data and knowledge sharing, which in turn advances the implementation and operationalization of the nexus approach.

9.1. INTRODUCTION

When the United Nations General Assembly agreed on the Sustainable Development Goals (SDGs) in September 2015, the stage was set for an integrated approach to international development taking account of economic, social, and environmental concerns in a holistic manner and with equal importance. The discourse in the realm of international cooperation (or global partnership) will, thus, necessarily involve discussions around managing trade-offs and maximizing synergies. These highlight interlinkages not only between individual SDGs, targets, and indicators, but also between various development priorities and social challenges.

International cooperation that is focused on providing a more coherent and integrated assessment of the challenges in the three dimensions of sustainable development provides an important foundation for operationalizing the nexus approach: (i) at a conceptual level, (ii) in terms of producing buy-in of key stakeholders, and (iii) at institutional and policy levels. In accordance with the SDGs (in particular Goal 17), cooperation should be characterized by multilevel governance, cross-sector collaboration, and a strengthened global partnership working toward sustainable development [*UN*, 2015]. To deal with this new complexity that the SDGs instil at a global level, societal problems must be defined according to specific boundary and scale conditions, which shed light on the intersections between ecological, social, and economic domains. This chapter will illustrate how the nexus approach can advance international cooperation as well as how far international cooperation may contribute to operationalizing the nexus. In the context of developing countries, it is important to take account of national normative frameworks, institutional environments, and organizational arrangements.

The depletion of environmental resources and the loss of essential ecosystem services is a particular concern for securing the livelihoods of future generations.

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Accomplishments in the field of greater holistic systems thinking through integrated approaches with regard to environmental resource management are first few steps toward addressing interrelations, between resources, services (resource uses), and institutional frameworks [*Scott et al.*, 2015]. These interactions and intersections [see *Kurian and Ardakanian*, 2015c] form the essence of analyzing and operationalizing the nexus approach to integrated management of environmental resources. Furthermore, they direct attention toward minimizing externalities, understanding synergies, and highlighting trade-offs between resources and sectors (e.g., water for drinking vs. water for energy production).

Despite an ever-growing literature on the ontology and methods to operationalize the water-energy-food nexus [*Endo et al.*, 2015; *Kurian and Ardakanian*, 2015a; *Rasul and Sharma*, 2015; *Yang et al.*, 2016] (in qualitative and quantitative terms) the role of international cooperation has not been addressed sufficiently. Merely the need to bring together stakeholders and decision maker from various sectors (e.g., water, agriculture, and energy) has been a recurring theme. This chapter seeks to shed light on the role of international cooperation in realizing the nexus and vice versa. To do so, we review general trends in international development cooperation over the past decades, explore the focus on nexus components in shaping cooperation, discuss the extent of nexus-focused cooperation, and finally shed light on lessons learnt. It will be gleaned on how ex-post analyses and reevaluation of existing cases from a nexus perspective have the potential to shape decision-making processes and cooperation frameworks. We present and discuss a nexus-focused review of the "Nile Basin Initiative (NBI)" and the "Nexus Observatory" initiated by The United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) to elucidate the role of international cooperation in operationalizing the nexus. A review of past international cooperation reveals investment priorities for environmental management, a review of NBI highlights the importance of engaging with the political dimension involving complex negotiation, and the "Nexus Observatory" initiative reflects on the importance of data, information, and their dissemination to attract international cooperation for the coproduction of nexus knowledge and the development of nexus competencies.

9.2. INTERNATIONAL DEVELOPMENT COOPERATION AND THE NEXUS APPROACH

To ensure coherence of this chapter, it is instructive to offer a short review of international development cooperation since the formation of the United Nations in 1945. Doing so will underscore the evolution of development theory and practice as well as the significance of the resources nexus (see Figure 9.1). This is of particular relevance, where international partnership goals may impact investments, especially finance and innovation, as argued by *Hoff* [2011]. Alignment of economic objectives with ecological health and social security goals, it is argued here, constitutes concrete steps toward better development outcomes and strengthened institutions. This excursion will also enunciate the strong focus of Agenda 2030 on integrated approaches that support holistic assessments of sustainable development challenges. Coupled with strong global partnership, Agenda 2030 sets the stage for invigorating dialogue on nexus concepts and increasing buy-in, in particular in the political realm often neglected by natural scientists.

The ensuing discussion will draw upon three levels of governance which influence and are influenced by the various junctures and general progress in international development cooperation: (i) norms (understood as shared values), (ii) institutions (understood as rules), and (iii) organizations (understood as those bodies that ensure compliance with operational rules). International, regional, and local normative frameworks can have profound effects on the nature, effectiveness, and success of international development cooperation. Growth theory following World War II attached immense value to the benefits of economic development modeled on the experience of industrialized states. It was believed that a strong economy would lead to greater investments and thus allow benefits to trickle down to all parts of society. This is one reason why discourse on international development cooperation more often than not is characterized by monetary or economic considerations. This is especially the case with reference to international development aid (IDA) or official development assistance (ODA). It is believed that increased financial support would go hand in hand with projects and programs that support sustainable outcomes. However, more IDA does not necessarily equal better environmental, economic, and social outcomes [*Bhagwati*, 2010]. For too long, the inherent interlinkages between biophysical, socioeconomic, and institutional processes have not received the necessary attention.

The weaknesses of silo-thinking and related unfavorable consequences for international cooperation and sustainable development have become apparent in the review of the Millennium Development Goals (MDGs). Inherently a results framework, the MDGs focused on social development in developing countries. Goal 8 on "a global partnership for development" was only added later to enhance participation of developed countries and increase international cooperation. Notwithstanding the strong and important value rendered upon overcoming social challenges, in particular the reduction of poverty, this global normative framework did not account for

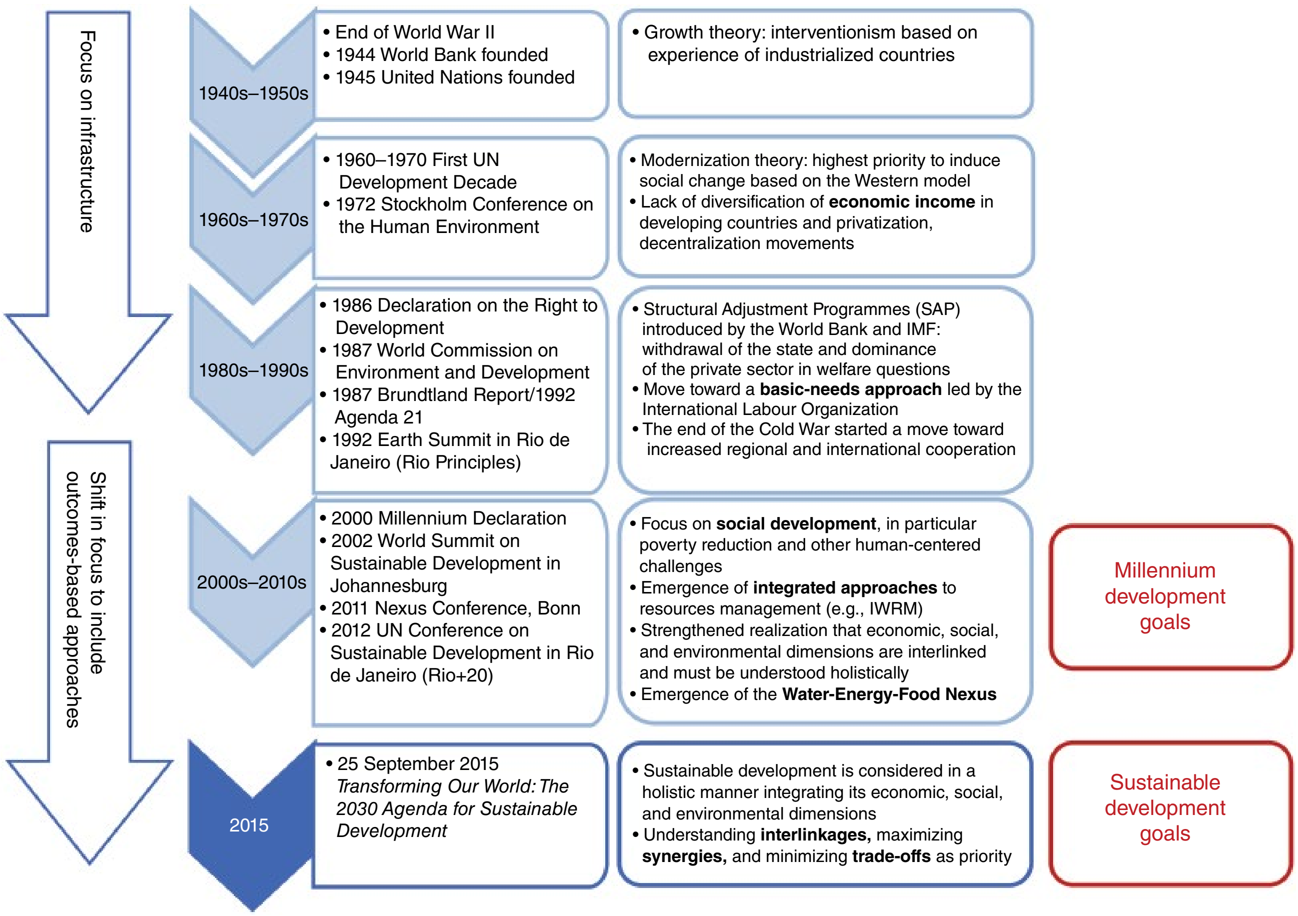

Figure 9.1 Chronology of selected international development trends.

programs in the area of economic development and environmental sustainability. Economic, social, and environmental programs often run in parallel. Occasionally, they support one another, but more often than not, while making strides in one area, they cause adverse effects in another. The lack of a holistic understanding not only limits international cooperation as will be argued in subsequent sections below, but in particular neglects any externalities and side effects (whether positive or negative) produced in the other two dimensions respectively. It is imperative to recognize that the nexus approach enables us to gain deeper insights into resource management that does not favor one resource or sector over another. Instead, it offers tools and methods to satisfy social and economic thresholds that take account of global changes without compromising environmental sustainability [*Yang et al.*, 2016].

Polarization between social values and economic growth objectives has been reinforced by the development of structural adjustment programs (SAPs) initiated by the World Bank (WB) and the International Monetary Fund (IMF) in the 1980s [*Easterly*, 2005]. SAPs, although allowing developing countries to overcome debts and, at least in theory, to continue their economic growth, have been criticized for imposing harsh conditions on participating states. Often, SAPs resulted in unbearable social costs and neglected long-term development needs as well as the specific local conditions (for a detailed critique see *Brohman* [1996a, chaps 4 and 5]). As a consequence, homogeneous policies were favored and boundary conditions, including cultural, political, social, and administrative dimensions, were not defined. This neglect for social (e.g., gender), economic, and environmental heterogeneity made many policies ineffective in their application. The lack of defining and understanding local/regional circumstances (boundary conditions) additionally contributed to negative outcomes. In particular, SAPs and other development programs capitalized on the weakness of institutions in developing countries.

With the emergence of the basic needs approach adopted by the International Labour Organization (ILO) in the 1970s, the nature of international development cooperation also began to change [*Brohman*, 1996c]. Greater consideration was placed on how resources are allocated between various groups of people and the social implications for individuals without decision-making power. A difference was also made between public and private goods. In particular, more emphasis was given to strengthening institutions to allow for greater public participation and to set the framework for integrated management [*Savedoff and Spiller*, 1999; *Louka*, 2006]. Nevertheless, development practices remained dominated by economic growth theory until the early 1990s [*Brohman*, 1996a]. (It is noteworthy, however, that the 1987 Brundtland Report mentioned sustainable development, which constitutes the beginning of a shift in thinking.) Interventions have been characterized by top-down, centralized development programs, which encouraged silo thinking and sectoral planning approaches. At various stages between 1950 and the early 2000s, development theory and practice experienced continuous shifts that put economic, social, or environmental goals at the center of the discourse. One aspect always taking a dominant position over the other two meant that interconnections between these dimensions were not considered, such as impacts on the environment caused by economic growth strategies.

The fall of the Berlin Wall in 1989 further influenced international cooperation greatly, opening new possibilities for defining common norms at the regional or international level, developing rules governing interactions between states, and encouraging foreign investments and development aid [*McWhinney*, 1991; *Reich*, 2007]. The opening of the ideological divide initiated a move from coexistence to increased cooperation to address global challenges, in particular those of a transboundary nature. Strides in the recognition of shared values and the need for strengthened institutions at global, regional, and local levels were especially prominent in the field of environment. The 1992 United Nations Framework Convention on Climate Change (*UNFCCC*, 1992] and the 1982 United Nations Convention on the Law of the Seas (*UNCLOS*, 1982], which entered into force in 1994, are prominent examples of revitalized global partnerships and codification of rules. These and other conventions pinpoint to the urgency of environmental protection to preserve the earth's ecological system and peoples' ability to survive. Additionally, they provide normative frameworks, principles, and a number of measures of standardization in relation to allocation and use of environmental resources and protection and preservation of vital ecosystems. In effect, the environment has turned into a public issue with effects on social and economic developments [*April*, 1991], which in recent times have gained prominence and are reflected in the discourse on international security, most recently through the SDGs, as well as human rights instruments. The human right to water and sanitation is a prime example. In 2010, the United Nations General Assembly recognized the human right to water and sanitation through its Resolution 64/292 after the Committee on Economic, Social, and Cultural Rights had define the right to water in its General Comment No.15 in 2002.

Albeit efforts and advances in formal norms and rules setting, operational and implementation challenges were and remain overlooked and underemphasized. Organizations are crucial in monitoring the practical application and enforcement of policies and laws. The effectiveness of these organizations depends highly on the institutional environment in place, whether locally, regionally, or compared to the global context. Development history shows that international cooperation or foreign aid can highly influence outcomes for the national economy, the national population, and national environmental protection schemes.

The postwar period was further characterized by the industrial revolution, which was pervaded by rapid economic growth (measured in Gross Domestic Product (GDP)) and development focused on exports to secure foreign investments. Especially developing countries appeared to benefit from this outward orientation, at least at first. However, a lack of diversification of markets and the omission to realize the needs of the local population soon led "(…) development theorists (…) to recognize that high rates of economic growth were not necessarily correlated with other basic objectives of Third World development" [*Brohman*, 1996b, p. 38]. Additionally, instead of furthering "cooperation" (understood as working together toward a common goal) at the international level, these postwar development models resulted in unsustainable global power relations as well as a number of negative economic, social, and environmental side effects in developing countries (e.g., soil degradation due to intensification of agriculture, widening rural-urban divides, etc.) [*Brohman*, 1996b]. Power imbalances, as will be seen in the case study on the Nile Basin Initiative, have significant impacts on sustainable development outcomes as they depend on the strength of norms, institutions, and organizations nationally to boost political influence regionally and globally.

9.2.1 Why International Cooperation?

International cooperation frameworks (whether through international conventions, regional river basin commissions, foreign aid, or other formal or informal means) are a key driver of how environmental resources are managed, protected, and used. Environmental challenges that are not confined to the geographical boundaries of one state, such as transboundary rivers or air pollution, can only be addressed effectively through international cooperation. This includes the setting of shared norms, and the formation of strong institutions and effective organizations.

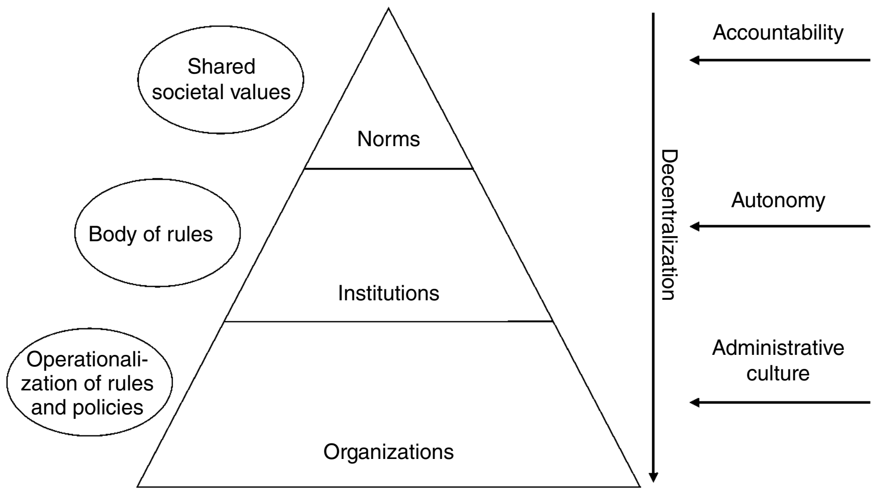

Figure 9.2 Levels of governance.

However, before it is possible to quantify the nexus, interlinkages between water, energy, and agricultural sectors need to be assessed against the architecture of the three levels of governance described in Figure 9.2. Likewise, the political dimension must not be overlooked as it may contribute to disputes over policies governing resource uses, budget allocations, and management plans more generally. Politics significantly influences the choice between various levels of cooperation and conflict [*Sadoff and Grey*, 2002; *Williams et al.*, 2014].

While international cooperation is of particular importance for transboundary challenges, states can also generate gains from cooperation to advance environmental management strategies nationally, namely between sectors as well as between various stakeholders, from policymakers to citizens. In the context of the nexus, benefits include mutual learning and developing an understanding of the nexus concept; data and knowledge sharing to combine biophysical, socioeconomic, and institutional dimensions; presentation of best practices and capacity building on the nexus; a forum for dialogue and building trust between stakeholders from diverse sectors and disciplines, which may in turn lead to greater regional integration and opportunities for cooperation in other areas (e.g., by tapping into the resource use potentials of states that can share benefits, energy in exchange for food). Additionally, cooperation and utilization of common methods (that have been adapted to the national context) to carry out nexus assessments will enable a progressive move toward harmonization of approaches and the standardization of monitoring frameworks. This in turn results in greater comparability between states and regions and would greatly enhance the quantification of the nexus as well as create innovation in how data are generated, analyzed, and shared and subsequently used for performing assessments.

The United Nations Economic Commission for Europe (UNECE) has developed a methodology to assess water-food-energy-ecosystem linkages and trade-offs through cooperation between riparian states of a transboundary water body as well as between sectors, mainly, water, agriculture, and energy [*UNECE*, 2015]. The first assessment covering three surface water basins in the Caucasus, South-Eastern Europe, and Central Asia was treated as an initial scoping exercise. It serves as one example that through cooperation on shared environmental resources and the involvement of stakeholders of the nexus relevant sectors, it is possible to define data management protocols, share data between states and sectors, establish monitoring frameworks that capitalize on nexus thresholds (for a more elaborate discussion on how thresholds contribute to decision making on the water-energy-food nexus, see *Yang et al.* [2016]) and indicators, identify capacity-building needs, nexus knowledge, and skills gaps, and, thus, improve intersectoral coordination. Nevertheless, it must be realized that increased cooperation alone, including the participation of stakeholders from various sectors, does not necessarily correlate with greater coherence in the management of environmental resources and policy development [*De Strasser et al.*, 2016]. Efforts to increase and strengthen cooperation, however, are essential for achieving the goals set out in Agenda 2030 mentioned earlier.

Sadoff and Grey [2002] in their discussion on the benefits of international cooperation in relation to transboundary rivers have defined four types of cooperation that cover ecological, economic, and political aspects, as well as its function as a facilitator of further cooperation, including greater regional integration. As they emphasize, it is crucial to understand the positive impacts that cooperation can have, not only on an environmental resource (e.g., improved quality of water of a river), but also beyond a resource's biophysical characteristics (e.g., increased policy coherence, strengthened institutions, greater equity). It follows that international cooperation on the nexus may enhance stability and integration in the region in combination with increased sustainable development globally, including a minimization of externalities and heightened benefit-sharing potentials (see also Table 9.1).

9.2.2. Why the Nexus Approach?

Following on from the previous discussion, the shift from economic growth toward a needs-based and later nexus approach has a number of implications that are worth highlighting. From a resources perspective, a move toward integrated approaches, such as integrated water resources management (IWRM), has prevailed in recent years. While "integration" constitutes an important first step in drawing attention to the impacts of management options of one particular resource on other resources or sectors, approaches remain devoted to sectoral goals. In the case of IWRM, water is the central entry point and improved water use efficiency for conflicting purposes constitutes the prime objective [*Jeffrey and Gearey*, 2006]. The nexus approach, on the other hand, not only tries to understand the interlinkages, synergies, and trade-offs between various resources and sectors, but also treats them first and foremost with equal importance [*Kaufmann et al.*, 2010].

Critics of IWRM have further highlighted an omission of crucial political and governance forces that influence resource management projects, programs, and their subsequent outcomes [*Wester and Warner*, 2002]. This is of significance as will be demonstrated in the next section. We will enunciate that successful international cooperation depends on a political negotiation process that considers the various interests and policy priorities of concerned states, especially where resources are shared [*Carroll*, 1999–2000] (for a discussion on international politics and cooperation, see *Snidal* [1991]).

In contrast to economically motivated international investments and IWRM approaches, the nexus approach

Table 9.1 Types of cooperation and opportunities for the operationalization of the nexus approach

Type of cooperation[a]	Sustainable development dimension	Nexus opportunities	Nexus methods
Increasing benefits to the resource/ ecosystem	Ecology	Ecosystems are assessed holistically Interlinkages, synergies, and trade-offs between environmental resources are assessed Discussion on environmental resources opens dialogue on nexus knowledge, nexus methodologies, capacity needs, and institutional frameworks	Multiple-use water services Multifunctional land use systems Integrated/coupled modeling tools that analyze fluxes and flows between various resources[b]
Increasing benefits from the resource/ ecosystem	Economy	Synergies and trade-offs between sectors (e.g., energy and agricultural competing demands over water) made explicit and most appropriate/ efficient management options (e.g., the choice of location of dams)	Life cycle cost assessment Payment by result
Reducing costs because of the resource/ ecosystem	Politics and Society	Institutional environment and arrangements in relation to resources assessed Potentials for regional and international cooperation to share data and knowledge, learn from best practices, enable mutual learning and capacity building, set the way for deeper cooperation, trust building and continuous dialogue Balancing of resource efficiency versus equity concerns	Nexus index may trigger action by decision-makers Regional Nexus Observatory consortia (points of excellence and regional data hubs) Setting thresholds
Increasing benefits beyond the resource/ ecosystem	Facilitation	Providing a number of management options that can be weighed against one another for environmental, economic, and social concerns Increased policy coherence across sectors and in the region Sharing of benefits within a region (e.g., food traded for energy)	Regional Nexus Observatory consortia (points of excellence) that allow for cross-fertilization within and beyond the region Coproduction of knowledge

[a] The types of cooperation have been adapted from *Sadoff and Grey* [2002].
[b] See *Mannschatz et al.* [2015a, 2015b].

offers a new perspective on regional and international cooperation. In view of the inherent objective of the nexus approach to advance coordination across sectors, encourage synergies, minimize trade-offs, and utilize feedback loops and monitoring methodologies, it can reasonably be assumed that international cooperation processes will be enhanced. This is particularly the case where international relations beyond the resources in question are concerned [*Sadoff and Grey*, 2002]. The nexus provides an important entry point to move beyond water and realize the co-benefits between sectors while at the same time reducing negative externalities. The valid critique of the water-energy-food nexus concerning itself with global considerations and, thus, having only little relevance at lower scales must be addressed [*De Strasser et al.*, 2016]. Cooperation and dialogue between different sectors has the potential to increase nexus knowledge and learning and, thereby, promote its application and operationalization. Albeit a number of advances in making the nexus approach more practical and analyzing interlinkages, synergies, and trade-offs, so that they become useful for decision maker, it can only develop in a transdisciplinary fashion, through a learning-by-doing, iterative, reflexive, and open process [see also *Kurian et al.*, 2016a]. Later sections will elaborate on a number of methods employed to aid making the nexus a reality (see also Table 9.1).

It has been recognized that the nexus approach must not overlook forces of global change that affect ecosystem functions and human well-being [*Kurian and Ardakanian*, 2015a]. *Scott et al.* [2016] consider how the unique characteristics of urbanization, including demographic makeup, political and economic structures, inequities in water or energy allocation, and other factors, drive the nexus. Similarly, international cooperation, influenced by national priorities and development goals, can provide greater understanding of interlinkages and trade-offs between political and policy processes, institutional frameworks, public financing, and pressing issues for human well-being. Analyzed in relation to relevant sectors (water, energy, agriculture) and resources (water, soil, waste) this can help identify nexus challenges. Nexus dialogues on transboundary, environmental questions that bring together stakeholders from different sectors and disciplines, including scientists, researchers, practitioners, decision maker, civil society, and grassroots, allow for a more holistic examination of nexus challenges. As will be illustrated through the case studies, transdisciplinary methods (the use of these methods is considered one means of operationalizing the nexus in practice [see also *Kurian et al.*, 2016a]) are essential not only for making explicit synergies and trade-offs between sectors and resources, but also for managing the complexities of significant factors and pressures that may prejudice a nexus assessment. These pressures include (i) political and economic power dynamics; (ii) matters of social equity and resource access and allocation; (iii) level of reliance on a particular resource, sector, or service; (iv) forces of global change, including climate change, urbanization, and demographic change; and (v) economic, environmental, and institutional risks and vulnerabilities.

It ultimately follows that competing uses and priorities (depending on drivers, pressures, and institutional arrangements) may cause tensions. The nexus approach attempts to overcome stresses and disputes by assessing biophysical fluxes and flows as well as social, economic, policy, and institutional impacts and relationships. This makes cooperation an essential ingredient for the nexus to become operational. Table 9.1 illustrates the numerous opportunities in this regard.

The next section will consider the case study of the Nile Basin Initiative using a nexus perspective and, thereby, underscore the significance of international cooperation for the operationalization of the water-energy-food nexus. An analysis of existing cases from a nexus perspective can be instructive for the design, planning, and implementation of future nexus projects and programs. Additionally, they may shed light on possible challenges and opportunities, where outcomes may have been improved were the nexus applied. This approach to analyzing challenges and opportunities for the operationalization of the nexus approach has already been used and deemed valuable in previous publications [*Kurian et al.*, 2016a, 2016b]. Subsequent sections will consider the approach UNU-FLORES has taken to operationalizing the nexus approach through cooperation by utilizing bottom-up approaches and the Nexus Observatory web-based platform.

9.3. CASE STUDY: INTERNATIONAL COOPERATION IN THE NILE BASIN AND THE NEXUS APPROACH

Globally, there are 263 rivers and lakes that are defined as transboundary [*De Strasser et al.*, 2016]. As was indicated in previous sections, resource management challenges that are not confined to one national state raise a number of issues that can only be addressed through concerted efforts involving a range of stakeholders. It further requires cooperation among riparian countries in order to ensure completeness of data and information regarding the transboundary water resource, whether concerning biophysical or social aspects, infrastructure projects, institutional arrangements, or economic use.

International cooperation usually arises in relation to a particular need or acute circumstances. In the situation of transboundary watercourses, such as the Nile River, international cooperation becomes a necessity for conflict prevention (e.g., amounts of water extracted for agriculture, water use for hydropower). Depending on the geographical location of a riparian state (upstream or downstream) as well as the political stability, economic conditions, and institutional setting, needs and resource use goals vary and may lead to rivalries over common/shared resources. The nexus approach, by broadening the scope of examination beyond water, aids the expansion of cooperation. *Amer et al.* [2005, p. 3] have posed the fundamental question that shapes all interaction: "How can large groups of people use limited natural resources in a sustainable and cooperative way?" This implies the prevention of conflicts, highlighting interlinkages, increasing policy coherence and resource governance, minimizing negative externalities and evaluating trade-offs, creating opportunities for mutual benefits (win-win), and improving cooperation more generally, between states and between sectors and to share successes globally [*De Strasser et al.*, 2016].

In the case of the Nile River, conflicts over the use of water from the river are exacerbated by the number of states competing for the resource. Because of its geographical reach, riparian states established the Nile Basin Initiative (NBI) in 1999. NBI is an intergovernmental partnership under the leadership of ten states that border the Nile: Burundi, the Democratic Republic of the Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. Additionally, Eritrea engages as an observer. The shared vision of cooperating states is "to achieve sustainable socio-economic development through equitable utilisation of, and benefit from, the common Nile Basin water resources" (for more information, see also the official web site of the Nile Basin Initiative: http://www.nilebasin.org/).

Historically, the Nile Basin is shaped by enormous regional differences as they relate to geographical, climatic, and other environmental characteristics, development status, priorities regarding national interests and long-term vision, challenges around poverty, and general lack of confidence and trust among riparian states [*Amer et al.*, 2005]. It must ultimately follow that preceding any conversation about applying the nexus approach for managing the transboundary resource, a base level must be set for cooperation to function. This includes first and foremost engaging in dialogue and building trust and confidence, so that concrete steps may be negotiated. The section on bottom-up approaches for regional cooperation will highlight this aspect in more detail. In the case of the Nile, it took more than 10 years to arrive at the current state, which makes it possible for researchers and decision maker from all riparian countries to collaborate on these important issues pertaining to human survival. It is striking that prior to NBI there was only little engagement between researchers from the various riparian countries, but that joint projects have become possible [*Amer et al.*, 2005].

In the early 2000s, the Nile Basin region was characterized by the following challenges and limitations [*Carroll*, 1999–2000; *Varis*, 2000]:

1. Water and food scarcity
2. Increasing energy needs due to global change factors (e.g., urbanization and population growth)
3. More extreme weather events (e.g., floods and droughts) and climatic variability
4. Political instability and colonial history of bilateral agreements
5. Disparate technical, legal, and financial capacities (e.g., institutional coherence, legal frameworks, data collection, and monitoring)
6. Lack of confidence and trust between riparian states
7. Lack of a common vision/goal

These pressures and disparities can be categorized into three areas: questions of resources (as they relate, for instance, to availability and their protection), services (e.g., questions of resource use/allocation), and risks (e.g., conflicts or extreme events) [*Kurian et al.*, 2016a]. These are summarized in Table 9.2. In the context of the NBI, these are to be framed under consideration of the equitable utilization principle, as was highlighted in the shared vision statement. Such a principle yields consequences for water use and allocation. First, the meaning of what is equitable must be defined. Whereas Egypt has historically made much greater use of the Nile water, other states, such as Ethiopia, have for a long time not been able to use the resource to its full potential due to internal and regional conflicts. Water availability also varies considerably between riparian countries, so that benefits are not equally distributed. Through the nexus, it is possible to look beyond the river and understand the breadth of other benefits that may be generated through cooperation. *Amer et al.* [2005, p. 11] state that "(…) if all national interests and responsibilities are pooled, trade-offs are made possible that allow for greater benefits for each of the member countries."

This is particularly significant from a nexus perspective, since the nexus approach is premised on striking a balance between various resource uses (e.g., for food production, generation of energy, drinking water) and resource allocation (e.g., agriculture, industrial uses, domestic uses), while considering forces of global change (e.g., climate change, urbanization, demographic change) and governance processes (e.g., institutional frameworks, equity concerns). While the above underscores the complexity of a nexus analysis, additional difficulties are afforded by cross-border problems. It is, thus, crucial to define scale and boundary conditions as well as critical intersections and interactions between biophysical, institutional, and socioeconomic domains and biophysical and institutional processes that shape the particular resource management problem. One means of doing so

Table 9.2 Nexus components shaping international cooperation

Category	Goal of cooperation	Nexus component
Resources	Sustainable use of environmental resources and protection of ecosystems	Synergies and trade-offs between resources and sectors made explicit and better understood
		Setting of common goals for the region
		Boundary and scale conditions defined
		Level of cooperation between sectors and disciplines strengthened; capitalize on the strength of the science-policy interface
		Data availability, harmonization, and sharing between sectors and in the region
		Comparable monitoring and assessment methods that support decision-makers to choose management and policy options as well as design results-oriented investment plans
		Feedback loops allow resource use cycles to be closed
		Increased policy coherence and improved resource governance, including normative frameworks, institutions, and organizations
Services	Sharing benefits (win-win)	Expansion of cooperation beyond the protection of environmental resources or conflict prevention to include socioeconomic considerations
	Economic integration	Strategic infrastructure projects (e.g., building of a dam in strategic location advancing preservation and protection of ecosystems and allowing for shared investments and the sharing of benefits, such as energy allocations for a number of riparian states)
	Promotion of human well-being	Assessment of demand versus supply and the application of payments for ecosystem services
		Assessment of efficiency versus equity concerns; setting of thresholds nationally and regionally
		Shared investments lead to more sustainable outcome
		Sharing of technologies and best practices that promote integrated resource management
Risks	Conflict prevention	Competing uses of environmental resources can be assessed in a holistic manner and nexus options balancing various needs developed (e.g., by using integrated models)
		Varying national priorities and challenges that favor one resource/sector over another; cooperation may lead to the identification of shared goals
		Institutional strength, negotiation power, and historical agreements or fragmented national/regional policies affect utilization of nexus benefits
		Building trust through nexus dialogues

would be the setting of thresholds. Not only could they address uncertainties, but also weigh biophysical drivers, such as climatic information or infrastructure projects, against major concerns of decision maker, such as energy and food provision. This method would allow the visualization of critical points within nexus interactions of sectors at which the minimum level of resource or service security is no longer provided for (e.g., enough food for the local population) [*Yang et al.*, 2016]. Further, it is key to establish comparable progress-monitoring frameworks and mechanisms imparting feedback loops that illuminate the impact of projects, programs, and policies [*Kurian and Ardakanian*, 2015b].

To illustrate impacts while strengthening governance frameworks, the DPSIR model could be of great service. Similar to the setting of weighing thresholds, it considers driving forces, pressures, state, impacts, and responses. This model is often used by the European Environment Agency to help decision makers understand better where the chain of causation related to the management of a resource can be broken. This in turn allows for the closing of resource use cycles. However, without first establishing a baseline for cooperation, these methods will not be useful and the nexus cannot be operationalized.

Any initiative that requires international cooperation involving several states is ultimately dependent "(…) on the *political will* of the governments to look for common goals, as well as their empowerment to implement policies" [*Varis*, 2000, p. 635 emphasis added]. Instituting such political will can only occur over time, especially where political instability and a history of conflicts over uses of Nile waters hamper negotiations without prior fostering of confidence and trust. Retrospectively analyzing the case of the NBI through the lens of the nexus affirms the need for cross-sectoral problem solving. Whereas previous agreements between Nile riparian states (it is noteworthy that they were not inclusive of all riparian states (e.g., Hydromet or TeccoNile)) only considered technical challenges, it was soon realized that such a sectoral approach does not bear fruit in the long-term. The emphasis, thus, moved toward examination of regional conditions as they relate to environmental, institutional, and in particular legal issues, economic, food security, as well as technical issues [*Carroll*, 1999–2000;

Cascão, 2009]. Ultimately, this must include attracting international donors, who may also serve as "neutral" facilitators for the cooperation and, subsequently, the negotiation process.

Any legal regime grounded in international cooperation can only be effective if all affected countries are included in the cooperation and negotiation process. The NBI experience endorses this notion. It was only possible to promote equitable utilization and increased sustainable management of Nile waters upon recognition of this crucial prerequisite. As *Carroll* [1999–2000] rightly argues, "(…) Nile states need accurate data and other information on the Nile Basin, collected by a neutral source, so that they may come to a common understanding of water resource issues in the basin." Following these steps, namely (i) knowledge generation and sharing, (ii) generating a common understanding, which can lead to a shared vision, and (iii) employing a neutral intermediary, are measures that move the abstract to the practical, planning to implementation.

In the case of the NBI, the WB and the United Nations Environment Programme (UNEP) took the lead in developing technical and legal capacities in the region. They also served as a "neutral" intermediary that could bring riparian states together and facilitate negotiations. Additionally, international organizations, such as the two mentioned here, serve as donors and have the potential to advance a consortium for international cooperation that attracts further donors as well as international expertise (e.g., from Europe) [*Carroll*, 1999–2000].

Similar to the nexus approach, trade-offs need to be made explicit and various interests and national priorities balanced against one another. This postulates a balance of negotiation power, which was difficult to attain considering the asymmetric power constructs of many of the riparian states in the Nile Basin [*Cascão*, 2009]. An iterative cooperation process, which addresses domestic challenges first, becomes necessary in order to enable states to articulate their needs and goals clearly. Adopting such an approach, however, demands a level of vigilance toward efforts of data and information gathering and sharing not being an excuse to shy away from negotiation on common goals and resource management [*Carroll*, 1999–2000].

An understanding of how the nexus is governed constitutes a first step in applying methods that allow for the closing of cycles and a balancing of resource use and allocation issues. A review of case studies, such as the NBI, demonstrates how the nexus could assist with regional and international negotiations and bring together representatives from politics, academia, and practice. This approach, by utilizing transdisciplinary methods, enables collaboration across sectors and disciplines and the setting of clear boundary and scale conditions, all characteristics of the nexus approach [*Kurian and Ardakanian*, 2015c]. (For a more detailed discussion on transdisciplinarity and the nexus, see *Kurian et al.* [2016a].)

The application of the water-energy-food nexus to existing cases further stipulates questions of policy relevance that recognize the reality of a need for greater cooperation on interrelated resources management problems. Early stakeholder engagement is key to aid identifying the most relevant policy aspects that need to be addressed through transdisciplinary nexus methods. These methods need to be capable of capturing the complexity of nexus issues as well as interrelations between resources, sectors, and various institutional levels. It is not surprising that this process can only occur, as was mentioned previously, in an iterative manner. This is true for the NBI considered here, but even more so in cases where no immediate transboundary problem triggers cooperation, but the desire to advance nexus knowledge, nexus understanding, and nexus competences.

The next section will consider methods used by UNU-FLORES utilizing international cooperation mechanisms to operationalize and test the nexus approach to the management of environmental resources. Consideration will be given to the value of bottom-up cooperation in addition to an analysis of emerging lessons from employing a web-based observatory to advance cooperation and highlight nexus challenges and opportunities.

9.4. EMERGING LESSONS OF THE NEXUS OBSERVATORY

9.4.1. Operationalizing the Nexus through Bottom-Up Regional Cooperation

The previous discussion has highlighted a number of challenges related to traditional international cooperation approaches, including tensions resulting from power imbalances, a lack of political buy-in, silo thinking and prioritization of economic gains over environmental protection or human security and well-being. International cooperation often involves political or monetary bargaining. As a think tank and member of the United Nations family, UNU-FLORES is in the unique position to bridge the science-policy divide by mobilizing researchers and policy-makers toward a common cause in a non-threatening manner. This implies that international organizations and nongovernmental organizations (NGOs) have an ever-increasing role to play in international development cooperation by utilizing innovative and creative means to generating political buy-in. Where projects/programs are designed using a bottom-up approach, ensuring that developing countries define priorities and development needs (in contrast to the experience in the twentieth century), longer-term commitment may be generated that goes beyond mere monetary gains.

Besides advancing the science-policy interface and political willingness for cross-country cooperation, bottom-up approaches also encourage mutual learning, development of trust, knowledge and data sharing, including through best practices. Through the process of cooperative problem solving, new knowledge can be generated or coproduced, a common understanding gained, comparable standards developed, and capacity needs addressed [*Endo et al.*, 2015]. It may also lead to investments by donors. Employing transdisciplinary methods in the design and execution of cooperation further stimulates collaboration that is more likely to produce better policy outcomes [*Kurian et al.*, 2016a].

For the nexus approach to the integrated management of environmental resources, a bottom-up approach implies engaging with decision maker and other relevant stakeholders to address a specific environmental problem. By employing a nexus approach in setting the boundary and scale conditions that would guide problem solving, it is possible to identify synergies between resources (water, soil, waste), resource uses (energy production, agriculture, food security), and governance processes, such as institutional arrangements, normative frameworks, and service provisions. Once synergies have been identified, trade-offs between these various components can be made explicit by utilizing scientific methods. In this manner, classification of knowledge can occur in quantitative and qualitative ways. These may include index development, scenario analysis, visualization, and benchmarking [*Kurian and Meyer*, 2014]. Through these instruments, it is possible to highlight options that minimize trade-offs, negative externalities, and associated risks.

Endo et al. [2015] describe a variety of inter- and transdisciplinary methods that allow the nexus to become operational through qualitative methods (describe the nexus context of a particular region) and quantitative methods (e.g., models or integrated indices). However, prior to starting cooperation on the nexus, stakeholders must be involved early on to define national and regional priorities and challenges. Only then can an assessment, like the one carried out by UNECE or the continuous dialogue between riparian countries of the Nile basin, pinpoint whether employing a nexus approach yields better results than sectoral approaches. Transdisciplinary research, which includes taking advantage of a mixture of methods, has the potential to highlight undiscovered interlinkages and alternative management options that have been neglected due to the complexity of any nexus analysis.

The Africa Consortium on Drought Risk Management is an example of regional cooperation using a bottom-up approach to address resources nexus issues [*Kurian et al.*, 2016a]. In 2015, UNU-FLORES entered into cooperation agreements with Ministries of three sub-Saharan African states, namely Ethiopia, Malawi, and Tanzania. In collaboration with national research institutes, the consortium aims to create African Points of Excellence (APE) that are able to advance national research, resource management, technical and institutional capacity, as well as continue a dialogue on data and information sharing in the region. A major aim of the cooperation is the establishment of a regional data hub that would allow for regular scientific and policy exchange as well as for good practice sharing. These initial steps of strengthening capacity and working toward a framework of cooperation through dialogue and trust building (e.g., through regional workshops or training events) are comparable to the historic timeline of the NBI described in the previous section.

The NBI, it is argued here, proved such a success, as it brought (beginning in 2002) *all* riparian states together at least once a year in a conference series that allowed the exchange of information involving both representatives from the political and academic planes [*Cascão*, 2009]. It is clear that political will and trust for successful international cooperation necessitates a number of crucial preconditions from a governance, institutional, and capacity point of view. Our experience of establishing the APE highlights a number of issues of legal significance, especially as they relate to issues of data on water resources, statistics on income and employment, and land use and land cover change. Our position as a United Nations University allowed us an opportunity to approach the issue of data sharing and intellectual property from a scientific, educational, and capacity development point of view. The significance of "neutral mediators" (e.g., international organizations) in fostering international cooperation was also highlighted by our analysis of the NBI.

An educational focus allowed us to bridge divides between developed and developing country universities and research institutes (e.g., Technical University of Dresden and Water Development Management Institute, Ministry of Water, Government of Tanzania), divides between sectors (water and soil) that have implications for the water-energy-food nexus, and divides across disciplines (e.g., geographic information system (GIS) and remote sensing and institutional analysis). In furthering cooperation in a structured way, we were able to operationalize the nexus approach by emphasizing integration that did not focus merely on management of environmental resources. Instead, we highlighted how resources translate into services that consumers use and the potential risks to service delivery that emerge for biophysical (e.g., drought) and institutional reasons (e.g., affordability of consumers to pay for irrigation or water services).

The experience of establishing APE also highlighted the importance of using data as a neutral but important incentive to foster international cooperation. By organizing proposal-writing workshops, followed by regional consultations involving decision maker, we were able to collectively identify policy-relevant research priorities. In the case of APE, the consensus that emerged focuses on the collection, sharing, analysis, and coordinated decision-making on drought risk monitoring. We were able to use regional consultations, roundtable discussions held at the UNU-FLORES-hosted biennial Dresden Nexus Conference, and training workshops in the region to convince decision-makers of the need to use data for PhD research that would address policy priorities. Rather than conducting research with a narrow country focus, APE encourages research to address issues such as drought risk that necessitate a regional focus. With decision maker and researchers from the region driving cooperation, we are confident that the nexus approach can become fully operational.

The next subsection will elaborate on the role web-observatories can play in furthering international cooperation on the nexus approach by providing a platform that would seamlessly integrate data to meet training, research, and policy advocacy needs.

9.4.2. Advancing Innovation and Applying Nexus Methodologies Utilizing the Functions of the Nexus Observatory

Web-observatories, as was argued elsewhere, have the potential to facilitate international cooperation, attract interest from potential donors, enable data and information sharing, knowledge consolidation and analysis, as well as knowledge translation and innovation in the use of nexus tools and methodologies [*Kurian et al.*, 2016a]. The Nexus Observatory is an initiative of UNU-FLORES that provides a framework for science-policy interactions by employing innovative methods to advance the nexus approach. Data classification, knowledge consolidation, analysis, and translation constitute essential functions. As illustrated in Table 9.3, three key data sources have been identified. These data need to be complemented by further information sources, such as remote sensing or GIS. Discussions around data, especially in the context of a web-based observatory, serve as a non-threatening facilitator of international cooperation on pressing development and societal problems.

In contrast to the NBI described in the previous section, the Nexus Observatory is not limited to one region only, but encourages the transfer of expertise from one region to another. This is possible through capacity development and training programs, such as through a regional consortium or a blended learning program (see also Meyer 2017), as well as through reviews and examination of case studies that may produce generalizable principles. Our analysis of the NBI from a nexus perspective highlights the importance of scientific inquiry in improving our understanding of societal problems and approaches to address them. For example, the effect of transboundary water cooperation is predicated upon robust scenario analysis and benchmarking. For this purpose, data from multiple sources (UN agencies, member state ministries, and private data sets) using multiple mediums (in situ, remote-sensed, and mobile) are crucial for effective modeling of future scenarios and possible environmental and institutional risks. The Nexus Observatory has also been experimenting with the use of indices as a tool to enable translation of scientific outputs into a form that may engage decision maker in discussions over important decisions regarding resource allocation for management of environmental resources. The Nexus Observatory initiative has initiated research on the applications of a drought vulnerability index and a wastewater reuse effectiveness index [see *Kurian et al.*, 2016a; *Kurian*, 2017].

It follows that the Nexus Observatory can serve as an important tool to activate international cooperation and generate political buy-in. The formation of consortia, such as the one in Africa discussed earlier, shows how the nexus approach, by taking into consideration intersections and interactions, can step in to prevent conflict before it arises and to foster cooperation instead of allowing for a problem to escalate. Our experience with APE highlights the following five iterative steps to building an effective consortium that advances the use of data for effective decision-making:

1. Identify priorities by consulting with researchers and decision maker.
2. Agree to build local capacity to respond to environmental risks (e.g., droughts).
3. Build consensus for a regional rather than a narrow sectoral, country, or disciplinary focus (thereby advancing the nexus approach).
4. Distil research lessons based on creative use of data to inform global monitoring mechanisms (e.g., SDGs).
5. Based on reuse and/or updating of data, incubate new research to address future policy challenges.

Table 9.3 Levels of engagement with key data sources [*Kurian and Meyer*, 2014]

Data (classification)	Knowledge (consolidation)	Information (translation)
UN agencies	Scale/boundary conditions/feedback loops	Trade-offs/synergies/resource optimization
States/ministries	Scale/boundary conditions/feedback loops	Trade-offs/synergies/resource optimization
Private data sets	Scale/boundary conditions/feedback loops	Trade-offs/synergies/resource optimization

9.5. CONCLUSION

The challenges and opportunities highlighted in this chapter constitute the first steps toward operationalizing the nexus through international cooperation. We have emphasized the relevance of the nexus approach to the management of environmental resources by using a prominent case study from the Nile River Basin as well as our own experiences from working with three African states. Further, the chapter outlined the history of international cooperation and how it is often related to specific development problems and national priorities.

Putting the nexus into practice requires an understanding not only of biophysical factors, but also, in particular, of political, institutional, and socioeconomic conditions. The NBI is especially illustrative of the inherent power relations at stake, where international cooperation is necessary for the sustainable management of a river or other environmental resources. The benefits of international cooperation are manifold and are expanded even further through the nexus approach. Important insights are to be gained from an analysis of existing cases through the lens of the nexus. The lessons learned can, thus, translate into generalizable principles, which in turn find their application in nexus projects and programs. Initiatives, such as the Nexus Observatory, have the potential to make the nexus visible by employing tools and methodologies that explicitly highlight synergies and trade-offs.

Although nexus-oriented research has started to gather pace over the last few years, it is premature to quantify the benefits of the nexus in any concrete terms at this stage. The true test of the practicability of the nexus will materialize when governments and donors adopt nexus governance principles and strategies in their planning procedures and management strategies. This requires strengthening cooperation in order to increase mutual learning and understanding of the nexus and its applications. This should be done in an iterative process, for example, through pilot studies, as is done in the Nile Basin. The Nexus Observatory serves as a mechanism to collect and analyze data from existing case studies of implemented projects to quantify benefits of the nexus at regional and local scales. Furthermore, through bottom-up cooperation the Nexus Observatory performs the role of a hub for the coproduction of nexus knowledge, the testing of nexus methodologies, and the development of nexus competences.

Much more work needs to be done to evaluate how far the nexus enhances international cooperation and vice versa. The discussion in this chapter, however, shows that the nexus approach is highly relevant in advancing sustainable development and has the potential to yield better management and policy outcomes in addition to enhanced cooperation between states, between sectors, and between disciplines.

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10

Water-Energy-Food Security Nexus in the Eastern Nile Basin: Assessing the Potential of Transboundary Regional Cooperation

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ABSTRACT

With increasing demands and pressures on energy, food, and water resources in the region of the Eastern Nile basin, development projects and also potential for conflict along the Nile waters have increased. This study presents data on resource use patterns and reviews literature on the cooperation potential between Egypt, Sudan, and Ethiopia in the sectors of water, energy, and food. It introduces the resource use profiles of the countries in the three sectors and summarizes common challenges to resource security and in regard to cross-cutting issues, such as climate risks and land degradation. The study also highlights the issues for transboundary cooperation using resources within and beyond the Nile. It emphasizes the importance of regional integration, using current country-specific potentials for easing river-sharing conflicts and fostering human development of riparian countries.

10.1. INTRODUCTION

The Eastern Nile represents the vital region for transboundary cooperation in the Nile. Egypt, Sudan, and Ethiopia (Figure 10.1) together share the largest part of the river and are home to a big share of population, economic power, and important ecosystems along the Nile. In recent years, the conflict potential over Nile waters is increasing. The increasing utilization of river water by Ethiopia, as the Nile's main contributor upstream, and Sudan and Egypt, as downstream countries, privileged by historic water use rights is threatening the region with transboundary water-sharing conflicts. Rapid river development is motivated by rapidly increased demands of natural resources, such as food, water, and energy, whose provision depends largely on the Nile ecosystem. With increasing demands and external drivers (e.g., climate variability), the vulnerability of available resources is growing and resource security is under risk. Hence, cooperation between the Eastern Nile countries has evolved into a necessity and academic debate in order to outline common policies and share the benefits of sharing the same water resources [*Tafesse*, 2009; *Mapedza and Tafesse*, 2011; *Hensengerth et al.*, 2012]. Yet, literature on benefit-sharing and transboundary cooperation in the Nile have largely focused on water issues related to the river Nile.

This study provides comparative insights into resource use patterns and the resource potential of the three Eastern Nile countries in regard to water, energy, and food. Resource security challenges in the region are outlined in consideration of internal pressures, from increasing resource use and intensification, and external drivers, mainly climate variability. The potential for transboundary cooperation is studied based on a review of recent literature and a mapping of possible issues. Such cooperation is illustrated here by understanding the regional and

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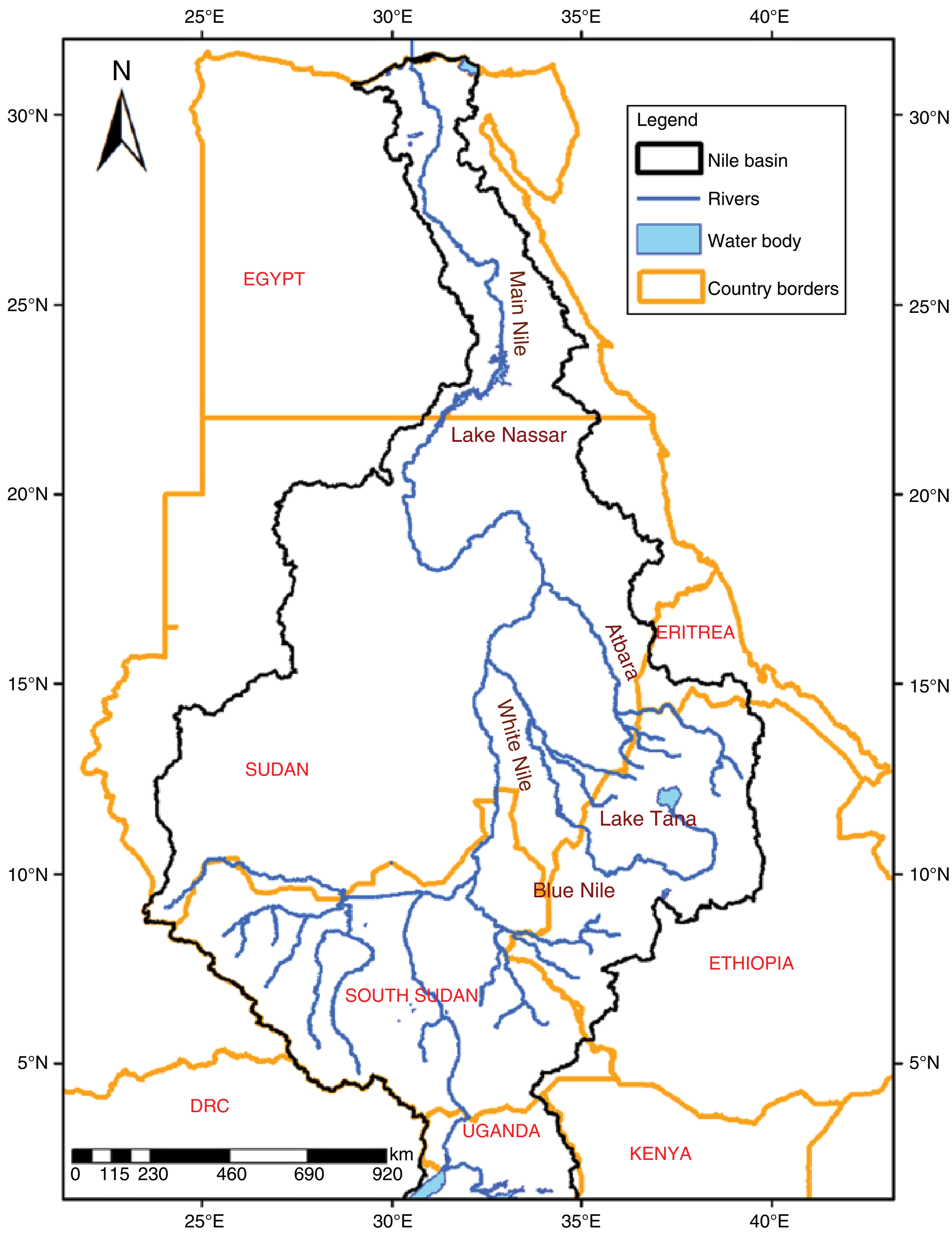

Figure 10.1 Map of the Eastern Nile basin. (*See insert for color representation of the figure.*)

country-level potential beyond the Nile river utilization. Nile-related conflicts can be eased by mobilizing other resource potentials to meet the resource needs of increasing populations and economies of the region. In this sense, regional integration and resource trade is a promising cooperative pathway in view of numerous specialization opportunities of the three countries. Cooperation can also be enhanced by mobilizing investments and encouraging technical cooperation among Eastern Nile riparian countries in areas of common interest. Future cooperative arrangements need to capture such cooperation synergies beyond the river while introducing macroeconomic reforms toward better integration in the region on both economic and human or individual levels.

10.2. PROFILE OF THE NEXUS COMPONENTS IN EASTERN NILE BASIN COUNTRIES

10.2.1. Water

Hydrology is a strategic issue for Egypt, Sudan, and Ethiopia alike. Available water and hydraulic structures are important for all the three countries of the Eastern Nile for covering their basic supply of electricity and food. In addition, reservoirs are used in Sudan for flow control.

10.2.1.1. Water for Energy

Sudan has eight known reservoirs of which two are under construction. The total design storage capacity of 8.58 km^3 for the larger dams obtains losses in the range of 60 to 34% and results in 6.17 km^3 of capacity [*UNEP*, 2007]. All of the dams, except Jebel Aulia, are affected by siltation. Sudan relies on reservoirs for controlling the Nile flow mainly for irrigation and, second, for generation of electricity. In contrast, Ethiopia is using its reservoirs mainly for energy production (see Figures 10.2 and 10.3). It recently constructed several small, medium, and large reservoirs, providing 99% of total electricity generation (around 5109 GWh) in 2011 [*IEA*, 2011]. Still, the great hydropower potential has motivated

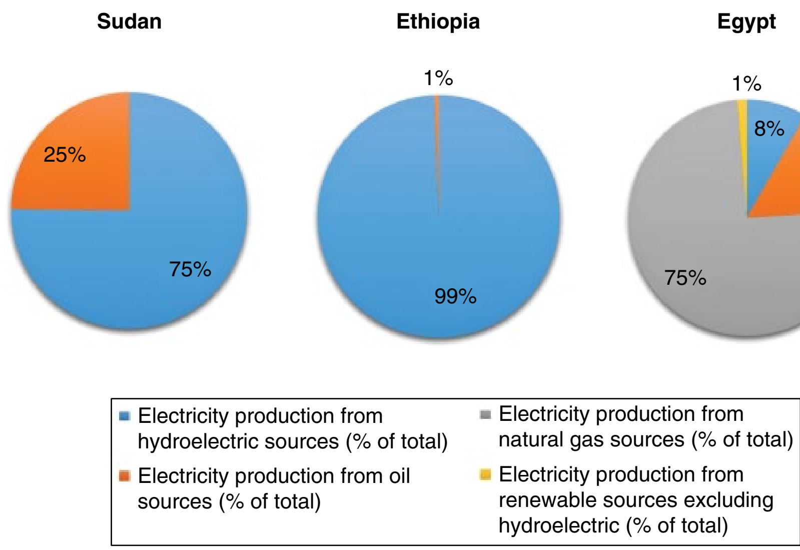

Figure 10.2 Electricity production in Egypt, Sudan, and Ethiopia. (*See insert for color representation of the figure.*)

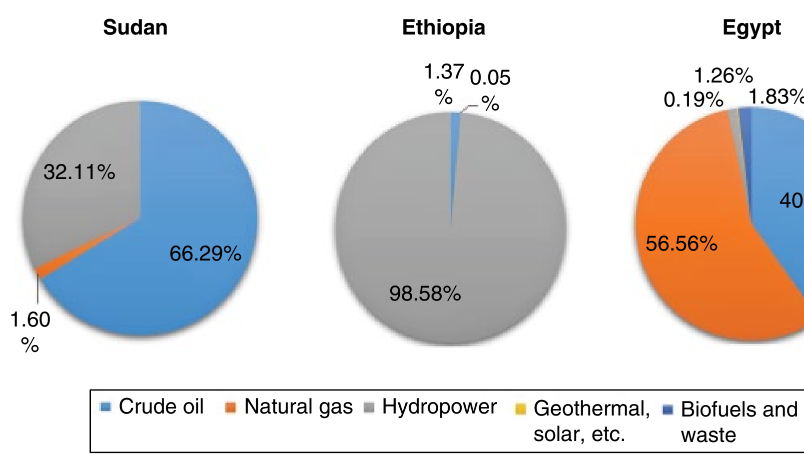

Figure 10.3 Energy production sources in Egypt, Sudan, and Ethiopia. Source: Data obtained from IEA Statistics [2013]. (*See insert for color representation of the figure.*)

the country to build new dams (e.g., the Grand Ethiopian Renaissance Dam (GERD)), some of which are under construction. Although the installed capacity in Egypt is 2692 MW, it cannot be exploited due to low water levels. Wastewater is being reused for biofuel production with active support from the government. Furthermore, the Aswan Dam is essential for enabling agricultural production in Egypt since it controls the river and provides for irrigation water.

10.2.1.2. Water for Land/Food

A common problem facing the region is the low water use efficiency (WUE) for agriculture. In Sudan, WUE in the 1 million ha scheme of Gezira is low, with cases of over-irrigation for all crops analyzed [*Deininger et al.*, 2011; *Al Zayed et al.*, 2015]. Depending on the crop type, the WUE in irrigation schemes in Sudan varies from 0.34 to 0.48 kg/m^3 [*Elamin et al.*, 2011]. Much higher WUE was estimated in Egypt. For example, wheat has a WUE of 1.2 kg/m^3 [*Zwart and Bastiaanssen*, 2004]. In many parts of the country, agriculture is based on traditional rain-fed farming due to low rainfall. On the other hand, the water efficiency and irrigation systems in Ethiopia are even less efficient. This situation makes the country increasingly vulnerable to food security [*FAO*, 2011b]. Crops in Ethiopia are grown during the two main rainy seasons, the Meher and the Belg. Irrigated agriculture accounts for less than 1% of the total cultivated area while surface water is solely used for irrigation. Technologies are not well developed and sprinkler irrigation accounts for only 2% of the total irrigation systems. Even in good rainy seasons, the food supply cannot be covered in view of the rapidly increasing population. Therefore, Ethiopia suffers from food deficit, which was historically exacerbated by volatility in the global market, leading to local price volatility [*Woldehanna and Tafere*, 2015]. In Egypt, only 0.2% of the croplands are rain-fed while the remaining area is irrigated. Surface irrigation accounted for 302,854 ha in 2000, out of which 171,910 ha was from sprinkler and 221,415 ha from drip or trickle irrigation. Due to better infrastructure, WUE is higher than in Sudan and Ethiopia [*FAO*, 2011c].

The three countries are facing different pollution-related challenges. For Sudan and Ethiopia, water pollution originated from the lack of systematic assessment or monitoring. In Sudan, water pollution occurs due to lack of treatment. However, the resulting environmental damages are limited since industrial development is low. Fertilizer consumption in agriculture of 11 kg/ha is low [*World Bank*, 2015]. In Ethiopia, there is almost no existing sewage treatment, and wastewater is directly discharged into the rivers. However, according to the Food and Agricultural Organization [*FAO*, 2011b], the water quality is not seriously affected by drainage water from irrigation. Considering pollution in water systems, Egypt's greatest problem is industry due to direct or after-treatment discharge of sewage. Besides, pollution issues related to the increase of fertilizer use and pesticides also exist.

10.2.2. Energy

10.2.2.1. Energy for Water

The country database of the *World Bank* [2015] provides important insights on the energy situation in the region. In 2011, Sudan had a low access rate to electricity of around 30%. Energy supply for water services is mainly regulated with diesel water-pumping units. As provision of drinking water and irrigation in Sudan is cost intensive, renewable energy systems, such as wind-power-regulated water pumps, were installed in rural areas. Water extraction from groundwater sources is commonly organized by hand wells or petrol-driven wells. Compared to other countries in the region, Egypt is the largest energy-consuming country in North Africa. With 100% access to electricity, its electrification rate is higher than that for Sudan and Ethiopia together. Energy consumption for water is also generally high in Egypt since water supply is dependent at higher levels on pumping water from the Nile [*Feytan et al.*, 2007]. Egypt has more than 560 pumping stations, with more than 1600 single pumping units for irrigation of cultivated land, and the amount of electricity needed to operate these stations is indicated to be 930 GWh [*Feytan et al.*, 2007]. Due to increasing water scarcity and demand, many desalination plants have been built in the last 30 years. In 2002, the amount of desalinated water was 100 million m^3. Egypt is also reported to be one of the countries with the least energy intensity in water supply [*ESMAP*, 2012].

10.2.2.2. Energy for Land/Food

The energy use in agriculture is very low in Sudan (87 kilo-tons-of-oil-equivalent or ktoe in 2011) in comparison to the international standards. Electricity use in this sector accounts for 26 ktoe while the total use of oil products is estimated to be 61 ktoe [*IEA*, 2011].

On the other hand, machinery use in agriculture is expanding. Machinery is used in farming systems with large-scale, commercial rain-fed cultivation in the dry and wet savannas of Sudan. Similarly, energy use in agriculture in Ethiopia amounts to 84 ktoe, which represent 0.3% of total energy consumption [*IEA*, 2011]. Reasons for this low rate are low mechanization, dominance of rain-fed agriculture, and low level of sector development. Largely, the agricultural systems are based on small-scale farming using either hand power or draught animals. As for Egypt, the energy use in agriculture has experienced a high increase in 2011 to around 60% of the total energy consumption in 2010 [*IEA*, 2011]. The total energy consumption in 2000 was 292 ktoe, with 75% accounting for electricity. In 2010, it increased to 3685 ktoe [*IEA*, 2011].

10.2.3. Land

10.2.3.1. Protected Areas and Reservoirs

The major problem for Sudan and Ethiopia is illegal logging, as fossil fuels are not economically accessible for poor people whereas for Egypt water pollution is the main difficulty. The proportion of protected areas in the former Sudan accounts for 4.2% of total land area [*World Bank*, 2015]. The portion of protected areas in Ethiopia is higher, amounting to 18% of terrestrial area [*World Bank*, 2015]. Many of such areas lack monitoring although conservation has been broadly introduced. A dramatic number of 200,000 ha of forest cover is lost annually, reducing the yield potential by 2% each year [*Reegle*, 2012]. In Egypt, the protected area covers 6.08% of the total land. Water pollution is one of the important problems for these protected areas. However, wastewater treatment is not included in governmental plans for rural Egypt.

In Sudan, hydropower stations and reservoirs cover a total surface area of 3114 km^2 [*FAO*, 2011b]. The total surface area used for reservoirs in Ethiopia is 720 km^2 as constructed and 1900 km^2 under construction [*GEO*, 2009]. Given its large potential for hydropower, the area for hydropower stations and reservoirs may increase in the future. On the other hand, the resource potential for dams in Egypt is almost fully exploited. Lake Nasser, which is the source for Aswan High dam that supplies Egypt with a small part of its energy, is the biggest reservoir in the country and covers a surface area of 5250 km^2. In the face of rainfall variability and scarcity, there are experimental plants for rainwater harvesting at the coastal zone in, for example, Alexandria.

10.2.3.2. Land for Energy

Land degradation is a serious problem for Sudan, which is related to fuelwood production in Egypt and Sudan (see Figure 10.4). Authorities regulate commercial logging; however, in practice, this process is not controlled. Eventually, in the 1990–2006 period, Sudan lost 11.6% of its total forests to deforestation [*Butler*, 2010]. On the other hand, biofuels are emerging as an important energy source for Sudan. Additionally, Sudan is the third largest sugarcane producer in Africa. The by-products are primarily ethanol and, second, biodiesel. The government is planning to expand the area for biofuel production up to 1.4 million ha [*IEA*, 2011]. In Ethiopia, an estimated 1.15 million ha is used with an additional 500,000 ha offered for investments [*ABN*, 2007].

Biofuels represent an opportunity for Ethiopia in order to decrease food insecurity with additional help of technological transfer. Revenues generated from biofuel production can be used for food purchases (e.g., through energy for food trade with Sudan). In Egypt, fuelwood is the main representative of biofuels. The government worked on reforestation plans with a special focus on water treatment as irrigation source for plantations in cities and on production of fuelwood. According to the International Energy Agency [*IEA*, 2011], energy production by biofuels and waste was 1617 ktoe, of which 24 ktoe was exported in 2011. Recently, national programs for the use of wastewater for afforestation announced that 84 ha was used for biodiesel production. The theoretical energy potential of residues is huge, with 417 PJ mostly generated in agriculture and consumed in rural areas [*Said et al.*, 2013].

10.3. WEF SECURITY CHALLENGES

10.3.1. Overall Resource Security Challenge

Resource security in the Eastern Nile basin is seriously challenged by human-induced land use changes, poverty, high population growth, rising demand for natural resources, and external factors such as climate change and variability. Sudan continues to struggle with the macroeconomic aftereffects of South Sudan's secession in 2011, as the country lost almost 60% of its fiscal revenues due to the loss of its oil resources [*Khan*, 2015]. Egypt continues to suffer economically from the aftermath of the Arab Spring in 2011, as well as from increasing water scarcity. Ethiopia has achieved promising economic growth, yet it remains one of the world's least developed countries as well as one of the most food-insecure countries, with more than 8 million people currently suffering from recurrent drought conditions [*Bewke and Conway*, 2007; *Viste et al.*, 2013; *Nicholson*, 2014]. Considering the different sociopolitical conditions, the countries share similar nexus challenges. Resource security largely depends on the Nile as renewable freshwater and energy source.

10.3.1.1. Food Security

The three countries are highly dependent on their internal agricultural sectors, which employ 73, 45, and 27% of the population in Ethiopia, Sudan, and Egypt, respectively (Figure 10.5). However, with increasing populations, demands, and climate variability, the food security in these countries is under threat [*Luan et al.*, 2013; *Power*, 2014; *Vanlauwe et al.*, 2014]. Currently, Egypt is dependent on the global food market to secure the food demand of its population despite their high internal water footprint. At the same time, a reduction in imports is unlikely given the limited land availability and production yield [*Bordignon*, 2013]. Ethiopia fails to cover its

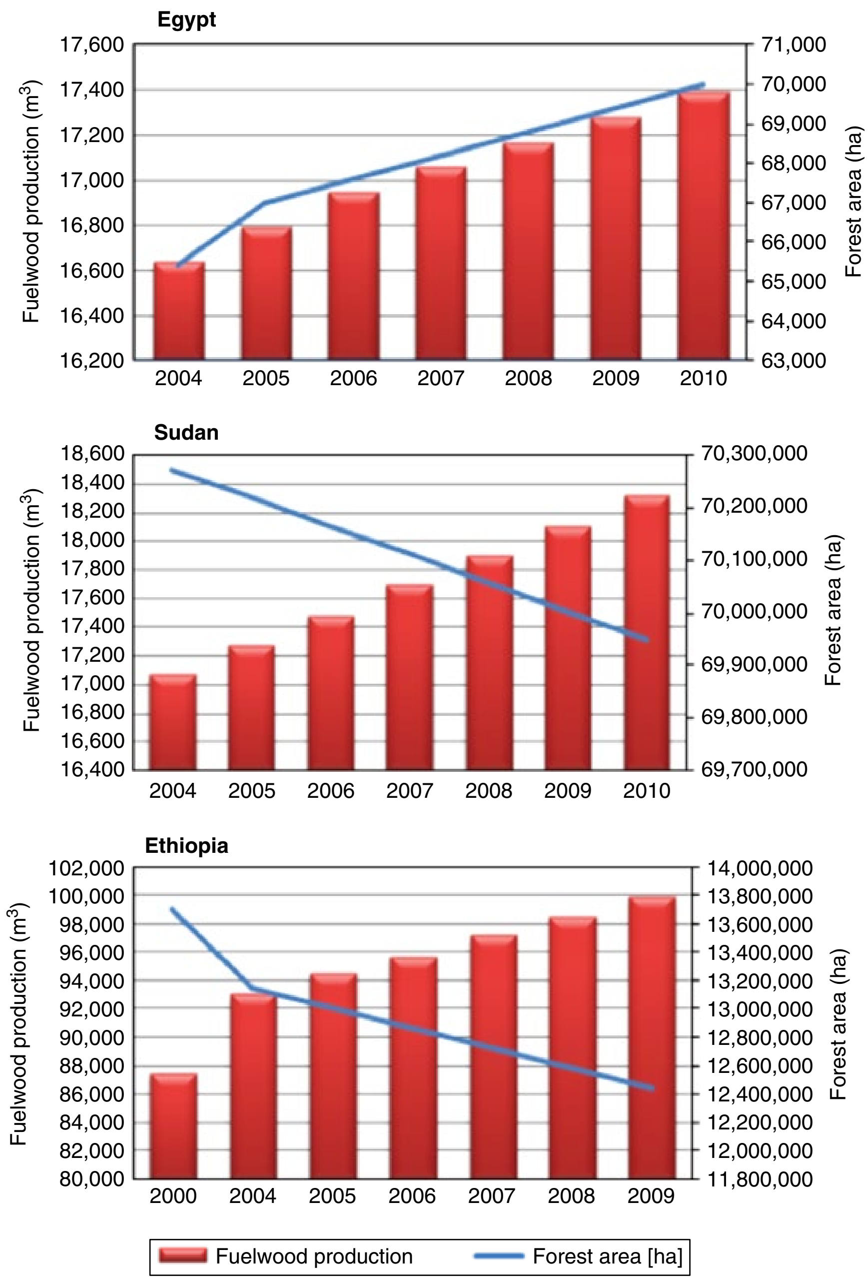

Figure 10.4 Fuelwood production and forest area in Egypt, Sudan, and Ethiopia. Source: Data obtained from Eurostat.

increasing population's food demand and continuously depends on external food assistance. Sudan also exhibits similar food scarcity problems even though the agricultural potential is high. A combination of conflict, insecurity, undeveloped infrastructure, restricted access to markets, and high food prices drives four million people in Sudan toward dependence on food assistance [*Khan*, 2015].

There are numerous common food insecurity threats between the three aforementioned countries. Farming practices have reduced the arable soil, and have caused desertification to spread [*Hegazi*, 2005; *FAO*, 2011a]. Continuous deforestation due to logging of firewood further increases these effects and leads to severe land degradation. Moreover, the loss of riverine forests increases siltation of reservoirs, diminishing their holding capacity and use for agriculture as well as energy production. Constant rural-urban migration turns arable land with scarce potential into residential areas, reducing the areas for agricultural production and, in turn, increasing poverty in both urban and rural areas. As urban populations continue to grow, competing demands for urban and agricultural uses of water increase the stress on the declining

		Egypt	Ethiopia	Sudan
Water	Water availability [m3/cap/a] (2014) [1]	699.1k	1 264k	975.1k
	Rainfall average [2]	51 mm/a	848 mm/a	416 mm/a
	Surface water [1]	51 km^3/a [99% Nile]	120 km^3/a	62.5 km^3/a
	Groundwater, actual (2011) [1]	1.3 km^3/a	20 km^3	7 km^3
	Total renewable resources, actural (2011) [1]	57.3 km^3	122 km^3	64.5 km^3
	Surface water entering the country, natural (2011/2012) [1]	84 km^3/a	0 km^3/a	99.3 km^3/a
	Surface water leaving the country, natural (2011/2012) [1]	0 km^3/a	97 km^3	84 km^3/a
Land	Arable land (ha/cap) (2012/2013) [6]	0.03	0.16	0.43
	Agriculture to GDP (2014) [7]	14.5%	41.90%	29.2%
	Employment in agriculture (2013) [7]	28%	73%	45%
	Prevalence of undernutrition (2014-16) [8]	< 5%	32%	n.a.
	Food security depends on... [18]	International food market	External food assistance	

		Egypt	Ethiopia	Sudan
Energy	Energy use per capita (ktoe/cap*a) (2011) [3]	987	381	355
	Electric power consumption per capita (kwh/cap*a) (2011) [3]	1743	52	143
	TPES (Total primary energy supply) (2013) [9]	77.54	47.94	14.43
	Crude oil reserves (in bbl) (2015) [4]	4.4 billion	430,000 bbl	1.25 billion
	Natural gas (2014) [4]	2.18 billion m^3	24.92 billion m^3	21.24 billion m^3
	Falling water, total hydraulic resources (in mio.kwh) (2008) [5]	125	650	48
	Access to energy	100% [14]	23% [13]	30% [13]
Cross-cutting issues	Agricultural activities based on water resources (Irrigated agriculture) [17]	99.8%	< 1%	7% [11]
	Energy use in agriculture (ktoe/a) [15]	292	84	87
	Energy in agriculture as a share of total energy consumption [15]	60%	0.3%	2.5% [12]
	Share of hydropower on total electricity generation	8% [16]	99% [19]	70.1% [10]
	Water pollution problems arising from...[19]	Industrial activities	Lack of treatment	

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Figure 10.5 Key facts for WEF sectors in Sudan, Ethiopia, and Egypt.

water resource [*Jaspers*, 2014]. Additionally, the lack of infrastructure and adequate treatment facilities poses a constant risk of water pollution, thus increasing the occurrence of waterborne diseases and leading to high under-five mortality rates and stunting. This and more threats are evidenced in Sudan [see, e.g., *FAO/WFP*, 2007; *Mahgoub*, 2014]. Climate change is expected to considerably reduce the cereal production in Ethiopia and Sudan [*Hope*, 2009].

10.3.1.2. Water Security

Serious concerns for the future of water security lie in increasing water demand of the Eastern Nile basin countries. Low water storage capacity and few water control systems lead to an inefficient use of the water resource. Moreover, a lack of treatment facilities results in constant water pollution, which is further increased by urbanization. As rainfall is highly influenced by sea-surface temperatures [*Gissila et al.*, 2004; *Bewke and Conway*, 2007; *Block and Rajagopalan*, 2007; *Elagib*, 2010, 2011], the heavily rain-dependent agriculture suffers from climatic phenomena like the El Nino warming [*Elagib*, 2014, 2015; *Khan*, 2015] and increased spatial disparities in water availability that create conflicts on local and transboundary levels [*Bordignon*, 2013; *Power*, 2014].

10.3.1.3. Energy Security

Energy demands in the region are growing fast. The energy portfolio in the region currently includes fossil fuels, biofuels, and hydropower with a large unexploited potential for the latter. In Egypt, energy security depends on available fossil fuels, which are relatively high in comparison to Ethiopia and Sudan. The latter two countries rely largely on fuelwood and increasing use of hydropower to satisfy their energy demands. Yet, environmental problems such as deforestation, soil degradation, desertification, siltation, and crop failures are common [*Tekle*, 1999; *Taddese*, 2001; *El Baroudy*, 2011; *Dawelbait and Morari*, 2012; *Hagenlocher et al.*, 2012; *Meshesha et al.*, 2012; *Biro et al.*, 2013], threatening both food and energy security in

Table 10.1 Sources of risk, cooperation opportunities, and constraints of the Grand Ethiopian Renaissance Dam (GERD) for the downstream countries, Sudan and Egypt

References	Issue
Risks	
McCartney et al. [2009] *McCartney and Girma* [2012] *Zhang et al.* [2015] *Alrajoula et al.* [2016]	• Depending on the GERD reservoir-filling operation (stage and rate), climate variability, and climate change scenarios, reduction of downstream flows at the Gezira Scheme in Sudan and Lake Naser behind the High Aswan Dam for Egypt • Loss of socioeconomic benefits brought about by Nile water to locals in Sudan • Reduced soil fertility in desert zone of northern Sudan as a result of reduced sediment transport
Cooperation opportunities	
Tesfa [2013] *Chen and Swain* [2014] *Zhang et al.* [2015] *Wheeler et al.* [2016]	• Regulation of minimum flow level in the dry season • Flood control through flow regulation in the wet season • Water conservation in the Ethiopian highlands • Sediment management • An agreed operational strategy of the GERD, drought management policy for the High Aswan Dam, and basin-wide cooperation minimize severe risks and bring advantages • Equitable utilization of transboundary water, cooperation, or determination will constitute a milestone for many forthcoming water development projects and peace across the basin
Constraints and pending issues	
Tesfa [2013] *Whittington et al.* [2014] *Zhang et al.* [2015] *Wheeler et al.* [2016]	• Noncooperative attitude of Egypt • Ethiopian rush, non-transparent manner, and ignorance of the guidelines prescribed by the World Commission on Dams for achieving sustainability • Need for Egypt not block the power trade agreements to make the finance of the GERD viable • No formal agreement between Ethiopia and Sudan for sale of hydropower • No specific arrangements between Ethiopia and the downstream countries as regards the filling rate rules of the dam reservoir • No formal agreement on the operation rules during the drought periods • Because of the foreseen economic feasibility, Sudan's leverage in the Ethiopian-Egyptian reconciliation to encourage benefit sharing and make these agreements a reality • Further analysis on the environmental impacts of the dam • Need for discussions on how to optimize the ongoing construction of the dam

the two countries. Hydropower development and trade are a controversial energy topic in the region, especially in light of the construction of the Grand Renaissance Dam in Ethiopia. Many studies have been undertaken to present a regional framework for possible benefits and risks. Model simulations have been carried out to infer possible outcomes for negotiations between the three countries. Table 10.1 overviews some of these results.

10.3.2. Cross-Cutting Climate-Related Challenges

Recent climate-related challenges are exacerbating the impacts of country-specific challenges in the Eastern Nile basin. The Eastern Nile countries have generally low levels of infrastructure development that could increase the resilience to expected climatic risks. Despite uncertainties and regional variabilities [*Bewke and Conway*, 2007], climate risks in the basin can be summarized as the following:

1. Increase in temperature [*Elagib*, 2010, 2011; *Jury and Funk*, 2013] could result in higher evaporation and evapotranspiration rates, and, consequently, arid conditions [*Elagib*, 2009].
2. Hotter and longer dry periods will increase drought events, especially in drought-prone regions [*Elagib*, 2010].
3. Increase in frequency and intensity of severe rainstorms could increase flood risk [*Youssef et al.*, 2011; *Cools et al.*, 2012].
4. Sea-level rise could threaten the agriculturally important Nile Delta [*Smith et al.*, 2014].

Projected climate change [*Kim et al.*, 2008; *Chen et al.*, 2012] in the region is expected to have severe negative impacts of such trends that will be directly felt across the water, energy, and food sectors of the region. Rising crop water requirements will lead to an increase in demand for irrigation water. Combined with the losses from reservoirs due to higher evapotranspiration, more water-sharing conflicts are expected. The crucial hydropower potential of the Nile is also vulnerable to changes in river flows, driven by climate variability and extremes. Climate extremes, such as droughts and floods, can pose significant health and economic threats, in conjunction with strong implications for poverty, food security, and overall economic growth. Degradation of livelihoods may accelerate and intensify rural-urban migration [*Cheung et al.*, 2008]. Furthermore, wetlands, which provide important ecosystem services, such as water filtration and fertile ground for agricultural productivity, are highly vulnerable to climate change and can negatively affect the continued quality of water in the basin. Such vital ecosystems are increasingly threatened by pressures due to the expected demand for water, energy, and food being exceeded. Finally, increased water temperature and changes in water level pose a threat to fisheries, resulting in widespread negative impacts on economies and food security.

10.4. BENEFIT-SHARING POTENTIAL FOR TRANSBOUNDARY COOPERATION

10.4.1. Framing Nexus Cooperation Issues

In the face of common security challenges related to natural resources, cooperation among riparian countries through intensifying regional cooperation can become a viable option to face future risks. We frame transboundary cooperation by highlighting three common cooperative arenas in international relations (Figure 10.6). First, international trade can alleviate Nile-related conflicts by increasing mutual cooperation benefits. Unequal endowments of natural resources among the three countries pave the way for exploiting the comparative advantage of each country through trade. Second, financial cooperation emphasizes investment opportunities that make use of each country's economic and resource potential and contribute to regional growth. Such opportunities are expected to grow with emerging financial markets and improving macroeconomic investment conditions. Third, exchange of know-how and expertise through technical cooperation builds valuable trust. This kind of cooperation in terms of consultancy and services constitutes a win-win business model with a promising future in the region.

10.4.2. Resource Trade Potential

The Eastern Nile countries will be facing a common challenge in regard to increasing demands due to growing socioeconomic pressures. Projected population growth for the three countries indicates that by 2050, Ethiopia will have 188 million, Egypt 151 million, and Sudan 80 million inhabitants [*United Nations*, *World Population*, 2015]. At the same time, estimations of water demand for 2025 show that, in a business-as-usual scenario, water consumption will rise by 73% in Egypt, by 205% in Ethiopia, and by 135% in Sudan (compared to 1990), and where such demands are expected in a more optimistic scenario considering efficiency, gains are 51% for Egypt, 106% for Ethiopia, and 124% for Sudan [*Seckler et al.*, 1998].

In order to satisfy future demands, resource development, intensification, and promotion of local markets will be essential. While local markets are essential for achieving supply security, regional trade through the exchange of energy, food, and related production technologies is necessary for regional cooperation. Energy trade between the states would meet the demand of increasing energy consumption in the agriculture and water sectors and could assure energy security in the Eastern Nile basin. Furthermore, considering the differences in resource potentials of the three countries, energy

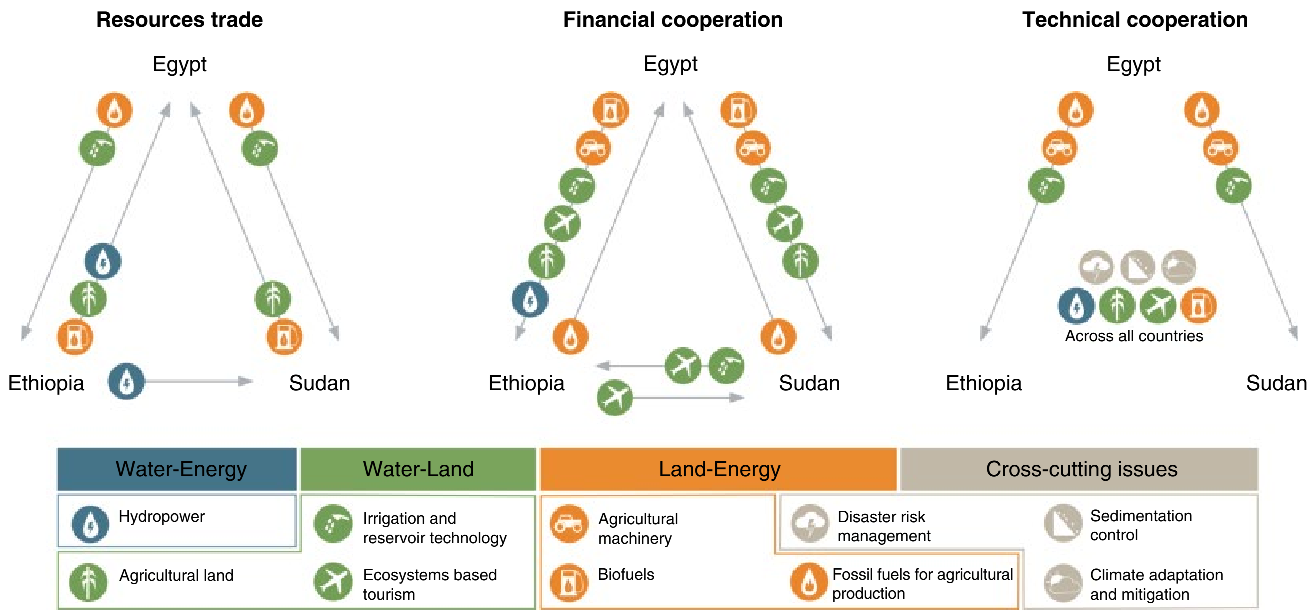

Figure 10.6 Cooperation framework indicating the directions of resource trade as well as financial and technical cooperation on key issues among the Eastern Nile basin countries.

resources trade is highly viable. Ethiopia has the potential to become the region's prime energy exporter owing to the big hydropower potential. Ethiopia's unexploited hydropower potential on the Nile river accounts to 15,409 MW, while the existing Nile capacity is 1946 MW, with around 6000 MW expected to be generated from the GERD [*NBI*, 2012]. This potential is much higher than that of Sudan with 4873 MW [*NBI*, 2012], of which around half is currently used by the Er Roseires and Merowe dams. In contrast, Egypt's hydropower potential of around 3600 MW is almost entirely used, especially by the Aswan dams. Apart from the Nile, Ethiopia disposes of other hydropower potential, which raises the total estimated potential to around 160,000 MW [*Swain*, 2011]. Egypt has moderate reserves of gas and oil and can export fossil fuel to Ethiopia with very low proven reserves, and even to Sudan, which now lacks such an energy source after the separation of South Sudan. On the other hand, cultivated land potential can also be used for producing biofuels as an interesting trade option alongside trade of food products. In this regard, Sudan seems to have a clear competitive advantage. The cultivable area accounts for 105 million ha, of which 2.7% is the irrigation potential. In contrast, the cultivable area in Ethiopia accounts for 13.2 million ha, of which 20.5% is suitable for irrigation. In Egypt, this area is 4.4 million ha, which is entirely dependent on irrigation [*FAO*, 2005]. Further, food-related trade in the Eastern Nile basin goes beyond imports and exports of food products and biofuel. Trading production technology for improving WUE in irrigation agriculture or construction of reservoirs is a further cooperative option. Here, Egypt has the largest portion of land under irrigation in the Nile country and a long-standing history of optimization of irrigation infrastructure and economic efficiency policies [*Wichelns*, 1999]. Besides, food-related trade is essentially a pathway to ease pressures on internal water resources considering the embedded virtual water contents. In this sense, livestock imports to Egypt from Ethiopia and Sudan, the two largest livestock producers in the overall Nile basin [*NBI*, 2012], are expected to continue to grow.

10.4.3. Technical and Financial Cooperation

Each country in the region, depending on its own resources, can achieve benefits from regional cooperation. The directions of investments and exchange of know-how will largely depend on socioeconomic factors such as economic power, investment incentives, and existence of expertise. Technical knowledge depends on the level of specialization and the country's historic industry priorities as well as educational comparative advantages. Investment opportunities exist in arable land in Ethiopia and Sudan, often called "land-grabbing." Egypt is increasingly involved in such investments, mainly in Sudan, supported by its well-developed private equity market [*El Hadary and Obeng-Odoom*, 2012]. Land investments in Sudan account for more than 4 million ha in comparison with around 1 million ha in Ethiopia, and such investments are largely used for food production [*Rulli et al.*, 2012]. Land investments in large irrigation schemes (e.g., Gezira Irrigation Scheme in Sudan) began in the early twentieth century. In contrast, Ethiopia has advocated land investments in recent years as a part of its overall development strategy [*Lavers*, 2012]. Land investment potential in the two countries is still high. Considering the large available arable land, meeting the urgent and increasing internal food demands is possible by the expansion of agricultural land. Furthermore, importing environment-friendly technologies can also increase agricultural efficiencies. Land and crop water productivities that vary within the Nile basin can be improved, with Egypt as the leading country in this regard using a higher degree of technology deployment like sprinkler or drip irrigation and higher economic assets [*Karimi et al.*, 2012]. Here, regional cooperation can help level differences in productivity through investments in agricultural technology or new reservoirs to expand or improve existing irrigation capacity.

Furthermore, there are also promising investment opportunities in the energy sector in Ethiopia, especially in the development of micro-hydropower for electricity and/or food production. There are more than 5000 suitable sites for mini- and micro-hydropower in Ethiopia [*Erbato and Hartkopf*, 2012] which can be utilized for producing cleaner and cheaper forms of energy along the Nile [*Bekele and Tadesse*, 2012].

Finally, sustainable tourism exhibits a big potential for regional cooperation and investment in the region, and also for economic development at large [*Fortanier and van Wijk*, 2010]. Investments in ecosystem-based tourism exist in many parts of the Nile in the three countries and extend to non-Nile regions. With around 10 million tourists yearly, Egypt is the leading touristic country in the region. This is compared to around half the number for Sudan at 600,000 arrivals and 700,000 for Ethiopia on average in 2011–2014 [*World Bank*, 2015]. Investments and transfer of know-how from Egypt or among the three countries, and use of the basin biodiversity and ecosystems, constitute mutual benefits for all three countries.

Another promising field for cooperation concerns the exchange of technical knowledge on key future and common challenges such as those related to climate. It is argued that the limited capacity of the African region in terms of both climate scientists and observations inhibit progress toward sustainable development [*Peterson and Baddour*, 2011]. Similarly, it can be acknowledged that the Eastern Nile basin is no exception. There are increasing demands for information to understand, monitor, and mitigate climate-related extremes, such as drought and floods. A sound hydro-climatic data infrastructure that ensures reliable observation networks in terms of coverage and resolution is lacking. Focus on preservation and management of old records is poor. The mismatch between political and physical boundaries is huge. In such a situation, the subdivision of eco-zones into numerous subareas cannot ensure the appropriate sequential process of data collection network design [*Burn*, 1997]. Full access to data by the research community and exchange of information among the riparian countries are extremely limited. In addition, the policy of enlightening the end users on necessary knowledge through, for example, sharing of timely and credible information and/or addressing the climate consequences is underdeveloped. Hence, improvement of the knowledge base on such challenges is essential [*Easton et al.*, 2010]. In this regard, strong transboundary partnerships and collaboration among the ministries, hydro-meteorological services, and research institutions of the basin countries and organizations should be solicited [*Selvaraju et al.*, 2011]. Organizing frequent capacity-building workshops for staff is highly emphasized. The aim should be to improve their technical capacities to access and use the available observations in addition to the use of analytical and modeling methodologies [*Vicente-Serrano et al.*, 2012]. Training on presenting, reporting, and disseminating the results is equally important. These activities help to improve the early warning and forecasting systems. All of these, in turn, present opportunities for managing current climate risks, addressing the key issues that concern planners and decision-makers, and facilitating sustainable agriculture and food security [*Selvaraju et al.*, 2011].

Another cooperation opportunity is offered through scientific cooperation on common problems for the Eastern Nile (e.g., the issue of sedimentation). In fact, significant land use/cover changes have taken place in the Upper Blue Nile during the past few decades. The widespread conversion of natural cover into agricultural crop and barren lands has modified the hydrological processes of the basin, resulting in accelerated soil erosion, increased stream flow, and sediment load [*Gebremicael et al.*, 2013; *Ali et al.*, 2014]. Sedimentation has severely affected the reservoir storage capacity and irrigation canals downstream in Sudan. There are obvious trade-offs associated with dam construction upstream. Though the GERD, currently being constructed on the Blue Nile, is expected to reduce sediment impacts downstream, there are also fears that this will consequently lead to decreased fertile soils of the agricultural lands along the Main Nile in the hyper-arid zone of northern Sudan. Hence, the formulation of science-driven effective, cooperative solutions aimed at controlling land degradation, protecting water resources, and fertile lands should attract attention.

10.5. CONCLUSIONS

Cooperation on water, energy, and land use issues is expected to play a crucial role in meeting future resource demands and resource security challenges in the Eastern Nile basin. Opportunities for generating mutual benefits is provided by the availability of both natural and human resources and the discrepancy in resource distributions, all of which can stimulate specialization, trade, investment, and technical cooperation. The relatively high availability of water resources in the upstream countries of Ethiopia and Sudan brings with it a high agricultural potential, which can be mobilized by investments from downstream (Egypt) and regional trade. Such cooperation would effectively address the common regional challenge of food insecurity due to low technology use, harvest failures, high production and transport cost, absence of markets, and speculations of food prices. With Egypt having a long history of irrigation development and better performance benchmarks, it is well positioned for technology export and exchange of know-how on agricultural management. Further, higher economic power in Egypt and more developed financial markets in the short term can facilitate investments in and technological exports to upstream countries. In the long term, mutual investments and technical cooperation are possible among all the three countries in related fields, such as crop management, reservoir technology, and sustainable tourism. Further, the energy sector holds many future cooperation possibilities. Hydropower is the main energy resource for upstream countries while Egypt disposes higher reserves of fossil fuels. Energy trade, investments in micro-hydropower and fossil fuel-based energy for irrigation, and exchange of experts are some examples of cooperation options. In fact, regional cooperation is under way in this regard (e.g., hydropower trading among upstream countries).

Finally, any future cooperation must involve cross-cutting issues like climate variability, climate-related risks, and sedimentation control. The development of a transboundary system of data and information network, access, and sharing principles is important to improve the basin's early warning system and, subsequently, water, energy, and food security. In this regard, exchange of technical knowledge on techniques for observing, analyzing, and using the data and, subsequently, transferring the information to decision-makers and end users are also important. Since land degradation is shown to be a transboundary issue in terms of causes and impacts, cooperative solutions aiming at regulating land use changes in the upstream countries to protect the land and water basin resources should be devised.

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11

Energy-Centric Operationalizing of the Nexus in Rural Areas: Cases from South Asia

Parimita Mohanty[1] and Satwik Patnaik[2]

ABSTRACT

This chapter has brought a few case studies from South Asia and showcased the linkages that exist between energy, water, and food in the rural areas. The case studies show how the provisioning of energy leads to assured water availability and better agricultural productivity and food security. Further the chapter discusses where the linkages lie and how the establishment of such linkages helps in transforming the landscape of villages and leads to a sustainable future.

11.1. INTRODUCTION

Water, energy, and food are essential resources for sustaining a society and meeting its needs in a sustainable manner is an extremely complex challenge. The interlinkages among the three resources present a multidimensional challenge that links resources, national policies, politics, and quality of life for all of us. The nexus between these three can help determine strategies to allocate these resources and utilize them effectively and collectively, rather than individually and in an isolated manner. The World Water Development Report has well appraised the interlinkages between water, energy, and food, and established the fact that the three sectors no longer should be addressed in isolation. Addressing these complex issues requires commitments and collaborative efforts among federal and state agencies, private enterprise, and nongovernmental organizations (NGOs). For example, water is an indispensable component for agriculture as a large portion of freshwater withdrawals in countries like India and China is used in irrigation to feed the teeming billions, thus demonstrating the close linkage between food security and water availability. However, there is a need to significantly reduce the amount of water required for the production of agricultural commodities while maintaining its availability for ecosystem services. Similarly, the use of energy services should be maintained to extract the amount of groundwater that is just appropriate for irrigation purposes. Subsequently, the produced food needs to be preserved and transported to retail chains in such a way that optimum consumption of energy is ensured. Hydroelectricity in the recent years has emerged as one of the most popular methods of electricity production; hence, the availability of water consequently determines the amount of energy produced. Thus, we arrive at an integrated model of water, energy, and food (WEF), where all these components are closely intertwined with each other [*Ahuja*, 2008, 2009].

Fabiola Riccardini in June 2015 expressed WEF as "well-being indicators for a better quality of life" and highlighted the complex interlinkages of these three sectors in the run-up to the Paris Climate Change Summit, as well as on how the exponential growth in demography would lead to competition among these sectors that will create new burdens for mankind. Hence, this complex,

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integrative approach shall form the basis of the WEF nexus. While there are numerous examples and efforts being taken for establishing the energy-water-food linkages in the urban sector, there is also an equal need to demonstrate this nexus in the rural sector so that more integrated strategies and future policies considering the nexus can be formulated and executed [*Intergovernmental Panel on Climate Change*, 2007; *Molden*, 2007; *UN Water*, 2014; *Yager et al.*, 2014]. Furthermore, many nexus cases are water-centric but energy-centric nexus operationalization could also be equally effective in rural areas. This chapter aims to demonstrate cases of energy-centric WEF nexus in a rural setting with cases from South Asia.

11.2. SOLAR ENERGY FOR WATER AND LIVELIHOOD: A CASE OF BAUNSADIHA VILLAGE, ODISHA, INDIA

Baunsadiha village of Thakurmunda block in Mayurbhanj district in the state of Odisha, India (Figures 11.1 and 11.2), is considered for a case study in which a solar-powered system was installed (capacity: 8 kWp) for providing access to water and promoting community-based livelihoods. It was part of an initiative undertaken by The Energy Resource Institute (TERI) in 2012 with the support of SAMBANDH, a local NGO.

Baunsadiha is a village in the Thakurmunda block of Mayurbhanj district. It is located at a distance of 6 km from the block headquarters and 206 km from Mayurbhanj district. It is about 261 km from the state capital Bhubaneswar. The village, which is well surrounded by forests and different types of horticultural plants in the buffer zone of Simlipal Biosphere Reserve, consists of 206 households, mainly comprising the schedule tribe population. The village is situated within Simlipal forest area and electricity is provided to households only for lighting purposes. Before the installation of the solar-powered system, there was no provision to access electricity for running motive power for irrigation purposes as well as for food processing. Hence the villagers depended mainly on the monsoon for agriculture. Keeping the seasonal availability of water in mind, several efforts had been made to promote organic farming and growing advanced varieties of crop saplings, which may need less water. For this purpose, SAMBANDH established a nursery to grow various climatically appropriate and high-yield crop saplings and planned to sell these to farmers at a reasonable price. However, the nursery remained dysfunctional due to the unavailability of water in certain seasons which was required to grow the saplings. Further, besides challenges in accessing water for irrigation, there was also an acute problem of getting safe drinking water in the village and the villagers had to depend upon nearby wells or ponds to fetch water for drinking purposes. Such unsafe, dirty drinking water led to a number of waterborne diseases in the region.

The village was also keen to participate in a few government programs for providing nutritious food to schoolchildren. For this purpose, a Self-Help Group (SHG) called Maa Malati Gramashree supplied sattu to 38 Anganwadi Centres (AWCs) under the state Child Development Programme. Sattu or chhatua is considered to be very nutritious food consisting of ground powders of pulses and cereals like horse gram (chana dal), green gram, jowar, wheat, oat, barley, and so on. Sattu is consumed along with fruit slices, sugar, or milk. The main purpose of supplying sattu was to provide adequate nutrients to the children and to avoid malnutrition among. Initially, in a month, the SHG supplied 8.4 tons of sattu to the AWCs. It had generated interest among the SHG members and all the members happily contributed to the group-based work. Initially, SHG managed to purchase all the ingredients required for the preparation of sattu, carrying out such as frying, grinding, and mixing the ingredients in the nearby market (as there was no provision for electricity for grinding). The raw materials were taken to a mill at Thakurmunda (which is around 20 km from the village) for frying and grinding. Frying was done at the mill using coal, while grinding was done using electric power. The mill charged US$0.05/kg of raw material. The cost of fuel was US$0.01/kg. In other words, the group incurred US$84 per month as expenditure for fuel. Similarly; US$85 was spent for transportation. In order to avoid these hassles, the frying and grinding were sometimes done manually at the village, of course with a compromise in the quality. Disruption of power causes delay and since sattu is to be supplied within a time frame, it often causes inconvenience. The raw materials and the sattu have to be transported to the mill and back to the village, where packaging is done by the members into packets of ½ kg.

The packaging machine operates on electricity; however, disruption of power supply, which occurs often, makes the task difficult as sealing has to be done manually. Moreover, packaging is mostly done in the evening when the women are free from their household chores. Needless to mention, disruption of power supply can make the work tedious.

This scenario demonstrates how inaccessibility to energy, one component of the WEF, can hamper access to the other components of the WEF (i.e., water and food) and forces a community to compromise on the standard of living. In order to address these challenges, a participatory assessment of energy intervention for providing access to water and supporting livelihoods was carried out in February–March 2012; Accordingly, a "solar power system" was installed in September 2012 and a solar-powered pulverizer (grinder) and a mixer (2 HP each) for

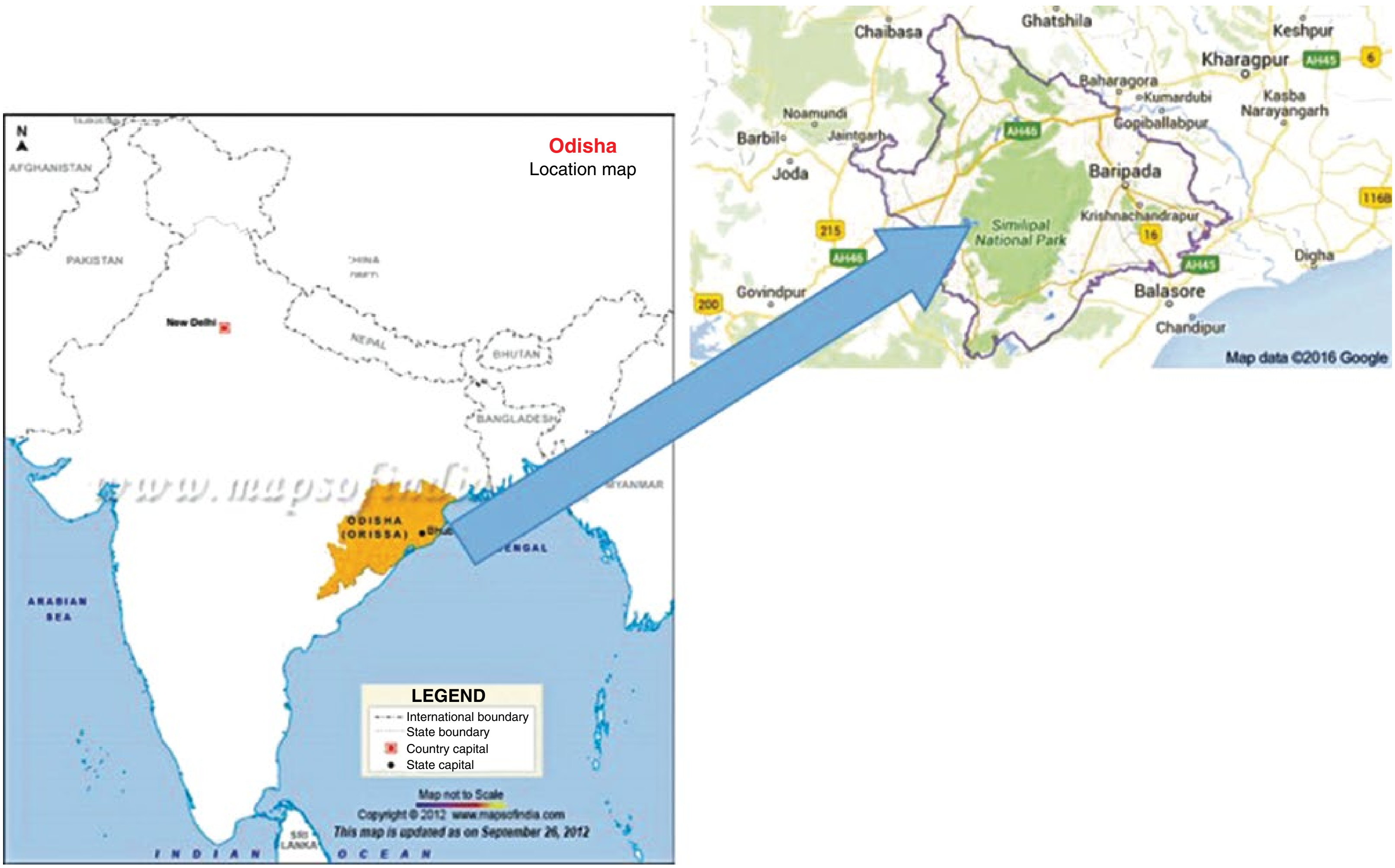

Figure 11.1 Location of the Mayurbhanj district in Odisha, India.

Figure 11.2 Solar-powered system installed in Baunsadiha village. (*See insert for color representation of the figure*.)

Figure 11.3 Solar-powered grinder used for sattu making. (*See insert for color representation of the figure*.)

processing food were provided (Figure 11.3). Besides the food-processing appliances, a solar-powered submersible water pump (capacity: 1.5 HP), a water purifier, and a freezer were installed (Figure 11.4). Two people from SAMBANDH were trained to operate and maintain the systems and assured their smooth operation. An amount of US$0.12 per unit has been fixed as the tariff for the use of solar power and US$3/day for the use of the submersible water pump.

Impacts of the intervention were assessed by interacting with members of the group through a structured interview in February 2014. Provisioning of energy has brought the following results.

11.2.1. Economic Gain of the SHGs through Food Processing in the Vicinity of the Village

Earlier, when there was no facility for grinding, the group had to depend on a mill at Thakurmunda. All the ingredients (8.4 tons) had to be cleaned and transported in bulk. Transport vehicles were hired for carrying the ingredients to the mill at Thakurmunda for frying and

Figure 11.4 Solar-powered pump. (*See insert for color representation of the figure.*)

grinding. The ingredients were mixed as per the recommended proportion after they were carried back from the mill. With the facility of grinding within easy access, the female members of the group no longer face the inconvenience of preparing the ingredients (fanning and cleaning) in bulk and transporting them to the mill. The ingredients are prepared, fried, and carried to the center in small quantities. As there is no compulsion for external dependence, the drudgery the women faced has reduced substantially. Not only was there reduction of drudgery but also financial benefit as the group could save the money earlier paid to the mill. Focused group discussions (FGDs) revealed that nearly US$480/month (US$0.05/kg × 8400 kg) had been saved. Moreover, around US$30 could also be saved on account of expenses toward cost of transportation of the ingredients to the mill. In total, the group could save US$510 per month.

11.2.2. Raising Nursery for High-Yield Crop Saplings

The submersible pump had been made available at the village center in April–May 2013. The water drawn with the help of the submersible pump was being used for nursery raising, providing drinking water for the village community, and kitchen gardening. There had been no technical problems.

Availability of water helped in growing high-value cash crop saplings such as mango, cashew, lemon, brinjal, tomato, and so on. The nursery has also helped in generating livelihood for a few women in the village as four elderly female members of Jagannath SHG worked in the nursery for 15–20 days a month on a daily-wage basis. Each woman received US$2/day as wage.

11.2.3. Access to Safe Drinking Water

The water purifier (100L/h) and freezer had been made available at the village center in September–October 2012. While the water purifier had been providing safe drinking water to the villagers, the freezer was being used to store medicines and helped in reducing the risk toward water-borne and other diseases.

Instead of adopting the conventional way of designing and planning a solar-powered system either only for household electrification or for pumping application, this case study has demonstrated how integrated planning and use of solar energy for livelihood generation activities and for access to water has brought better food security, economic gain, and overall development in the region.

11.3. SOLAR WATER PUMP FOR IRRIGATION: A CASE OF RAJASTHAN STATE, INDIA

Rajasthan (Figure 11.5) is one of the largest states in India that covers 10.5% of the country's geographical area but shares only 1.15% of its water resources. The state is

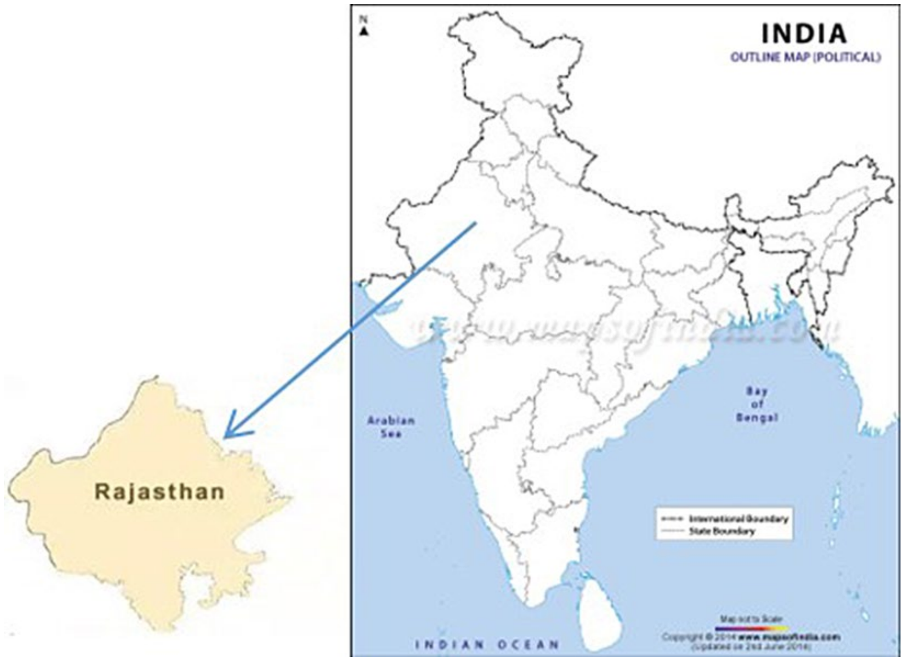

Figure 11.5 Location of the state of Rajasthan on the map of India. Source: Maps of India.

predominantly agrarian as the livelihood of 70% of its population depends on agriculture-based activities. Most of the state (60–75%) is arid or semiarid. In the last 50 years, a threefold increase in the human population and a doubling of the livestock populations have put tremendous pressure on the fragile water and land resources of Rajasthan.

Depleting groundwater levels has been the biggest threat to rural livelihoods and food security in India, particularly in the northern, western, and central parts. The dependence of irrigation on groundwater has increased with the so-called Green Revolution, which depended on intensive use of inputs such as water and fertilizers to boost farm production. Rather than extending surface water irrigation to unirrigated regions, policy-makers began providing incentives for groundwater extraction. For example, in a few states, government policies allow massive subsidy (almost free) on electricity supply for irrigation purposes. Such low electricity tariffs have led to excessive water usage, causing a sharp fall in groundwater tables in many parts of India. Falling groundwater tables prompted the use of expensive deep-water equipment, which added to the debt burden of farmers, and worsened the crisis.

The historical inequities in electricity supply to different regions have also skewed cropping patterns. Being relatively water-abundant, the east is more suited to growth of water-intensive crops such as sugarcane and paddy. However, scant power has ensured that such crops, which require irrigation, have hardly found a place in their natural habitat. On the other hand, availability of electricity at a very cheap price in the initial years in the south and west of India with naturally low water tables encouraged sugarcane and paddy cultivation, weakening these regions of the already low groundwater table. However, in recent years, the fractured financial condition of state electricity utilities has forced the reduction of electricity supply to farmers, even though many farmers are now willing to pay for their electricity. Balancing the needs of irrigation and groundwater conservation remains a tough challenge for policy-makers in India. In such a situation, solar power for irrigation may bridge the gap and solve both the water and electricity crises in rural India.

Table 11.1 gives an overview of the energy and agriculture scenarios in Rajasthan.

The scenario has changed after the intervention of the solar-powered water-pumping system. A total of 12,000 ha of additional land has been brought under irrigation. Earlier, only one monsoon-fed crop was possible; however, with the solar-powered water-pumping system, at least two crops are grown every year and 24,000 ha has been irrigated. Many farmers having three crops migrated to more remunerative horticulture/cash crops like vegetables and fruits. Transformation has started in the lives of the farmers and their families as incomes have gone up. Table 11.2 shows the benefits accrued due to the solar-powered water-pumping scheme.

As per 2012 statistics, out of 15.7 million ha of total agricultural land in Rajasthan, only 35–38% was irrigated. Electricity losses were around 45% and as the farmers lived

Table 11.1 Energy and agriculture scenarios in Rajasthan before intervention of the solar-powered water-pumping program

1	Land	10.5% of the country
2	Water sources	1% of the country
3	Total agriculture land	15.7 million ha, only 35–38% irrigated
4	Net irrigated area	6.4 MH (micro-irrigated 1.2 MH)
5	Rainfall	Average 575 mm; but very erratic with uneven distribution and recurring droughts
6	Livelihood	60% population depends on agriculture/horticulture: low productivity
7	Irrigation	One-third of cultivated area; rest: unreliable, inadequate, or unavailable
8	Irrigation source	70% of the irrigation is by wells/tubewells energy through grid/diesel, 27% by canals irrigation
9	Irrigation method	90% groundwater used for flood/furrow, a little for sprinkler and drip
11	Groundwater	Groundwater table going down, quality of water deteriorating; out of 249 blocks, 200 in highly critical zone
12	Availability of electric grid	Grid extension infeasible in remote areas

Table 11.2 Impact of solar-powered water-pumping scheme

Area irrigated per pump per crop	Ha	3
Total area irrigated, two crops a year (4000 pumps × 2 × 3)	Ha	24,000
Water required for surface irrigation per hectare	m^3	5,000
Water saved per hectare due to drip irrigation (40% of 500)	m^3	2,000
Total water saved (24,000 × 2,000)	million m^3	48
Additional crop production value for each farmer due to irrigation through solar-powered pumps	US$	30,000
Total additional crop production value due to irrigation through solar-powered pumps	US$ million	33

Source: http://www.fao.org/nr/water/docs/SPIS/11_Goyal.pdf.

in remote areas, electricity supply was also a big challenge. On the other hand, Rajasthan receives the best solar insolation on earth with 6–7 kWh/m^2/day with 325 sunny days a year. The state has the most attractive destination to harness solar energy, especially for irrigation. Harnessing solar energy for the agricultural sector is a big boon to the state. With this objective and seeing the complementary nature of the energy and water resources, the state of Rajasthan came up with a statewide solar-powered water-pumping scheme. The vision behind this scheme was that (i) it would act as an alternative for conventional energy in the agricultural sector; (ii) long queues for new electric connections could be avoided; (iii) large investment needed by farmers could be avoided; (iv) it would be a boon for saving precious energy and water resources; (v) no need for electric transmission arrangements leading to no transmission losses; and (vi) large-scale adoption of technology would lead to cost cutting of the solar-powered water-pumping system, making it affordable for the farmers with minimum or no support from the government in the future.

In order to promote this scheme, the Rajasthan government in 2011–2012 introduced 3 HP DC submersible pumps. These solar-powered water pumps varied in size from 2200 to 3000 Wp (20–75 m head capacity). The total cost of the system was US$6800–7000, out of which 86% was subsidized by the government (including both central and state governments). The scheme was expanded both in number as well as coverage over the years. The initial target of the government was to install 50 pumps, which was increased to 500 pumps by the end of 2011–2012, and to 10,000 pumps by 2013–2014. Similarly, the scheme was expanded from 14 districts in the state during the period of 2011–2012 to 33 districts during 2012–2013.

The government of Rajasthan permitted clubbing subsidies under various programs to 86% of the capital cost. The horticulture department had fixed targets via the Chief Minister Budget announcements. The Commissionerate of Horticulture, Rajasthan, conceptualized this scheme with active assistance of the Commissionerate officials, in particular the Agriculture Research Officer. The regulatory framework for effective implementation of the scheme was developed and active assistance was provided to the districts for smooth implementation. The Rajasthan Horticulture Development Society shortlists and empanels manufacturers-cum-suppliers of solar- powered water pump sets.

Although high subsidy was given in the initial phase of the scheme (with a gradual reduction of subsidy in subsequent phases), the scheme was effectively implemented on a large scale and triggered cost reduction of the overall system in subsequent phases due to mass-scale dissemination. The scheme helped in substituting for up to 5 HP electric connections and/or saved excessive usage of diesel (a diesel pump set runs at least 8 h a day and requires 2.5 L of diesel for every hour). It had also stimulated water access in unelectrified remote areas. Judicious use of water through micro-irrigation and solar-powered water pumps saved unnecessary withdrawals and wastage of groundwater in the state, which has witnessed a significant depletion in groundwater levels.

Besides solar energy for irrigation, several assessments indicate that despite the depletion of water resources, the state still has significant potential for harvesting and conserving water if an integrated water resources management approach is adopted, and proper policies and investment actions are implemented using recent technologies. The state has been taking various initiatives in this regard such as in situ water conservation on vast arable lands, recharging of the soil profile, runoff harvesting and its efficient and economic utilization through drip, sprinkler, or conservation irrigation.

Issues related to water management in Rajasthan are highly complex and need to be resolved through the involvement of government departments, research institutions, NGOs, and other stakeholders. The present case study is an effort to demonstrate how policy intervention, integrated with government fund utilization, can address water resource crises and strategies to improve water availability and management efficiency for various uses.

11.4. MICRO HYDRO SYSTEM FOR RURAL ELECTRIFICATION AND LIVELIHOOD: A CASE OF THINGAN, MAKWANPUR, NEPAL

Nepal is one of the few countries in South Asia that has the highest potential to exploit its water resources for power generation through mini and micro hydropower development. However, it lags behind in exploiting the potential prudently, and depends hugely on traditional fuels (e.g., fuelwood, agricultural residue, and animal dung) and fossil fuels. In 2008/2009, Nepal spent 61.5% of its export earnings just on petroleum products. The situation may worsen if the present oil price increases in order to meet the ever-increasing demand for petroleum products. For example, if the present oil price (US$120 per barrel) increases to US$150 per barrel, the export earnings should increase twofold to meet the demand of petroleum products.

In this evolving scenario, Nepal may not be able to afford to continue spending its national income on imported fossil fuels that are not only expensive but also equally climate unfriendly, and vulnerable to various risks such as political, price fluctuations, and natural disasters, among others. On the other hand, due to its rugged topography and steep slopes, it may not be feasible to connect many rural areas with national grids. In such conditions, a decentralized system, preferably a hybrid one, may help ensure electricity supply, reduce dependency on traditional fuels, and contribute to the overall development of the area.

This case study shows how the micro hydro resource available in a village "Thingan" in Makwanpur district (Figure 11.6) has triggered the implementation of a hybrid system (micro hydro, solar, and wind) to supplement the agriculture and other livelihood generation activities.

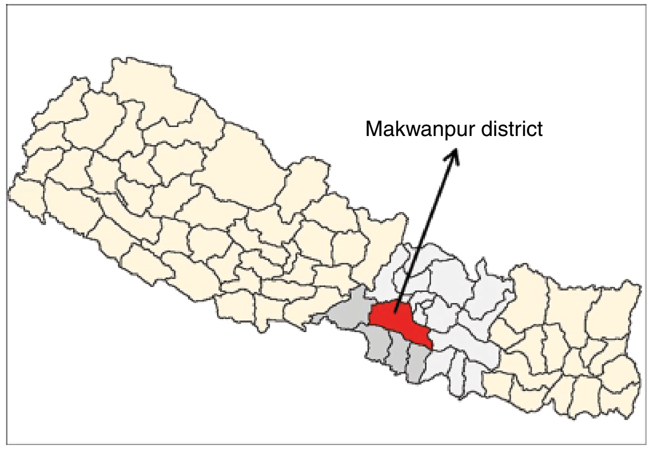

Figure 11.6 District Makwanpur on the map of Nepal.

Thingan village is located in Makwanpur district, which is a mere 42 km south of Kathmandu. The village has around 300 households spread around nine wards. Thingan Bazar is the main market having a number of shops, poultry firms, and hauling and milling units. The village also has a health post, police post, church, and school.

The conventional grid extension was found techno-economically infeasible for this region due to the geographical difficulty and inaccessibility. This left the village with very limited options for meeting their energy demand and the villagers were bound to depend on traditional fuel. Before the implementation of the power plant, the villagers used kerosene for lighting purposes and diesel for running the existing mill for a few hours a day. There was no street light in the village, which increased the risk of snake bite/poisonous insect bite at night. Each household has around 2–5 acres of land, which is used for paddy or vegetable cultivation. Since the availability of water was not ensured and mainly relied on the monsoon, the villagers grew a single crop. They often hired diesel pump sets to provide water to their agricultural lands. In many cases, the farmers spent around Rs 50,000–60,000 per annum on diesel pump sets for watering the lands.

In 2010–2011, the Nepal Solar Volunteer Corps (NSVC) carried out a detailed assessment to explore the possibility of generating power from a stream running in the vicinity of the village. Subsequently, in 2012, a 20 kWe micro hydro system was installed (Figure 11.7). A power distribution grid was designed and installed to transfer locally generated electricity to the community for various applications. Subsequently, a 5 kWp solar PV system and 3 kWe wind electric generator were also installed to meet the small lighting load of certain households.

Currently, only four out of nine wards of the Village Development Committee (VDC) have been electrified from this tri-hybrid power-generating station. Lighting is

Figure 11.7 20 kWe micro hydro power plant in Thingnan village. (*See insert for color representation of the figure*.)

the main end use of the system. Every house in the village was provided with four LED bulbs of 7.2 W each and also with a power socket for charging mobile phones and for using other low-power-consuming devices like laptops, TV, radio, fans, and so on. The health post uses a refrigerator for 24 h a day basically for making ice for preserving medicines. A library has been established in the church in the village and it uses a laptop and an LED projector as per need. This system was donated by the NSVC team and was basically used for documenting movies for education and sometimes for entertainment.

The villagers have started using the electricity generated from the micro hydro power plant for irrigation purposes. Currently, around 200 acres of land is used for dual crops and thus the agricultural productivity of these lands has increased. Besides these developments, a village-level meeting was conducted to assess future energy demand of the village community. It was found that villagers use manual means or have to travel to traditional water mills carrying loads on their back for grinding the food grains which is too time consuming and a real drudgery. Hence, there was a demand for electric-driven agro-processing mills such as hullers and grinders (few of them seem feasible) in the area. The village community has formulated a village energy committee and appointed two personnel to operate and manage the hybrid power system. One of the responsibilities of the operators is also to collect the electricity tariff from each of the consumers and deposit it in the funds for future repair and maintenance as well as for contribution to future expansion. The salary of the operators is also generated from the tariff collection.

This case study shows how the availability of water/stream contributes not only to generating electricity, which is used for various applications, but also triggers the socioeconomic development of the region.

11.5. SUMMARY

The case studies described in this chapter present the strong linkages that exist between energy, water, and food. The first case, which was an energy-centric nexus, shows how the provisioning of energy facilitated the availability of water, which in turn was used for small-scale agricultural purposes, as well as for other socioeconomic development of the village. On the other hand, the third case, which was a water-centric nexus, shows how the availability of water has brought electricity to the village and triggered overall development of the villages. While both the "nexuses" promote sustainable development of the regions, they differ in terms of primary assessment and design, planning, and operationalization of the project. Further, the capacity-building requirement for operating and managing the energy-centric and water-centric nexus projects is different and thus needs to be identified appropriately. Again, the first and third case studies were implemented more on a pilot scale to demonstrate the linkages between different resources and the convergence of different developmental programs, which can be replicated in other regions through the adoption of proper business modules. The second case study shows how the policy intervention of an integrated government fund can address water resource crises and implement strategies for water management to improve water availability and management efficiency in a water-scarce state.

In addition to the socioeconomic development of the region, all these projects have taken care of the sustainability of the project with rising energy demand. The design and sizing of each of the projects were made in such a way that the energy demand of the locality for the next 5 years has been considered while sizing the power system. In addition to the energy demand, the components and equipment of all the power systems were chosen to be grid interactive in nature so that when a conventional grid arrives at the villages, these existing solar systems would not be redundant and could well be integrated into the grid. In such a scenario, this power system will not only assure reliability of electric supply but also contribute to revenue generation by selling power to the conventional grid. Such an option will not only help in addressing the energy access issues but will also contribute to energy security of the country.

All the case studies have described the water-energy-food nexus in rural areas which may differ from that of urban areas as their priorities and challenges are different. While the nexus in rural areas revolves around livelihood generation and enhancement in agricultural productivity, the nexus in the urban sector focuses more on land use, social inclusion, and waste and transport management, in order to address the rapid urbanization trends and achieve a more efficient and effective use of resource cycles in urban and peri-urban areas. Therefore, the planning strategies and policies as well as the implementation mechanism should be formulated based on the target sectors.

Despite the huge potential of linking energy, water, and food in the context of sustainable development in rural areas as shown in the case studies, it is yet to be mainstreamed into the policies and regulations of many countries. Thus, from this nexus perspective, stakeholders from relevant disciplines need to think and act for cooperation to realize the benefits of greater interrelations. For proper implementation of policies framed as a result of such interlinkages, proper institutions must be established along with leaders who will encourage and give proper incentives for greater convergence of all these sectors. In order to upscale such projects successfully, few enablers such as appropriate institutional and regulatory frameworks, policies, sustainable financing and business modules, as well as capacity-building measures need to be in place.

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Section III
Nexus in Practice

12
The Water-Energy-Food Nexus from a South African Perspective

Olusola O. Ololade[1], Surina Esterhuyse[1], and Audrey D. Levine[2,3,4]

ABSTRACT

The Republic of South Africa is a water-scarce country where about 13% of the land is arable and the population experiences significant disparities in equitable access to water, energy, and food. South Africa is also witnessing unprecedented development supported by a growing and diverse economy that relies on unstable energy resources. These paradoxes provide a unique opportunity to explore how the interconnectedness, interdependencies, and security of food, energy, and water systems can lead to new policy paradigms and to identify research needs for moving South Africa onto a sustainable development path.

12.1. INTRODUCTION

About 95% of the world's population growth occurs in developing countries that face significant challenges due to pervasive malnutrition compounded by persistent water scarcity as exemplified by conditions in sub-Saharan Africa [*Rockstrom et al.*, 2003]. In fact, it is widely acknowledged that the security and resiliency of the water, energy, and food (WEF) systems necessary for life are at a critical tipping point throughout Africa [*Siddiqi and Anadon*, 2011; *Scott et al.*, 2003; *McCornick et al.*, 2008; *IEA*, 2010]. Many people, especially in rural areas, lack access to dependable sources of water, food, and energy. Population growth and increased urbanization, coupled with environmental stressors, climate disruption, and economic uncertainties have intensified the need to consider interdependencies among WEF systems [*Bazilian et al.*, 2011; *Gulati et al.*, 2013; *Leese and Meisch*, 2015]. The capacity to replenish surface and groundwater resources is compromised by increased variability and unpredictability in the frequency, intensity, and duration of rainfall events due to climate disruption. Changes in the water budget across the continent impact crop production with direct negative consequences for food security [*Mendelsohn et al.*, 2007]. *Leese and Meisch* [2015] suggest that scarcity of WEF life-supporting resources can threaten human existence and trigger extreme behavior.

This chapter focuses on the WEF nexus in South Africa, a water-scarce country where about 13% of the land is arable and the population experiences significant disparities in equitable access to water, energy, and food [*StatSA*, 2011]. South Africa is also witnessing unprecedented development supported by a growing and diverse economy that relies on unstable energy resources [*South African Government*, 2008; *PARI*, 2013]. These paradoxes provide a unique opportunity to explore how the interconnectedness, interdependencies, and security of food, energy, and water systems can lead to new policy paradigms and to identify research needs for moving South Africa onto a sustainable development path.

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12.2. WEF NEXUS PERSPECTIVE IN EXISTING POLICY FRAMEWORKS

As a prelude to considering the WEF nexus, it is useful to consider the capacity of governance structures to accommodate this inclusive approach for resource management. The *Constitution of the Republic of South Africa* (Act 108 of 1996) [*RSA*, 1996], enacted 20 years ago, provides a valuable context for the WEF nexus through several provisions. The *Constitution* includes a *Bill of Rights*, which defines specific environmental rights (Environment, section 24) and food and water security (Health care, food, water, and social security, section 27). The following excerpts from the *Bill of Rights* are pertinent to the WEF nexus:

1. Every person has the right to
   (i) an environment that is not harmful to their health or well-being
   (ii) have the environment protected, for the benefit of present and future generations through reasonable legislative and other measures
   (iii) sufficient food and water
2. Environmental protection measures should
   (i) prevent pollution and ecological degradation
   (ii) promote conservation
   (iii) secure ecologically sustainable development and the use of natural resources while promoting justifiable economic and social development

There is also legislation that specifically addresses water and energy. The *South African National Water Act* (Act 36 of 1998) provides a holistic and inclusive hydrologic cycle approach to managing "all" water. Water use allocations are centralized through Catchment Management Agencies. The *Water Act* also includes water "Reserve," which requires that water is set aside to support basic human needs and the environment. The country's electricity sector is regulated by the Department of Energy (DoE) through the *Electricity Regulation Act* (ERA) of 2006 (No. 4 of 2006) and the *National Energy Act* of 2008 (No. 34 of 2008), which require consideration of the country's overarching energy needs and implementation of the *Integrated Resource Plan* (IRP). Other relevant legislation includes the *National Environmental Management Act* (Act 107 of 1998) [*RSA*, 1998], which requires that all development in South Africa be socially, economically, and environmentally sustainable to provide for all present and future generations.

Collectively, the existing governance frameworks can provide a robust springboard for incorporating the WEF nexus in practice. However, explicit linkages between water, energy, and food governance do not currently exist. As new policies are developed, it could be possible to leverage current frameworks and develop complementary governance structures.

12.3. OVERVIEW OF WEF NEXUS COMPONENTS

Provisioning of water, energy, and food to support societal needs requires that the resources are available and accessible in the quantity, quality, and location where they are needed. Equally important are the physical, social, and cyber infrastructures to manage these systems. Historically, the interplay of geography, hydrology, and geology has governed land use practices (urban, agricultural, mining, etc.) in South Africa. Overall, water scarcity is a serious concern and South Africa is considered to be a water-stressed country according to the Falkenmark Water Stress Indicator, which is determined from water availability, water quality, water demand, water affordability, and service coverage interrelationships [*Jobson*, 1999].

An overview of the relative locations of South Africa's population centers, agricultural areas, and mining zones is provided in Figure 12.1. South Africa's freshwater resources include rivers, surface impoundments, and groundwater that, collectively, support the water needs of the people, the environment, agriculture, industry, and energy. The geographical distribution of South Africa's water resources (surface and groundwater sources) in relation to climatic zones is shown in Figure 12.2. The Orange and Vaal rivers are the main perennial rivers that serve as a water supply for some 300 towns in the interior of the country; however, about 65% of South Africa's population relies on access to groundwater resources [*Woodford et al.*, 2005] that are dependent on precipitation for freshwater recharge and replenishment. South Africa's rainfall averages about 497 mm/annum (well below the global terrestrial average of 860 mm/annum), which translates to an annual freshwater availability of less than 1700 m^3/person [*Institute for Futures Research*, 2009]. In addition, less than 10% of the precipitation contributes to surface water resources [*O'Keeffe et al.*, 1992, p. 843]. During the nineteenth century, South Africa instituted the "national hydraulic mission" to address localized disparities in water availability that emerged during the gold rush and mining boom when high volumes of water were required by the mining and manufacturing industries in the dry central parts of the country (refer to Figures 12.1 and 12.2). This era was characterized by large surface water engineering projects that included dam building, inter-basin transfers, and large-scale inter-catchment exchanges [*Turton and Meissner*, 2002, p. 43], while financial investment in groundwater systems lagged behind [*DWS*, 2010].

From the WEF nexus perspective, the necessity of ensuring resilient water, food, and energy systems is paramount for public health protection, particularly in population centers and urban areas. It is interesting to note that, unlike many parts of the world where major urban areas develop near freshwater sources, South Africa's largest metropolitan

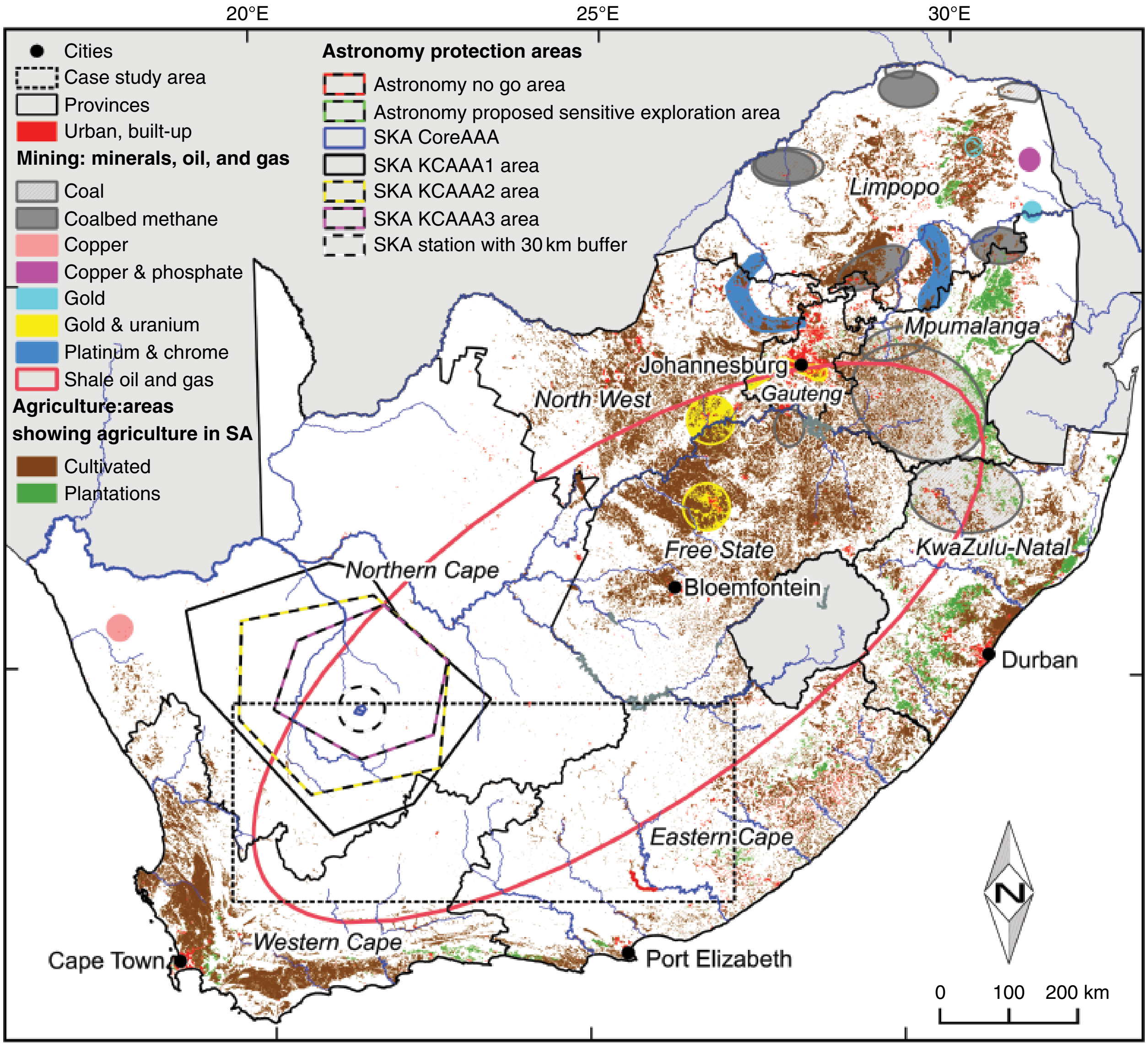

Figure 12.1 Locations of South Africa's population centers, agricultural areas, mining resources, and other land use patterns. (*See insert for color representation of the figure*.)

area, Gauteng (with its major city, Johannesburg), developed due to the employment opportunities associated with proximity to mineral resources and extractive industries. Therefore, Johannesburg's population relies on properly functioning infrastructure (transportation, water conveyance and storage, energy systems) for timely and reliable delivery of freshwater, food, and energy. In contrast, the limited availability of freshwater in the central and northwestern parts of the country is evidenced by relatively low population densities and minimal crop cultivation (see Figure 12.1).

It is important to recognize the role of transboundary water transfers. Gauteng's freshwater is supplied through the Lesotho Highlands water project. This large-scale water transfer project transports water from Lesotho's Mohale and Katse dams via long-distance (over 80 km) large-diameter (over 4 m) tunnels [*Van Vuuren*, 2012]. The water discharged from the tunnels enters the Ash River just outside the South Africa/Lesotho border where it is impounded at the Vaal dam and then conveyed to Johannesburg and further north to Pretoria [*Van Vuuren*, 2012]. South Africa has approximately 500 large dams that supply water for irrigation and water consumption in large cities, without which this semiarid country would not have been able to pursue or sustain economic and development activities [*Van Vuuren*, 2012]. Clearly, maintaining the infrastructure for these systems and protecting water quality is a high priority.

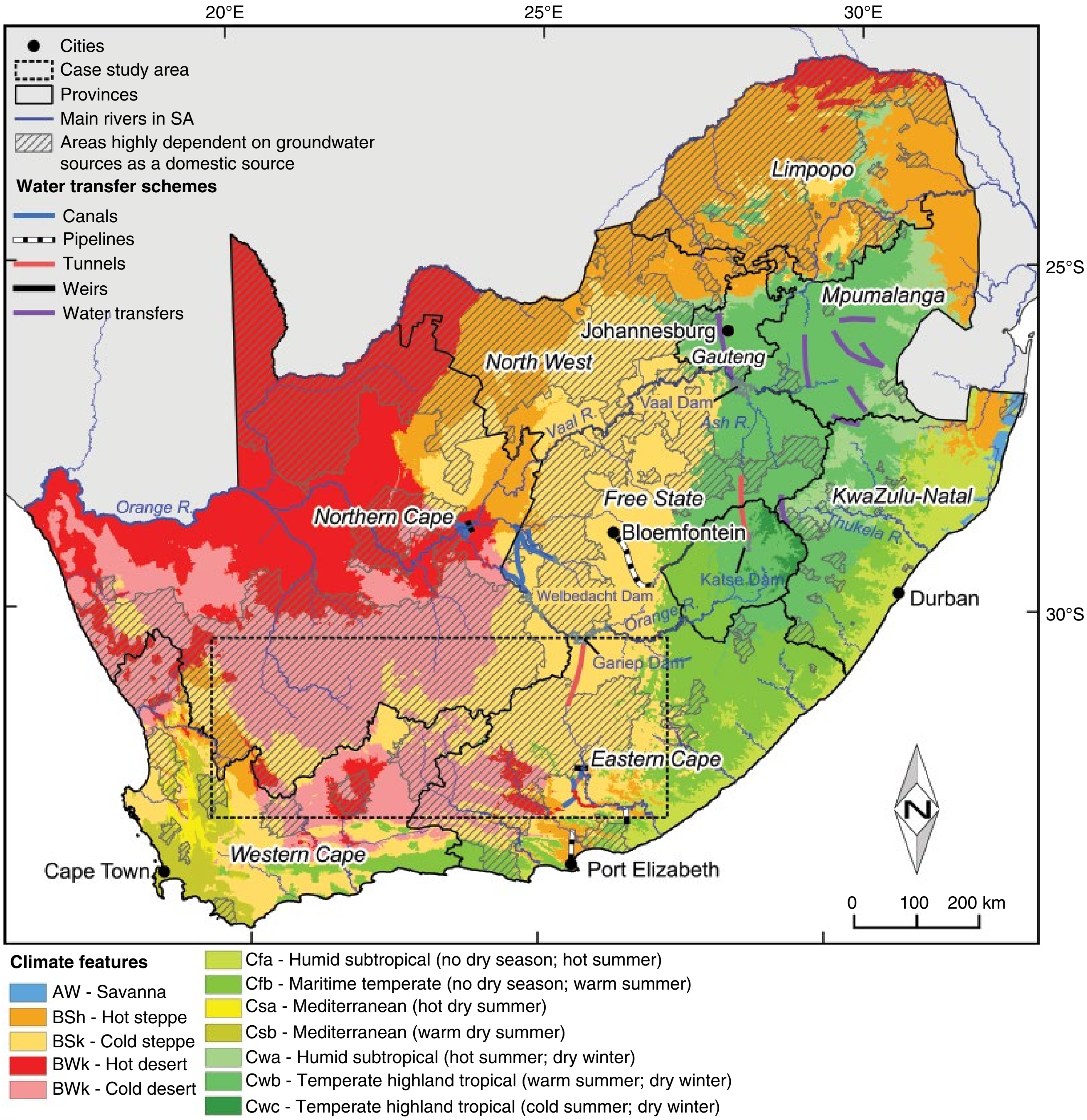

Figure 12.2 Overview of South African climate zones, areas of high groundwater use, and main rivers. (*See insert for color representation of the figure.*)

The locations of other major metropolitan cities on the coast (e.g., Cape Town, Durban) have been instrumental in fostering international trade, another key element in the WEF nexus. Interestingly, the southern hemisphere's largest radio telescope facility (the Square Kilometer Array (SKA)) and largest visual astronomy telescope (the Southern African Large Telescope (SALT)) are situated in the western part of the country, where it is relatively dry with minimal competition for other land uses (see Figure 12.1). In South Africa, energy and water resources are inextricably linked in that water may limit the expansion of energy sources [*DOE*, 2013], while the development of energy sources may also significantly impact on water security, as some forms of energy generation (such as from coal) require significant volumes of water [*Sparks et al.*, 2014]. The majority of energy in South Africa is derived from coal. According to *Sparks et al*. [2014], there is a need to move from using conventional sources to generate electricity toward renewable energy generation options, which consume less water per MWh. The locations of major coal fields in the eastern parts of the country, where coal is extracted for power generation, are shown in Figure 12.1. In general, mining and resource extraction activities are in close proximity to where the resources occur and, as such, can impact the local availability and quality of water with secondary impacts on competing water uses, such as agriculture. In some cases, water is transported to the energy generation hubs, of which the most important example is the transfer of water from Lesotho to Gauteng, the economic hub of South Africa, for mineral extraction, energy production, and support of municipal and industrial activities [*Turton*, 2015].

Since 2008, electricity generation in South Africa has been undependable, necessitating periodic load-shedding events. The lack of reliable sources of electricity has compromised industrial productivity and has triggered ongoing economic repercussions that threaten to lower the South African gross domestic product (GDP) [*Grootes*, 2015]. The low and inconsistent annual rainfall coupled with high evaporation rates contribute to a lack of perennial rivers and constrain the availability of water for thermoelectric power production or hydroelectric power generation. Possible future development of unconventional oil and gas (UOG) resources can also impact water systems (locations for UOG resources can be seen in Figure 12.1 as "shale oil and gas" and "coalbed methane").

The linkages between water and food are evident by comparing freshwater availability to the locations of the primary agricultural hubs for crop production, livestock, and aquaculture. Traditionally, food production in South Africa occurred where water resources were available, such as along major perennial river systems (the Orange River) or in places where shallow groundwater was available for crop production [*DWS*, 2010]. The majority of the grain is grown through dryland production, which relies on rainfall as the only source of irrigation water. Grain and livestock production in water-scarce areas is particularly vulnerable to severe droughts, flooding, and other climatic perturbations. About 1.5% of South African land is under irrigation, with 30% of the country's crops produced from it [*RSA*, 2009]. Water quality can impact the yield and quality of food production which, in turn, can impact water quality. Key water quality issues include salts, nutrients (nitrogen and phosphorus), pesticides, commercial chemicals, metals, and radionuclides. In some cases, the use of technologies for monitoring and treating water to an appropriate quality may be necessary to sustain food production. South Africa was a net food exporter from 1985 to 2008; however, population growth, decrease in agricultural yield, and food deficit in recent years have converted the country into becoming a net food importer [*Bazilian et al*., 2011].

While there are many intersections between water, energy, and food systems across South Africa, there are several physical locations that bear witness to competing and conflicting demands. For example, some of the most arable land with available inland freshwater sources overlaps with regions of coal deposits (such as the maize production areas in Mpumalanga) or shale formations (such as the maize, wheat, and sugar production areas in Kwazulu-Natal). These same areas could potentially support renewable energy development such as solar or wind. Current challenges include mitigating and remediating impacts of acid mine drainage (AMD) from coal mining on agricultural land and inland water bodies [*Ochieng et al*., 2010; *McCarthy*, 2011; *Dabrowski and de Klerk*, 2013]. The acidification and elevated metals concentrations affect the quality and efficiency of food production systems [*WWF-SA*, 2011]. These locations could potentially serve as a real-time "test bed" for optimizing the WEF nexus toward improved sustainability.

According to *Pahlow et al*. [2015], the consumption of agricultural products accounts for 93.8% of the total national water footprint of South African consumers which averaged to about 56.7 billion m^3/year from 1996 to 2005. Crop production and meat production account for 75 and 32% of the total national agricultural water footprint, respectively. Sunflower seed production constitutes a larger proportion (83%) of the crop water footprint. It has been reported that agriculture consumes about 60% of all available water extracted in South Africa while the energy sector consumes only 2% [*Wassung*, 2010; *WWF*, 2014]. However, limited quantitative information is available on the water balance across the energy supply chain in South Africa [*Sparks et al*., 2014]. The energy footprint of food supply is affected by the relative intensity of irrigation, water quality impairment, food processing, distribution, and waste management. While some insight into the energy footprints of water and food can be gleaned from the analysis of energy expenditures for production, these data tend to be inconsistent and not readily accessible. It is envisioned that improved data will emerge as an outcome of WEF research activities globally and within South Africa.

12.4. WEF SECURITY IN SOUTH AFRICA

The security of water, energy, and food systems is governed by multiple interacting factors. A key issue is the relative alignment between supply, demand, and accessibility of the components of each system. The current status of water, energy, and food availability in South Africa is given in Table 12.1. It is important to recognize that about

Table 12.1 Summary of key factors that affect current and future water, energy, and food security in South Africa

WEF nexus components	Statistics	Implications
Water security		
Water availability	Surface water: 9500 million m³/annum [*DWS*, 2013] Groundwater: 7500 million m³/annum [*DWS*, 2013]	The over-allocation of surface water resources means increasing pressure on already stressed groundwater resources to meet the growing water demand Climate change will further exacerbate freshwater availability
Water allocation	Surface water: more than 80% allocated [*DWS*, 2010] Groundwater: approximately 50% used [*DWS*, 2010]	
Projected increase in water demand	1.2% per year through 2025 [*DWS*, 2013]	
Energy security		
Electricity availability	Total generated capacity: 48,220 MW Capacity from coal (76%): 36,860 MW [*DOE*, 2013]	Current generated capacity barely meets the current demand. Future development will require more electricity and additional energy sources
Projected increase in average annual electricity demand	1.9–2.8% through 2030 1.3–2.4% through 2050 [*DOE*, 2013]	
Food security		
Food import/export status	Net exporter of food (1985–2010) [*DAFF*, 2010; *Bazilian et al.*, 2011] Net importer of maize (2014–2015), projected net importer of maize (2016–2017) [*Sihlobo and Kapuya*, 2015]	South Africa has been a net exporter of food since 1985. However, drought conditions are wreaking havoc on crop production and have influenced food export figures for South Africa. According to FAO (2015), South Africa will experience a drop of 28.9% [*Sihlobo and Kapuya*, 2015] in grain production compared to 2014
Grain production (tons)	13 million (2013 data) [*FAO*, 2015] 16 million (2014 estimate) [FAO, 2015] 11 million (2015 projection) [FAO, 2015]	

60% of South African households are considered to be food insecure [*Development Bank of Southern Africa*, 2011], a situation that is compounded by poverty and disparities in access to WEF systems.

Water security is a measure of the availability and accessibility of water to support the needs of the people, the ecosystem, and the economy [*Hoff*, 2011]. Similarly, energy security includes "access to clean, reliable and affordable energy services" for domestic, industrial, and commercial needs [*AGECC*, 2010]. Food security refers to physical and economic access to sufficient, safe, and nutritious food to meet everyone's dietary needs and food preferences to ensure well-being at all times [*FAO*, 2009].

Water security directly impacts the security of food and energy systems due to the interdependencies among these systems. Over half of South Africa's catchments lack adequate water availability to meet the water demand. In addition, over 80% of surface water resources have already been allocated, leaving only about 40% of available groundwater resources to support future development [*DWS*, 2010]. The prolonged drought conditions that South Africa has experienced in recent years, coupled with deteriorating infrastructure, has depleted water supplies and led to sporadic curtailment of water delivery in some parts of the country [*SAICE*, 2011; *Crowley*, 2015]. Economic growth, along with population growth, will place additional pressures on water availability and quality. As the use of irrigation increases, food security will become more susceptible to energy fluctuations and costs [*Jooste*, 2012; *Gulati et al.*, 2013]. Given all of these constraints, there is strong evidence that South Africa faces a growing water-related environmental, economic, and social crisis [*Turton and Meissner*, 2002; *Turton et al.*, 2006; *Bond and Dugard*, 2008; *Herold*, 2009].

A comparison of the current portfolio of energy sources in South Africa is provided in Figure 12.3. As shown, about 80% of the energy generated in South Africa is derived from coal [*Econometrix*, 2012; *DOE*, 2013]. By 2030, according to the National Development Plan, an additional 20,000 MW should be produced from renewable energy sources such as solar (photovoltaic and concentrating solar power) and wind [*NPC*, 2012]. The extraction of natural gas from shale and coal formations is also a consideration, contingent on satisfying water, environmental, social, and economic constraints that are at the heart of the WEF nexus. The trade-offs between renewable energy, fossil fuels (conventional or unconventional), and nuclear sources are an ongoing source of debate across South Africa, suggesting the possibility of an increasingly constrained energy system.

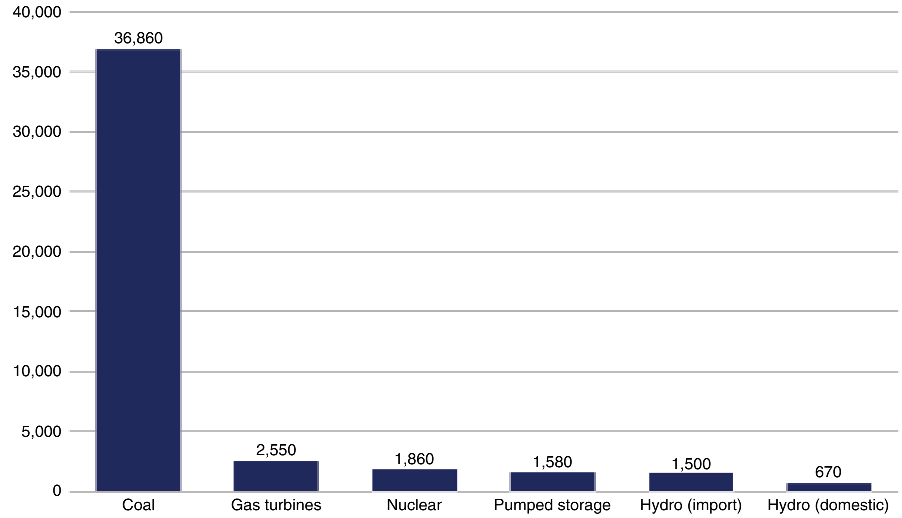

Figure 12.3 Comparison of South Africa's major sources of electricity. Source: Adapted from *DOE* [2013].

12.5. OPERATIONALIZING THE WEF NEXUS: A CASE STUDY OF THE KAROO REGION IN CENTRAL SOUTH AFRICA

Currently, there is intense interest in the possibility of generating new sources of electricity from the Karoo region in central South Africa, shown in Figure 12.4. Water resources and climatic features for this region are shown in Figure 12.5. The Karoo is a semi-desert environment, with an average annual rainfall ranging from 100 mm in the west to 400 mm in the east [*Schulze et al.*, 1997]. From an infrastructure perspective, the Karoo has historically served a rural population with an economy based on agriculture, livestock production, and some tourism. The majority of the Karoo is natural rangeland used for extensive livestock grazing and about 1% of the land area supports large commercial farms [*Burns et al.*, 2015]. Farms in the western Karoo are primarily oriented to raise small livestock (goats, sheep, angora goats) and to produce a variety of meat, wool, and fabric products. In the Karoo Midlands, cattle-holding is increasing in scale [*Development Partners*, 2009]. In addition, smaller farming units with intensive agriculture, sustained by irrigation, are being established next to major rivers such as the Sundays, where citrus is produced. Currently, no large-scale electricity is generated in the Karoo study area, except for small solar farms that contribute small amounts to the Eskom power grid [*Greenway*, 2014; *De Aar Solar*, 2015].

The central part of the Karoo provides a snapshot of emerging WEF nexus challenges. This region of South Africa is attracting serious interest for extracting unconventional energy sources such as shale gas or coalbed methane [*Econometrix*, 2012], and several exploration licenses are currently under consideration [*PASA*, 2015], as shown in Figure 12.4. Exploratory drilling could commence in the near future, depending on time frames for obtaining licenses and environmental authorizations. However, development of UOG requires water to support drilling and hydraulic fracturing.

Currently, water resource systems and the supporting infrastructure within the Karoo are severely constrained. In addition, water is imported to support urban areas such as Bloemfontein, as shown in Figure 12.5. For example, the Welbedacht Dam, completed in 1973 with an initial storage capacity of 115 million m^3, impounds water from the Caledon River, which has a catchment area of about 15,245 km^2 and a natural mean annual runoff (MAR) of approximately 1210 million m^3/annum (from 1920 to 1987). However, only about 14% of the storage capacity (16 million m^3) is currently available due to unmitigated siltation [*DWS*, 2016]. To compensate for the reduced water availability, the Knellpoort Dam was completed in 1988 [*DWS*, 2016]. However, the continued siltation and associated water quality deterioration are impacting water security in the region and introducing additional stressors on the already limited water resources. Smaller towns in the Karoo (Beaufort West, Queenstown, Graaff Reinet, Sutherland, and Carnarvon) all depend on groundwater for water supply, as there are no nearby perennial rivers to supply water and the cost of water transfer schemes is too high for these small municipalities. Beaufort West depends on a mix of groundwater supply and reclaimed municipal wastewater, with 70% of its supplies coming from groundwater [*Turner and Grimmer*, 2013]. It implemented a direct water reclamation plant in 2011 during drought conditions to recycle sewerage water for its residents [*Marais and Von Durckheim*, 2011].

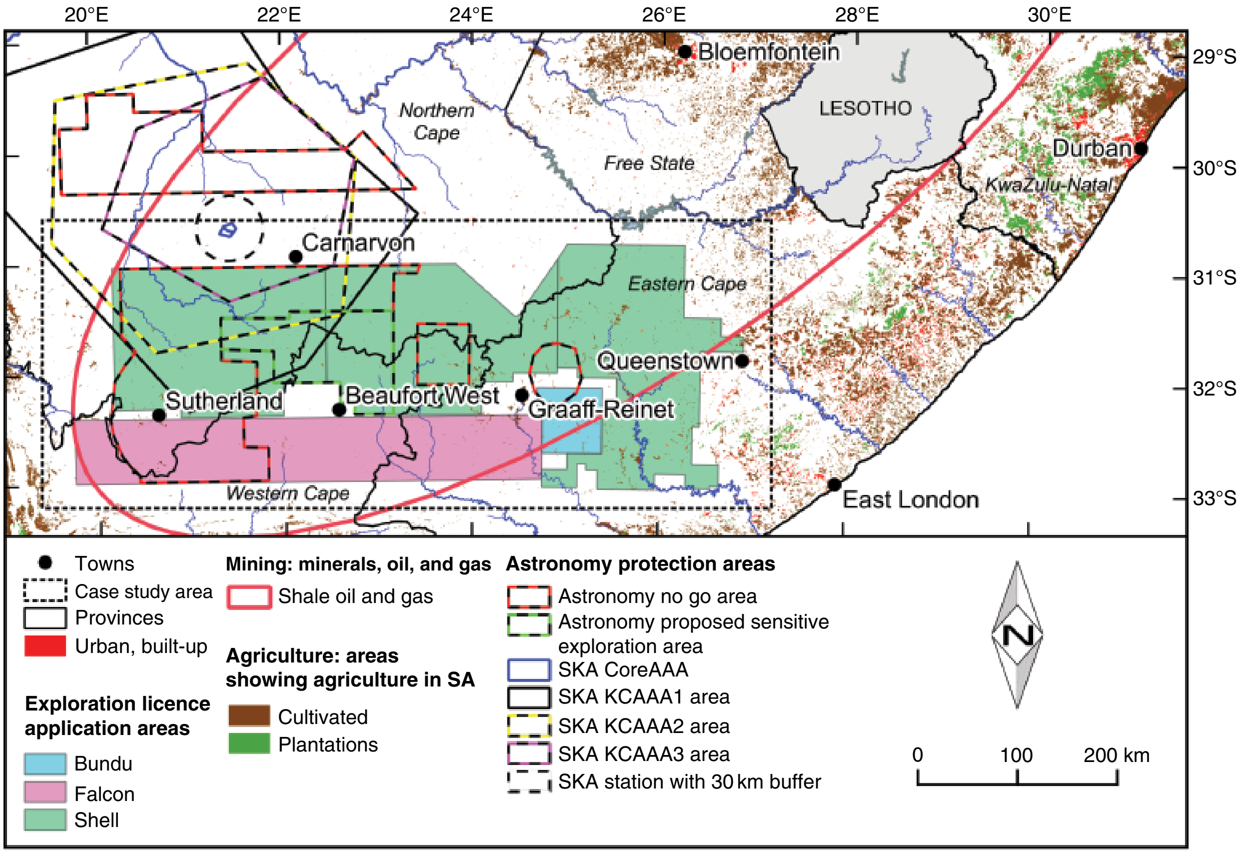

Figure 12.4 Overview of land use patterns in the central Karoo region, energy resource exploration zones, and astronomy protection areas. (*See insert for color representation of the figure.*)

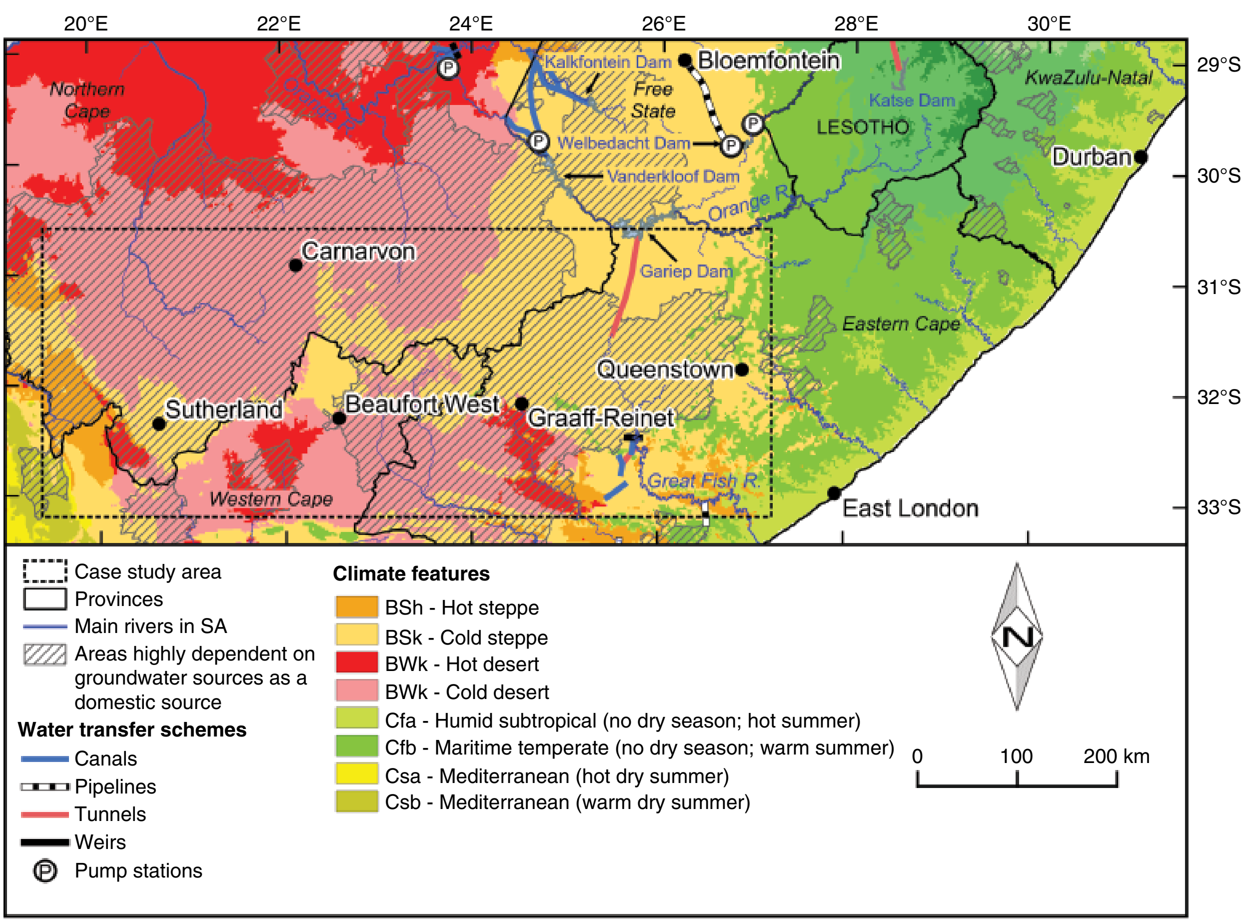

Figure 12.5 Overview of water resources and climate patterns in the central Karoo region. Source: Adapted from *Esterhuyse et al.* [2014]. (*See insert for color representation of the figure.*)

Thus, development of UOG will introduce further competition on the already constrained water infrastructure [*Turner and Grimmer*, 2013]. There are also concerns about potential impacts on the transportation infrastructure and air quality, particularly if water is imported from other parts of the country. While many questions remain about the WEF nexus in the Karoo, the region has potential to serve as a case study to develop the relevant data, metrics, and analytical tools to support decision making and policy development. There is a critical need to quantify the baseline conditions, socioeconomic factors, and land use changes along with projections of future population growth and climate variability to provide a better understanding of water security and its linkages with food and energy securities. A stepwise approach to incorporate the WEF nexus could provide insights into the sustainability of various energy alternatives and the types of governance and investments that are needed for success.

12.6. IMPLICATIONS OF WEF SECURITY IN SOUTH AFRICA'S FUTURE

The United Nations has suggested that the WEF nexus could play a major role in achieving its sustainable development goals (SDGs) by reducing negative economic, social, and environmental externalities and by increasing resource use efficiency. While the methodologies for operationalizing the WEF nexus are still evolving, South Africa can benefit from test-driving an integrated strategy toward sustainable development and moving beyond historical approaches that tackle water, energy, and food security challenges individually. While the *National Environmental Management Act* (Act 107 of 1998) [*RSA*, 1998] acknowledges the interdependence of socioeconomic and biophysical systems, these aspects are not yet managed in an integrated way in South Africa.

WEF nexus operationalization could benefit from the streamlining of regional-scale nexus linkages (such as the development of interlinked policy frameworks). However, interlinked policy framework development is currently hampered by the fact that policy development and implementation is fragmented among different government departments that comprise different spheres of government [*Esterhuyse et al.*, 2016]. Another way to improve operationalization of the WEF nexus is by implementing local-scale nexus applications in addition to streamlining regional-scale nexus linkages.

There are a growing number of examples of how the WEF nexus approach has been used on a local scale in South Africa to improve land, energy, and water use efficiencies. The integration of irrigation and nutrient (nitrogen) inputs in food production was successful at increasing milk yields by improving pasture conditions with minimal impacts on the environment in an area that had previously suffered from lack of access to water and nitrogen that led to impaired dairy cow productivity [*Fessehazion et al.*, 2012].

Another example is the use of biogas, which has been expanding in the rural areas of South Africa that are off the national grid and are dependent on subsistence agriculture. As of October 2013, there were 38 biogas operations registered by the National Energy Regulator of South Africa (Nersa) in the country [*SAinfo reporter*, 2013]. In some cases, local-scale anaerobic digestion of waste material (livestock manure, kitchen waste, agricultural residue) yields biogas, which can serve as an energy source, and has residues that can serve as soil conditioners. The availability of water is crucial in biogas generation and the use of alternative water sources, such as reclaimed wastewater, is promising. The household-level benefits include reduced expenditures for energy and fertilizer, potentially higher farm production, and reduced risk of chronic respiratory and eye diseases due to the use of a cleaner cooking fuel [*DOE, DBSA and SABIA*, 2013]. Another advantage is that the local communities experience increased water and energy security due to reduced dependence on water supply networks or power grids.

12.7. SUMMARY

There is a clear need to develop an interlinked policy framework in the process of strategic planning to improve the security and sustainability of water, energy, and food systems in South Africa. The severe constraints that water scarcity in South Africa places on other nexus elements (e.g., in terms of electricity generation, national development, and food production) underline the importance of operationalizing the WEF nexus approach. Operationalization of the WEF nexus approach would support short-term and long-term decisions about resource management in South Africa which could provide valuable data and insights to ensure sustainable management of these resources. The trade-offs between renewable energy, fossil fuels (conventional or unconventional), and nuclear sources need to be reconciled with water, in relation to the environmental, social, and economic constraints that are at the heart of the WEF nexus. Research and development that can capitalize on WEF synergies are needed. Even though the current policy framework supports the inclusive approach of the WEF nexus in practice, the integration of water, energy, and food governance does not as yet exist. To ensure proper support from the South African government, there should be a clear understanding of how the nexus approach can complement or leverage the existing governance approach.

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13

Water-Energy-Food Nexus: Examples from the USA

Soni M. Pradhanang

ABSTRACT

Availability and predictability of water resources can have direct impacts on food and energy systems and vice versa. The water-energy-food (WEF) nexus is intricately linked to everyday life. Like many other countries in the world, the United States has, and is currently facing many challenges with strained water, energy, and food systems. This necessitates a shift in thinking in order to understand that what we do every day affects the WEF nexus and the nexus, in turn, affects our everyday life. A reliable supply of water, energy, and food is one of the most important global challenges of the present time and the future, and we know that the WEF nexus will help address this intricate system in a better way. This chapter presents examples from the water, energy, and food sectors and explores the connections between these three in the context of the globalization and development in the United States, aiming to bring awareness to interactions, interdependencies and management challenges of these three resources.

13.1. INTRODUCTION

Water resource scarcity, variability, and uncertainty are becoming more prominent both domestically and internationally. Because energy, food, and water are interdependent, the availability and predictability of water resources can directly affect food availability and energy systems. We cannot assume the future is like the past in terms of climate, technology, and the evolving decision landscape. These issues present important challenges to address. The main thrust of this chapter is to explore the connections between water, energy, and food in the context of the United States and to bring awareness to some of the numerous ways these valuable resources interact with and are dependent upon one another, and how their management affects the environment.

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Many federal agencies are engaged in the water-food-energy (WEF) nexus in the United States. Their close interaction and integration can play an important role by bringing more science, technology, and analytical capability to the WEF nexus, drawing on expertise in research and development (R&D) programs, and engaging the strengths of the national labs and the universities around the United States In addition, many issues surrounding the WEF nexus affect assets owned and operated by private sector entities; development of public-private partnerships can help leverage capacity of federal organizations involved in engaging in the WEF nexus [*DOE*, 2014].

As the natural environment and infrastructure work together to provide water supplies, which nourish food and energy systems, these in turn create health and prosperity for society. Society, the economy, and the environment are the action arenas for the nexus and determine levels of sustainability, which are driven by the global trends shown in Figure 13.1.

Water-Energy-Food Nexus: Principles and Practices, Geophysical Monograph 229, First Edition.
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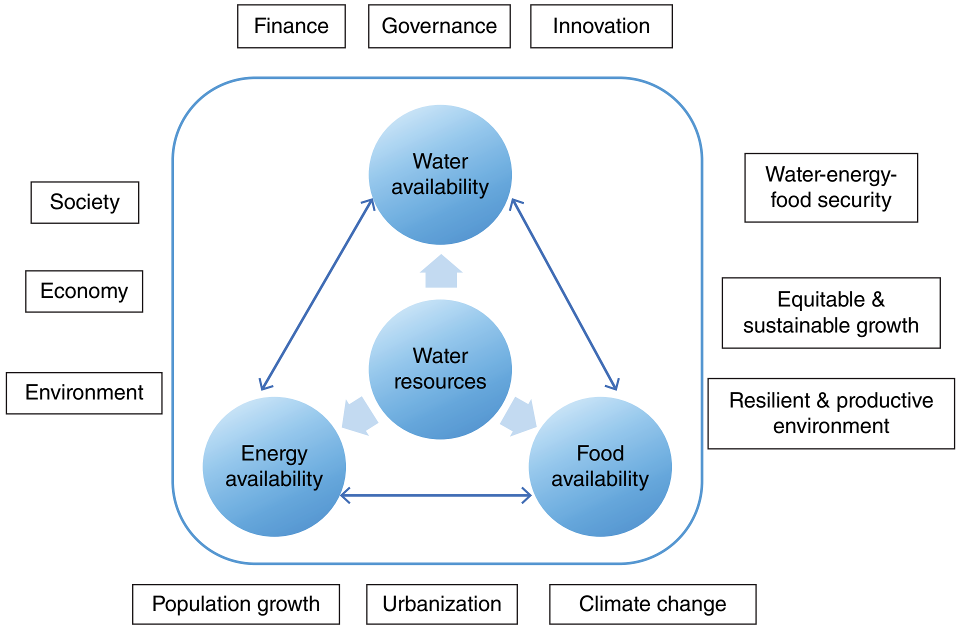

Figure 13.1 The water-energy-food nexus in the context of sustainability challenges. Source: Adapted from *Lofman et al*. [2002].

Water and energy are the two most fundamental ingredients of modern civilization. Without water, survival is questionable. Without energy, we cannot grow food and power homes, schools, or offices. Water is needed to generate energy and energy is needed to deliver water. Both resources are limiting each other and both may be running short. As the world's population grows in number and affluence, the demands for both resources are increasing faster than ever.

Nationwide, the two greatest users of freshwater are agriculture and power plants. Thermal power plants (those that consume coal, oil, natural gas, or uranium) generate more than 90% of U.S. electricity, and they are water hogs. The sheer amount required to cool the plants impacts the available supply to everyone else. And although most of the water is eventually returned to the source (some evaporates), when it is emitted it is at a different temperature and has a different biological content than the source, threatening the environment. Understanding the nexus between energy and water has become increasingly important in a changing world, as growing populations demand more energy supplies and water resources. Energy and water are intimately interrelated. Water use can be categorized into various sectors, ranging from supplying drinking water to public, agricultural use to electricity production directly through hydroelectric power generation at major dams and indirectly as a coolant for thermoelectric power plants. Thermoelectric power plants, comprised of power plants that use heat to generate power, such as nuclear, coal, natural gas, solar thermal, or biomass fuels, are the single largest user of water in the United States [*Webber et al.*, 2008; *Mantell*, 2009; *Stillwell et al.*, 2010]. Water is also a critical input for the growth and production of biofuels, such as corn ethanol. We use a significant amount of electricity to produce, deliver, heat, and treat water supplies and to treat wastewater. Despite the interconnections, historically these two sectors have been regulated and managed independently of one another. The Energy Update report by World Economic Forum [*WEF*, 2008] stated that "planning for energy supply traditionally gave scant consideration to water supply issues and planning for water supply often neglected to fully consider associated energy requirements."

At the same time, we use a lot of energy to move and treat water, sometimes across vast distances. The California Aqueduct, which transports snowmelt across two mountain ranges to the thirsty coastal cities, is the biggest electricity consumer in the state. Another important aspect of using water and other resources efficiently is to think about where our food comes from and how it is made. California produces more food than any other U.S. state, supplying a large part of the country's milk, beef, produce, and nuts. It is also one of the nation's driest states. As a result, California's agricultural sector exerts enormous pressure on the water supplies of the entire southwest, often shipping those limited water resources overseas as food exports. As convenient resources become tapped out, providers must dig deeper and reach farther [*Webber et al.*, 2008]. Some of the prominent examples that show connection between and among these resources are presented in the following section.

13.2. THE NEXUS IN FOCUS

13.2.1. Case 1: Energy Intensity of Water Use in Sacramento-San Joaquin Delta

California provides an excellent setting to examine the relationship between water, energy, and the environment. The state has an elaborate conveyance system which transports water from wet areas to dry areas, has facilitated the creation of millions of acres of fertile farmland, and consumes a tremendous amount of energy to make this possible (Table 13.1). California is a large state with a variety of climates, geographies, population, and urban centers. California gets its water from a great variety of sources and locations, and each one relies upon a different method of transport and a different amount of energy use. California's water supply mix is illustrated in Figure 13.2 [*CDWR*, 2003].

Water and energy were the main drivers for jumpstarting the Golden State's economy in the twentieth century. However, climate, geography, and population settings make the water, energy, and food linkage complicated. California has been experiencing massive water storage and some of the state's largest population centers are in the arid, southern coast, which requires water to be conveyed from the wetter, northern parts of the state, and from the Colorado River. Moving and treating all that water takes almost 20% of the state's electricity [*Klein et al.*, 2005]. In addition, California has competing interests for the state's water resources. With so many competing interests, conflicts emerge. As a main crop- and fruit-producing state, there is a large demand for agricultural water, primarily for irrigation, while continually growing cities need drinking water for the growing population. Unfortunately, the source of much of the state's water, the Sacramento-San Joaquin Delta, is already struggling to maintain its ecological integrity while fulfilling other water demands [*Lin*, 2008]. Formed by the intersection of the two rivers of the same name, the Sacramento-San Joaquin Delta is the largest estuary in the western United States and empties into the San Francisco Bay. The delta provides 27 million people (two thirds of the state's population) with drinking water, while irrigating 3 million acres of land [*Mount et al.*, 2012; *Ragatz*, 2012]. The California Water Code notes that wasting water is an unreasonable use of energy [*Attwater and Markle*, 1987; *Hanak*, 2007]. However, little or no effort had been placed on the planning of existing resources to meaningfully address the interplay between the two issues, that is, water and energy.

Table 13.1 Energy used to deliver water to various users in California

Representative points of delivery	Energy intensity (kWh/acre-feet)
Environmental flows in the Sacramento-San Joaquin Delta	0
Westlands Water District	435–1008
San Jose area	1165
Santa Barbara area	2826
Northern Los Angeles Basin	2580
Southern Los Angeles Basin	3236

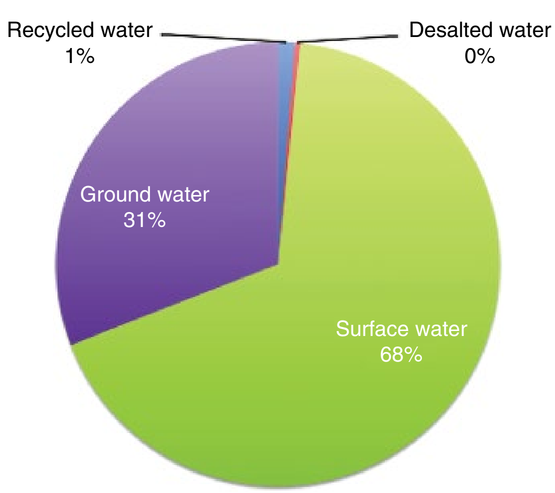

Figure 13.2 Primary sources of water in California in acre-feet per year.

The Westlands Water District is one of the largest agricultural water users in California and the western United States. It encompasses 600,000 acres of irrigated land producing over 60 varieties of crops, and is one of the big players in the fight to win water resources. It has a service contract with the United States Bureau of Reclamation for up to 1,150,000 acre-feet of water per year from the Central Valley Project (CVP). The district faces long-standing problems associated with soil quality and poor water drainage and is now negotiating with the Department of the Interior to retire permanently fallow agricultural lands [*Cohen et al.*, 2004]. This struggle pits farmers in the region against environmentalists and wildlife and water agencies, which seek to limit the water available for irrigation to protect indigenous species of fish in the delta. The Chinook salmon fishery, for example, was an important commercial fishery until the 1950s, when fish stocks began to drop. The decline in population was so great that the fishery had to close in recent seasons. Fishermen blame the collapse of the Chinook salmon fishery on water being pumped out of the delta, but it's likely that other factors like habitat loss and pollution contributed as well [*Yoshiyama et al.*, 1998].

To accommodate these competing interests and manage water resources in a more sustainable way, a plethora of agencies and regulatory bodies have been established. Both state and federal authorities are responsible for oversight of resources that move water around the state. Westlands proposes to keep water formerly used to irrigate retired lands and reallocate this water to remaining agricultural lands within the district. Determining the energy implications of this policy requires forecasting the impact of water supply changes on cropping patterns. For example, land retirement without reduction in CVP deliveries creates greater reliability and availability of water per acre of land still farmed. These reliability benefits are one reason why Westlands has been pursuing its own land retirement program [*Cohen et al.*, 2004]. If significant amounts of energy can be embedded in agricultural water use, agricultural water allocation decisions can have large energy impacts that warrant inclusion in analyses of water policy alternatives, which need to include harvest, cultivation, and other energy inputs. It is also important to understand the changes in land use or cropping patterns that are likely to result from a land retirement decision.

13.2.2. Case 2: Water-Energy Nexus in Texas

The importance of interdependencies between these resources has to be fully realized in order to understand the water and energy nexus. Vulnerabilities are introduced when the interdependencies of energy and water are not properly considered. Constraints of one resource introduce constraints in the other. For example, extreme weather conditions such as droughts and heat waves create constraints in water resources, which in turn affect energy availability and production. This chain of constraints causes domino effects leading to grid outages that affect the energy system which can become constraints in the water and wastewater sectors. Similar examples can be seen in the case of excess water that causes flooding events. The water necessary to produce electricity varies based on a number of factors, including the fuel used, how efficient the power plant is, and how it is cooled. Of the fuels commonly used in the Texas electric grid, for a given cooling technology, traditional nuclear generation uses a lot of water, as do traditional coal-powered plants; however, gas-combined-cycle plants use a little over half as much water as traditional coal-powered plants. As resources become more constrained due to population growth and water and energy suppliers confront new challenges, including water quantity and quality associated with climate change, the vulnerabilities associated with drought, and extreme events such as flood, heat waves, and hurricanes also increase.

Texas is the largest generator and consumer of electricity in the United States. The state of Texas has extreme variability in water availability from the relatively water-rich eastern half of the state to the arid western half of the state. A study [*Stillwell et al.*, 2010] showed that approximately 157,000 million gallons of water per year are consumed for cooling the state's thermoelectric power plants while generating approximately 400 terawatt-hours (TWh) of electricity. This amount of water is enough for over 3 million people for a year, each using 140 gallons per person per day. At the same time, each year, Texas uses an estimated 2.1–2.7 TWh of electricity for water systems and 1.1–2.2 TWh for wastewater systems each year. The amount of energy used in wastewater systems can generate enough electricity for about 100,000 people for a year. These estimates for water and wastewater combined represent approximately 0.8–1.3% of total Texas electricity and 2.2–3.4% of industrial electricity use annually. Another study [*Webber et al.*, 2008] that evaluates total electricity demand by 2018 shows that, in a business-as-usual scenario that includes current power generation and announced future power plants, the total electricity generation by Texas is projected to increases to nearly 490 TWh annually by 2018. Meanwhile, municipal water supply demand is predicted to grow to 10.2 million megaliters per year (ML/year) by 2060, from a current level of about 5.6 million ML/year [*Ward et al.*, 2007].

As shown in Figure 13.3, electricity consumption for residential purposes constitutes 37% of the total electricity use in the United States and a similar amount (~33%) in Texas. Since Texas is home to many energy-intensive refining, chemical, and manufacturing facilities, industrial electricity use is higher, as a percentage of total use, than in the country as a whole. Figure 13.4 shows the percentages of electricity generation by source for both the United States and Texas. Many of the electricity generation sources in Figure 13.3 require water for cooling to condense steam. The water needed for cooling varies with type of fuel, power generation technology, and cooling technology.

Energy and water are linked in many ways, and for electricity generation, the link is mainly as cooling water for the thermoelectric generation processes that account for a larger percentage of the electricity in Texas. Figure 13.5 shows spatial distribution of electricity used in cooling power plants in Texas. Total water consumption for electricity generation statewide is more than 595,000 ML/year: enough water for 3 million people for a year, each using 530 L per person per day (L/kWh: liters per kilowatt-hour). The demand for water decreases as the demand for electricity goes down. Additionally, technologies that conserve water at power generation facilities can also lower water consumption, but do not always work for certain systems. For example, for steam-based processes, using less water can often cause a concomitant drop in the plant's power efficiency. The growing use of wind power also plays an important role in decreasing the

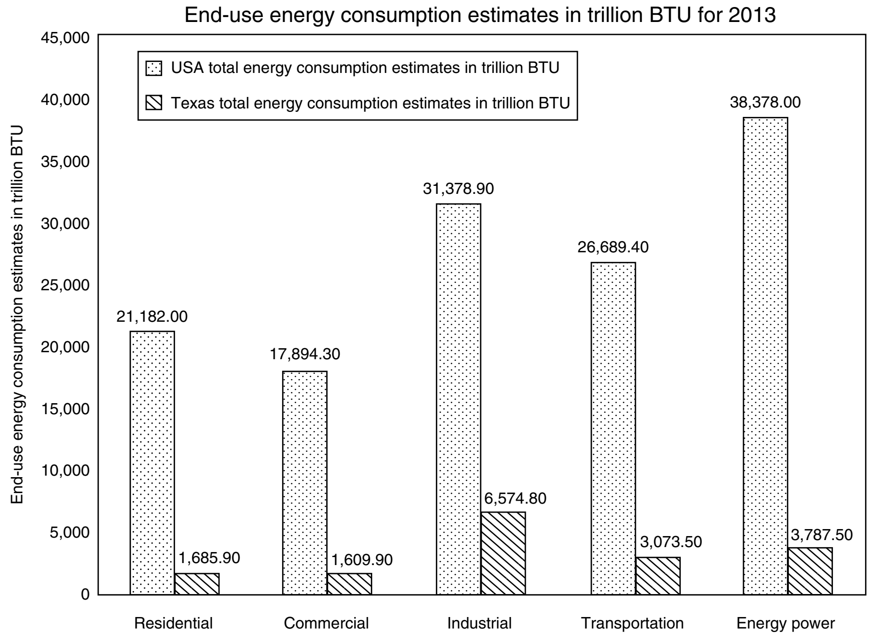

Figure 13.3 United States and Texas electricity consumption, in percent, by sector for 2013. Source: Adapted from *Ward et al.* [2007] and *USEIA* [2016].

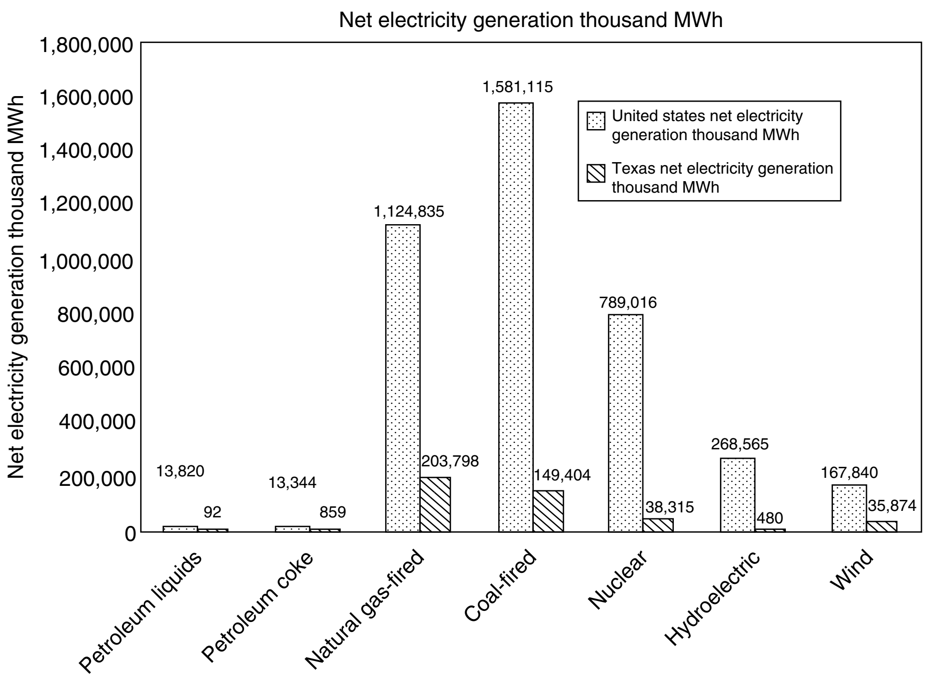

Figure 13.4 United States and Texas electricity generation, in percent, by source for 2013. Source: Adapted from *USEIA* [2016].

water demand for electricity in Texas. Wind power does not require any water for electric generation, and solar photovoltaic power uses water only for washing the panels. Energy efficiency also saves water by reducing the overall demand for electricity.

As long as thermoelectric power plants use water-cooling technologies and water and wastewater treatment plants use electricity for processes, it will be important to consider the energy-water nexus in planning and resource management. With population growth, the effects of

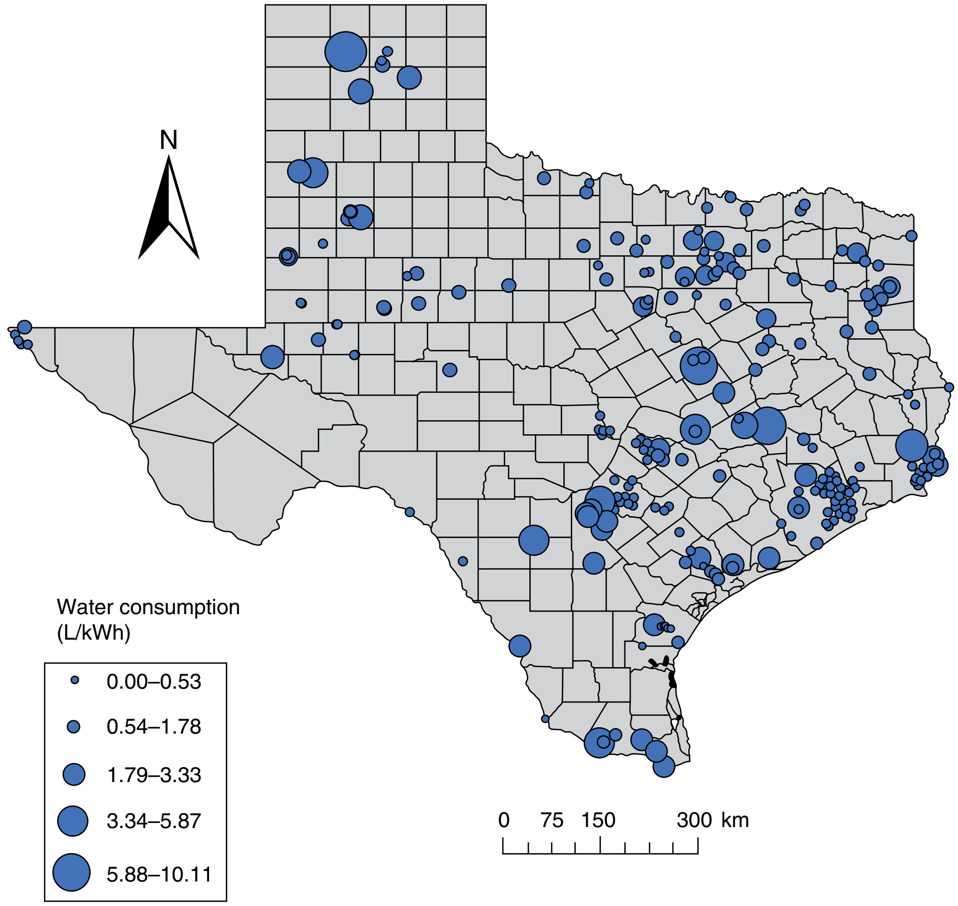

Figure 13.5 Water consumption for thermoelectric power generation in Texas. Source: Adapted from *Stillwater et al.* [2010].

climate change already impacting the hydrological cycle, and new carbon-pricing policies under consideration, understanding the trade-offs between energy and water becomes even more vital than ever for resource planning and management.

13.2.3. Case 3: Energy and Water Associated with Food Wastes

The Food and Agricultural Organization of the United Nations (FAO) projects that to feed the 9 billion people anticipated in 2050, global food production will need to rise by 70% of the current production [*Wise*, 2013]. The FAO reports that in the past decade the number of chronically hungry people rose to 1 billion [*Finley and Seiber*, 2014]. Our food is created by the conversion of distributed solar energy to concentrated chemical energy. In the United States, nearly 315 million people consume food with a total energy content of ~1×10^{18} J annually, which represent about 1% of national annual energy budget (of ~100 quads) for the United States [*DOE*, 2007].

Table 13.2 Water requirements for food commodities

Product	Unit	Equivalent water (m^3/unit)
Cattle	Head	4000
Sheep and goats	Head	500
Fresh beef	kg	15
Fresh lamb	kg	10
Fresh poultry	kg	6
Cereals	kg	1.5
Citrus fruits	kg	1
Palm oils	kg	2
Pulses, roots, and tubers	kg	1

Source: Adapted from *Finley and Seiber* [2014].

More energy is consumed in producing, transporting, processing, handling, storing, and preparing food (Table 13.2).

Certain foods, particularly animal products, require even more energy than others. For example, producing the 43 million tons of meat, poultry, and fish that Americans consumed in 2004 required approximately 800 TJ of energy (1 TJ = 1×10^{12} J), whereas only 75 TJ was needed to supply 74 million tons of grains [*Cuéllar and Webber*, 2010]. Food is also a water-intensive resource, and there is a strong nexus between food and water consumption. According to a study [*Hoekstra and Mekonnen*, 2012], 92% of the annual global water footprint is attributable to agriculture. Therefore, any discarded food is directly attributable to wasted water. The fraction of wasted food has increased more recently due to factors such as urbanization, increasing consumer choice, increasing affluence, smaller household sizes, and consumer preferences for more perishable foods [*Kantor et al.*, 1997]. Approximately 2.5% of the U.S. energy budget is "thrown away" annually as food waste. This is equivalent to the energy contained in hundreds of millions of barrels of oil. In addition, about 25% of all freshwater consumed annually in the United States is associated with discarded food; globally such waste consumes as much water as in Lake Erie.

Innovative research and technologies that use energy- and water-efficient production to produce food need to be given high consideration. Focus should also be given to improve food, energy, and water efficiency by reducing food waste. Wasted food not only does no good from a nutritional point of view, but also requires energy to dispose of it. Table 13.3 summarizes estimated food wasted in the United States. Clearly, reducing waste will ultimately improve sustainability and total food supply. However, we need to consider the entire food system, including the consumption and use of animals and the inherent inefficiencies of current animal food production [*Breckel et al.*, 2012].

Per capita food waste in the United States has increased by 50% since 1974 [*Hall et al.*, 2009]. In 2010, discarded food represented the single largest component of the municipal solid waste stream reaching landfills and incinerators; less than 3% of that waste was recovered and recycled as compost [*USEPA*, 2017]. This component of garbage represents a significant cost to local governments (and ultimately taxpayers who already paid for it once as consumers), which is why many municipalities like the City of Santa Monica, California, and Charleston County, South Carolina, are adopting food waste collection and composting programs [*Hanlon et al.*, 2013]. Given the water- and energy-intensive nature of growing, processing, packaging, warehousing, transporting, and preparing food, it follows that wasted food means wasted water, energy, and agricultural resources [*Levis and Barlaz*, 2011].

Considerable amounts of energy and water are associated with discarded food.

Food waste has significant ecological consequences. If we did a better job of meeting demand by capturing food that currently gets discarded, a significant amount of land conversion from forests, grasslands, and wetlands to agriculture might be avoided and, subsequently, we could potentially reduce our adverse impact on biodiversity. We could also decrease pesticide and fertilizer runoff and their negative ecological and water quality impacts if fewer total acres of farming are required. At the disposal end, nearly all food waste ends up in landfills, allowing it to decompose and release methane, a greenhouse gas that traps 21 times more heat than carbon dioxide. Food waste is particularly egregious at a time when hunger is a growing problem and an increasing human rights issue [*Parfitt et al.*, 2010].

The solution is a combination of radically reducing food waste at its source while ensuring that what gets wasted becomes a resource, not trash. One opportunity is to reconnect the whole supply chain from farm to table and table to farm by composting food waste and using it as fertilizer to grow crops [*Hanlon et al.*, 2013]. Significant reductions in food waste can often be achieved through simple changes in food purchasing, storage, and preparation. Using "unavoidable" food waste as a resource involves diverting it from landfills and utilizing it to generate energy or create fertilizer from compost. Increasing the efficiency of our food system is truly a triple-bottom-line solution. It offers the environmental benefits of efficient resource use, the financial benefits of cost savings, and the social benefits of alleviating hunger through food donations. The complexity of the problem and the wide and varied set of potential remedies mean that everyone can be part of the solution.

Table 13.3 Food wasted in the United States

Food group	Percentage wasted
Grains	32
Vegetables	25
Fruit	23
Tree nuts, peanuts	16
Dairy	33
Meat, poultry, fish	16
Eggs	31

Source: *Finley and Seiber* [2014]. Reproduced with permission of American Chemical Society.

13.3. KNOWING THE NEXUS

The concept of the WEF nexus continues to grow with expanding boundaries. Because of the intricate linkages among the WEF systems and their external resource and ecological environments, the nexus system could now even be presented with additional dimensions such as water-energy-land-food, water-energy-climate-food, and ecosystem-water-food-energy linkages. The nexus is now a part of everyday life: from food consumers to industrial plant managers. With many challenges facing our strained water, energy, and food systems in the United States, a shift in thinking is necessary to understand that what we do every day affects the nexus and the nexus, in turn, affects our everyday life. A reliable supply of water, energy, and food is one of the most important global challenges of the present time and the future, and knowing the WEF nexus will help address this intricate system in a better way. There are many WEF nexus issues that we know and many that we are not aware of. The following are some examples of what we know and what we do not know.

What we know:

1. Most modern societies rely upon intensive natural resource use.

2. The nexus is comprised of water, energy, and food systems that rely upon each other to function and therefore greatly impact each other.

3. Freshwater resources cannot always meet the water demands of agriculture, energy generation, public drinking water, and industry.

4. As conventional fossil fuel reserves diminish, fuel becomes more costly in terms of price and environmental impact due to greater reliance on harder-to-reach unconventional sources accessed through deep-water oil drilling or hydraulic fracturing.

What we don't know:

1. We have a poor understanding of where, when, and how much water is used. Water use data exist but are not coherently stored and managed.

2. We do not have a clear picture of the quantity and quality of the nation's groundwater.

3. We are not effectively monitoring the condition, or coordinating the management, of food, water, and energy systems.

4. We do not have a good understanding of the true economic costs of environmental degradation, habitat destruction, and overuse of natural resource as the associated costs are excluded from the price of goods and services [*DOE*, 2014].

The nexus approach to evaluating food, water, and energy systems is meant to ensure that natural resources are used efficiently and produced enough to be available for future generations. The sustainability of water, energy, and food could be attained only through the linkage of these three resources. Adopting the nexus approach in a large-scale, system-wide manner may be challenging because we have limited knowledge of how food, water, and energy systems operate and interact. Government policy, especially at the federal level, must set the stage by improving data monitoring and gathering programs, getting rid of isolated resource management programs, and illuminating how these systems and processes overlap through reports and studies. Otherwise, a policy relevant to a single resource might actually end up having a negative impact on the rest of the food, water, and energy system. These steps must be combined with sensible policies and regulations that encourage cooperation between individual citizens, governments, and businesses so that all decisions are seen as sustainable and legitimate.

To achieve robust WEF nexus quantifications, the directions for future research endeavors include key indicator identification and comprehensive sustainability scope definition, establishing multilevel and technology-specific WEF footprints databases, synthesizing bottom-up and top-down approaches, and developing an integrated and flexible analytical framework with spatial- and temporal-specific constraints consideration.

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14

WEF Nexus Cases from California with Climate Change Implication

Qinqin Liu

ABSTRACT

The water, energy, and food (WEF) nexus has complex linkages that are related to climate change (CC) and resource management practices. CC creates critical challenges in sustainability and security of water, energy, and food for integrated water management. The overall objectives of this chapter are to summarize WEF nexus cases from California with CC implications and to identify related information gaps for multidisciplinary research needs to address these challenges. These case studies indicate CC has direct or indirect effects on sustainability and security of water, energy, and food. There is a large variation in energy intensities for groundwater and federal, state, and local water supplies, both within each hydrological region and among the ten hydrological regions in California. Regional decisions were critically important to address water-energy conflicts and to meet local CC challenges. These examples can be applicable for the United States and other countries to use the diversity of regional water resources for energy and food production with the similar CC challenges. Future interdisciplinary research and support could bridge information and data gaps that are important for using best management practices to obtain efficiency of water, energy, and food systems related to CC.

14.1. INTRODUCTION

The water, energy, and food (WEF) nexus has physical linkages that are very complex, including water resources for food and energy production cycles, and the energy demand of the water cycle for transport and treatment, and end uses [*Taniguchi et al.*, 2013; *Jablonski et al.*, 2015; *Liu*, 2014, 2016]. Climate change (CC) can impact sustainability and security of water, energy, and food resources at both the regional and global scales. Actions in one sector can have impacts on the others. Better understanding of the WEF nexus with CC implication is critical in addressing the increasing demand for freshwater, energy, and food in the context of increasing stresses from CC, population growth, and urbanization. This understanding will also help those who devise strategies for integrated management of the resources to obtain multiple benefits, evaluate trade-offs, and balance goals and interests to adapt and mitigate against CC.

Research in the WEF nexus with CC implications is limited [*WEF*, 2011], but case studies have explored factors affecting nexus components, including CC and competition for water, energy, and land in the future of the global food system [*Biggsa et al.*, 2015; *Godfray et al.*, 2010; *Vogt et al.*, 2010]. Other studies have implicated CC as a global driver impacting ecosystem sustainability related to WEF nexus issues [*Barnosky et al.*, 2013; *Taniguchi et al.*, 2013; *Jablonski et al.*, 2015; *Liu*, 2014, 2016; *Rasul*, 2014]. Recent regional studies in California have addressed the WEF nexus issues, including aspects of sustainable agriculture irrigation management and groundwater vulnerability [*Gurdak et al.*, 2016; *Wada et al.*, 2016]. Another study has analyzed the diversity of water, energy, and food sources

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that is important for the Asia Pacific region and global security and sustainability [*Taniguchi et al.*, 2015].

The Climate Change Program at the California Department of Water Resources (DWR) has also begun to fill energy intensity data gaps for the state water supplies. A regional approach was used to estimate the energy intensity required for the extraction and conveyance of water in 10 hydrological regions in California. These case studies provide good examples of water and energy relationships and CC in California [*CWPU*, 2013; *California Department of Water Resources*, 2015a], which are critical for public decision making about sustainable water supply choices for agricultural food production, energy generation, and urban consumption. This chapter summarizes WEF nexus cases from California with CC implication and identifies knowledge and information gaps as well as challenges and research needs. These studies and findings can be useful for the practical applications to better use diversity of regional water resources for energy and food production in the United States and other countries with similar climate and hydrological conditions.

14.2. NEXUS COMPONENTS WITH CLIMATE CHANGE IMPLICATION

CC projections for California include warmer air temperatures, diminishing snowpack, precipitation uncertainty, increased evaporation, prolonged droughts, and sea level rise [*IPCC*, 2014]. CC affects water, energy, and food. In terms of water, it impacts on the quantity, quality, and timing of water supply for energy and food production. For example, CC can lead to a reduction of available water for energy generation, for food production, and for urban, industrial, and environmental sectors. Projected changes in climate and impacts in California include the following [*Third Assessment of California Climate Change Report*, 2012; *CWPU*, 2013]:

1. Increase in average temperature ranged 4–9°F by the year 2100
2. Loss of snowpack with 48–65% loss in snow water content by the end of this century
3. Drought with more dry years and less water, affecting food, energy, and the environment
4. More frequent flooding and fire, reducing water quality in watersheds
5. Rising sea levels
6. Increasing energy demand
7. Changes in species and habitats

These changes have direct or indirect effects on sustainability and security of water, energy, and food. Limited land resources and infrastructure for energy supply, and growing water stress bring more challenges for providing water and energy to grow enough food for increasing populations. The United States particularly depends highly on California for food supply, especially during the winter. The California Global Warming Solutions Act of 2006 (Assembly Bill 32 (AB 32)) created a comprehensive multiyear program to reduce greenhouse gas (GHG) emissions in water, food, energy, and other sectors. The *AB 32 Scoping Plan* [2014] provides multisector approaches for California to reduce GHGs to achieve the goal of reducing emissions with defined targets in 2020 and 2030. California CC actions provide examples on how to address these challenges in the water, energy, food, and environmental sectors. Many of the GHG reduction measures have been adopted in California's water, energy, food, and environment sectors. For example, the *California Water Action Plan* [2014] established strategies and a roadmap for water resource reliability, ecosystem restoration, and resilience to cope with CC challenges. The Water Conservation Act (Senate Bill X7-7) established a requirement for a 20% reduction in urban per capita water use in California by 31 December 2020. Water and energy saving could help to reduce GHG emissions from water and energy uses for food production and processes. Integrated water management approaches are used to address CC impacts on water, energy, food, and the environment. Resource management strategies (RMS) have been evaluated for their relationship to CC, water, and energy in urban and agricultural management as well as other resources [*CWPU*, 2013; *California Department of Water Resources*, 2017]. The following section provides specific information on related nexus cases from California with CC implications including quantification of GHG emissions from the energy uses in the water sector.

14.3. WATER-ENERGY NEXUS IN CALIFORNIA

14.3.1. Water-Energy Nexus with Climate Change Implications

A major source of GHG emissions from the water sector in California comes from energy uses. Water systems need energy just as energy generation requires water. Energy is used throughout the water cycle for extracting, conveying/transporting, storing, treating, distributing, end uses, and treating and disposing used water. For example, supplying water, treatment of wastewater and storm water, and disposal of sewage all require energy. Drinking water must be pumped into the treatment plant, pretreated, and then pumped to consumers. In areas where freshwater is scarce, drinking water may need to be brought in from a long distance and over a high elevation, creating high energy intensity. Water and energy, therefore, have a complex relationship containing multiple interdependencies, sometimes referred to as the "water-energy nexus" [*Kenney and Wilkinson*, 2011; *CWPU*, 2013]. Understanding the nexus is crucial for decision making, and can assist resource managers in improving system efficiency with limited water and energy supplies to meet increasing future demands under CC impacts. The water-energy nexus is related to CC as reducing energy intensity from energy and water uses helps minimize GHG emissions. The energy intensity of water is defined as "the total amount of energy required for the use of a given amount of water in a specific location, calculated on a whole-system basis" [*CWPU*, 2013; *California Department of Water Resources*, 2017]. However, the water-energy nexus in the water cycle may be different in other states where water conveying/transporting may not be necessary. Specific information on water-related energy use in California is presented in Figure 14.3 in Section 14.3.3, including electricity, natural gas, and crude oil consumption.

Figure 14.1 California water systems in each hydrological region. Source: *California Department of Water Resources* [2015a].

GHG emissions in the water sector are closely correlated to how much fossil energy is used. More fossil energy used in the water sector could lead to higher energy intensity and increased GHG emissions. Strategies to reduce GHG emissions are primarily focused on reducing the amount of electricity and natural gas used within the sector. The most current available data and information to estimate electricity (Giga-Watt-hours) used in California's water sector, and related GHG emissions are expressed in million metric tons of carbon dioxide-equivalent ($MMTCO_2$-e). Table 14.1 shows the water sector used 56,871 GWh electricity, which is about 19.2% of the total state electricity consumption of 296,203 GWh [*CEC*, 2005]. The GHG emissions from this electricity use in the water sector are estimated to be 17.4 $MMTCO_2$-e. Electricity (37,452 GWh) used for urban water is much higher than the electricity (10,560 GWh) used for agricultural water. The energy intensity (4.16 MWh/AF) from urban water is higher compared with energy intensity (0.32 MWh/AF) in the agriculture water since urban water uses much more energy for conveying/transporting, treatment of wastewater, and end uses. GHG emissions (11.4 $MMTCO_2$-e) from energy used in urban water are three times higher than GHG emissions (3.4 $MMTCO_2$-e) from energy used in agriculture water. The electricity saving is estimated as 7488 GWh from 20% urban water reduction with SBX7-7 water conservation implementation, and associated 2.29 $MMTCO_2$-e GHG emission reduction is estimated from this electricity saving. GHG emissions can be reduced from urban water and energy saving in CC mitigation efforts from food processes and other urban- and industrial-based water use efficiency, recycling, and conservation programs.

It is also important to know how the other side of the water-energy nexus relates to the amount of water used in producing energy, including water used (i) in the energy sector for extraction of natural gas and other fuels; (ii) as the working fluid for hydropower; (iii) as the working and cooling fluid in thermal generation systems (coal, natural gas, geothermal, nuclear); and (iv) in the cultivation of biofuels, assuming little water is used in wind power. CC will affect water supply for energy production and the water-energy relationship including in-state hydropower, agricultural groundwater, and urban water uses [*CWPU*, 2013; *California Department of Water Resources*, 2015b]. As water demand grows, energy demand may increase concurrently. Meanwhile, increasing temperatures from CC will likely boost energy demand for cooling in summer and water demand for energy and food production. Population growth drives demand for water, energy, and

Table 14.1 Electricity uses and related GHG emission in California water sector

	Electricity use	Related GHG emission
Electricity category	Gig-Watt-hours (GWh)	Million metric tons of carbon dioxide equivalent ($MMTCO_2$-e)
Total electricity generation plus net imports[a]	296,203	90.45
Electricity used in water sector[b]	56,871	17.4
Electricity used in urban water[c]	37,452	11.4
Electricity used in agricultural water[c]	10,560	3.4
Electricity saving from SBX7-7 implementation in 20% urban water reduction[d]	7,488	2.29 (GHG emission reduction)

The quantification is based on most current available data and information (such as electricity use, although not all pumps in California run by electricity; we still lack current data on diesel or natural gas uses)

[a] Total electricity generation plus net imports was 296,203 GWh, related GHG emission was 90.45 $MMTCO_2$-e, and the statewide GHG emission factor in 2013 was estimated as 0.3054 $MTCO_2$-e/MWh from the following data sources:

(i) http://www.ecdms.energy.ca.gov/

(ii) https://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_sector_sum_2000-14.pdf

[b] The California water sector took 19.2% of the total electricity consumption in the state [*CEC*, 2005], related GHG emission was about 17.4 $MMTCO_2$-e with the GHG emission factor of 0.3054 $MTCO_2$-e/MWh.

[c] Based on the CEC study [2005], the electricity consumptions in 2001 was 37,452 GWh (urban water) and 10,560 GWh (agricultural water) and related GHG emissions were estimated using the GHG emission factor of 0.3054 $MTCO_2$-e/MWh.

[d] (i) The average annual water uses (1998–2010) in the state were about 9 MAF in the urban sector and 33 MAF in the agricultural sector, respectively [*CWP*, 2010]; the water conservation actions could help to reduce future water uses in both sectors, combing the water data with the earlier electricity data (see note c); the energy intensities were estimated as 4.16 MWh/AF for urban and 0.32 MWh/AF for agriculture, respectively.

(ii) SBX7-7 required the urban water use reduction per capita by 20% statewide by the year 2020, or a statewide urban water use reduction by 1.8 MAF based on the previous average annual urban water uses [*CWP*, 2010]. Using the urban energy intensity obtained, the electricity saving is 7488 GWh, and related GHG emission reduction is 2.29 $MMTCO_2$-e with the emission factor 0.3054 $MTCO_2$-e/MWh.

food resources. Increased water use efficiency and development of local water sources are important to offset these trends, and reduce overall water and energy demand as well as GHG emissions for CC adaptation and mitigation.

There are also conflicts and trade-offs between water and energy for food production related to CC. For example, quantity of agricultural water use may be in conflict with related energy use for energy intensity value in California. Figure 14.2 indicates that the amount of agricultural water (33 MAF) used for food production was greater than urban water use (9 MAF). Conversely, the energy intensity (0.32 MWh/AF) in agricultural water was much lower than energy intensity (4.16 MWh/AF) for urban water. Agricultural surface irrigation used more water with gravity flow for crop production, which may contribute to low energy intensity with low GHG emissions (Table 14.1) for agricultural water in California. CC adaptation response to meet future water demand in agriculture for food production could increase energy use to obtain or save more water as a trade-off between water and energy, including pressurization from drip irrigation for water saving and groundwater pumping for more water. Drip irrigation may help achieve water conservation by reducing evaporation, and water can be more precisely applied to the plant roots or onto the root zone. Installing drip irrigation to save water could use more energy due to pressurized irrigation systems that need energy to produce the required pressure in a network of valves, pipes, tubing, and emitters. Increased energy use can conflict with CC mitigation goals. Coordination of adaptation and mitigation efforts is important to manage CC risks for water-energy-food security, which can be overlapping, complementary, or conflicting. A coordinated effort could be to use renewable energy, along with best agricultural management practices using recycled water and the most suitable drip irrigation systems for land topography, soil, water, crop, and agro-climatic conditions to address the water-energy conflict and trade-off related to CC for food production.

14.3.2. Water Systems in California

Water in California is managed at the federal, state, and local levels. These systems manage over 40,000,000 acre-feet of water per year, serving over 30 million people and irrigating nearly 6 million acres of farmland [*California Department of Water Resources*, 2015a]. Because of California's seasonal and geographical precipitation patterns, large interannual precipitation variability, and geographical distribution of population, storage, and conveyance of water play a major role in California's water management. Several inter-basin water transfer projects have been set up in California by the federal government, state government, and local water agencies. These systems capture and store winter precipitation and spring runoff from the Sierra Nevada Mountains and convey it through natural river channels, aqueducts, and pipelines to cities and farms throughout the state. Hundreds of smaller projects owned and operated by local water agencies and irrigation districts capture, store, and convey water from local streams, rivers, and lakes to customers.

Along with California's large inter-basin transfer projects and small local surface water projects, millions of acre-feet of groundwater are also used to meet the water demands in California. Groundwater makes up between 30 and 60% of annual water supplies and serves as a critical source of water in dry years when surface water resources are scarce. For example, in 2014, California's agriculture pumped 5 million acre-feet of groundwater to make up for 6 million acre-feet in surface water reductions in

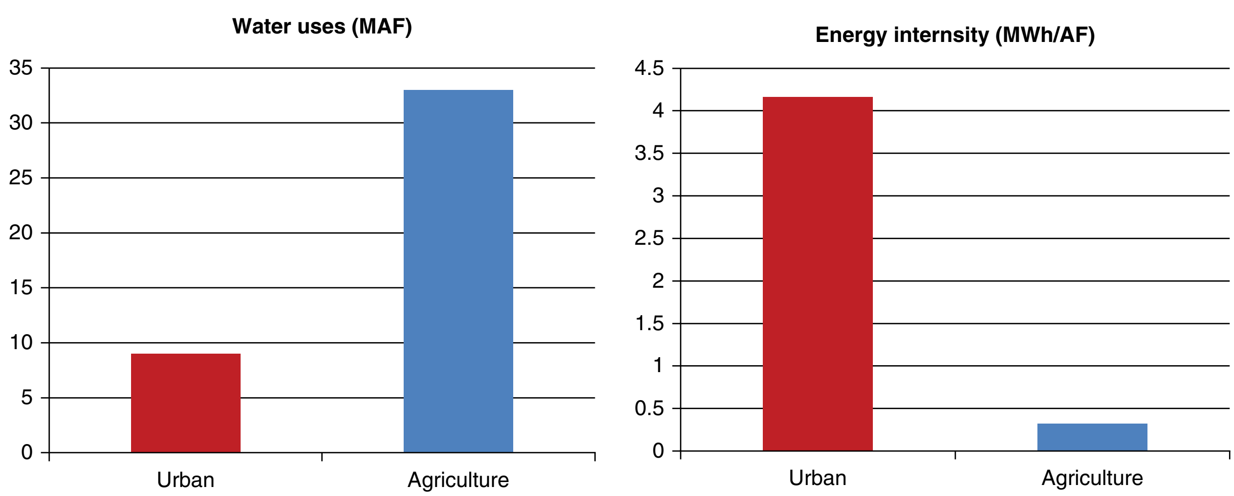


Figure 14.2 California urban and agricultural water uses and related energy intensities. Source: Data from *CWP* [2010] and *CEC* [2005].

response to the drought [*California Department of Water Resources*, 2017]. Figure 14.1 shows California's diverse set of local, state, and federal water projects superimposed over the state's hydrologic regions, providing context for the regional energy intensity figures in the following section.

14.3.3. Distribution of Energy Use in California's Water Sector

The extraction, conveyance, storage, treatment, distribution, and use of water, and subsequent collection, treatment, and disposal of wastewater can be very energy intensive. The energy required to heat water for end users is particularly large, as it includes fuel oil, propane, electricity, or natural gas. According to the *CEC* [2005] and *CWPU* [2013], this water-related energy consumes approximately 19% of the state's electricity and 32% of statewide natural gas (non-power generation). Approximately 75% of the water sector's electricity consumption is by end users, including water heating and cooling, advanced treatment by industrial users, and on-site pumping and pressurization for irrigation and other purposes. The other 25% (approximately) of electricity consumption within the water sector occurs in drinking water and wastewater system operations, including water extraction and conveyance, drinking water treatment and distribution, and wastewater collection and treatment. Figure 14.3 depicts this water-related energy use in California, including electricity, natural gas, and crude oil consumption [*CEC*, 2005; *CWPU*, 2013; *CPUC*, 2010a, 2010b].

The methodology used to evaluate energy uses in this water-energy pie chart (Figure 14.3) includes estimates of distribution of energy in California according to its energy balance update and decomposition analysis for industry and building sectors [*CEC*, 2013]. About half of all energy use is derived from the burning of crude oil and its derivatives such as gasoline. The other half is divided between natural gas and electricity. The detailed section pulled out of the state-wide energy usage shows the percentage of each type of energy expended in uses related to water. This information comes from the 2005 Integrated Energy Policy Report [*CEC*, 2005]. The detailed information on this methodology has been discussed in related documents [*California Department of Water Resources*, 2017].

14.3.4. Energy Intensity Range in California's Water Cycle

The energy intensity range measured in kWh/million gallons (MG) in California's water use cycle [*CEC*, 2005; *CPUC*, 2011] is shown in Table 14.2. Different water quality needs may have different energy requirements for treatment, just as different water sources may require different treatment intensities. Generally, treatment of water that is either high in salinity (such as seawater) or produced from some oil or gas operations, or that contains large amounts of organic material, such as municipal wastewater, has relatively high energy requirements. Pumping also has a range of possible energy intensities, depending on the circumstance. The quantity of energy required for pumping primarily relates to elevation of the water being pumped. Table 14.2 shows that the energy intensity range (kWh/MG) related to water treatment and distribution is not regionally specific. Inter-basin transfer could be an order of magnitude higher in energy intensity than local surface water distribution or groundwater pumping, and a very high amount of treatment energy is used for desalination. Evaluation of the energy

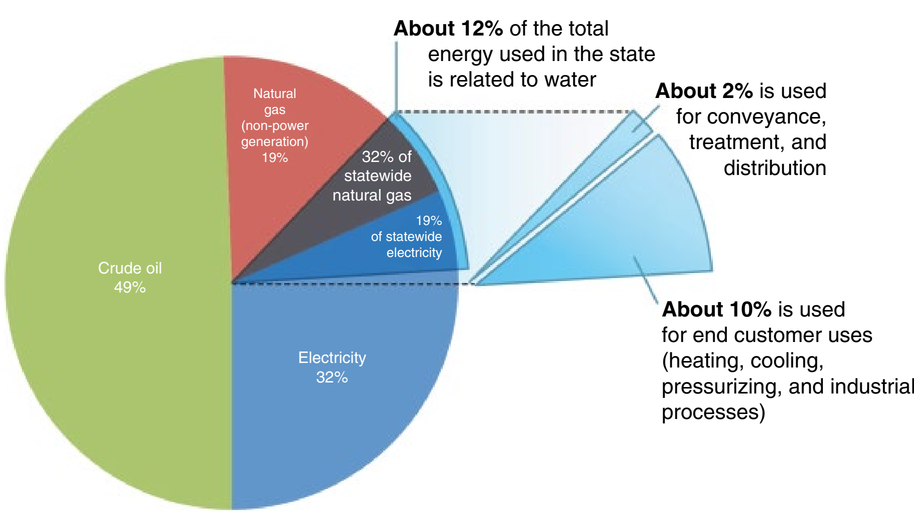


Figure 14.3 Energy use related to water in California water system. Source: *CWPU* [2013].

Table 14.2 Summary of energy intensity range (kWh/MG) in California water cycle

Water cycle	Energy intensity range (low to high)	Reference
Pumping/water conveyance	0–14,000[a]	*CEC* [2005]
Pumping/drinking water distribution	700–1,200	*CEC* [2005]
Treatment/drinking water	100–16,000[b]	*CEC* [2005]
Treatment and distribution/wastewater	1,100–4,600	*CEC* [2005]
Pumping/recycled water distribution	400–1,200	*CEC* [2005]
Pumping/agricultural ground water extraction	500–1,500[c]	*CPUC* [2011]

[a] Pumping energy used for water conveyance: 0 for gravity fed and high for State Water Project.
[b] Treatment energy used for drinking water: high for desalination.
[c] Pumping energy used for agricultural ground water extraction: low for North CA coast and high for CO River Basin.

required for water pumping and treatment processes in California's water system is useful for any decision making regarding saving water and energy, using renewable energy, and reducing GHG emissions.

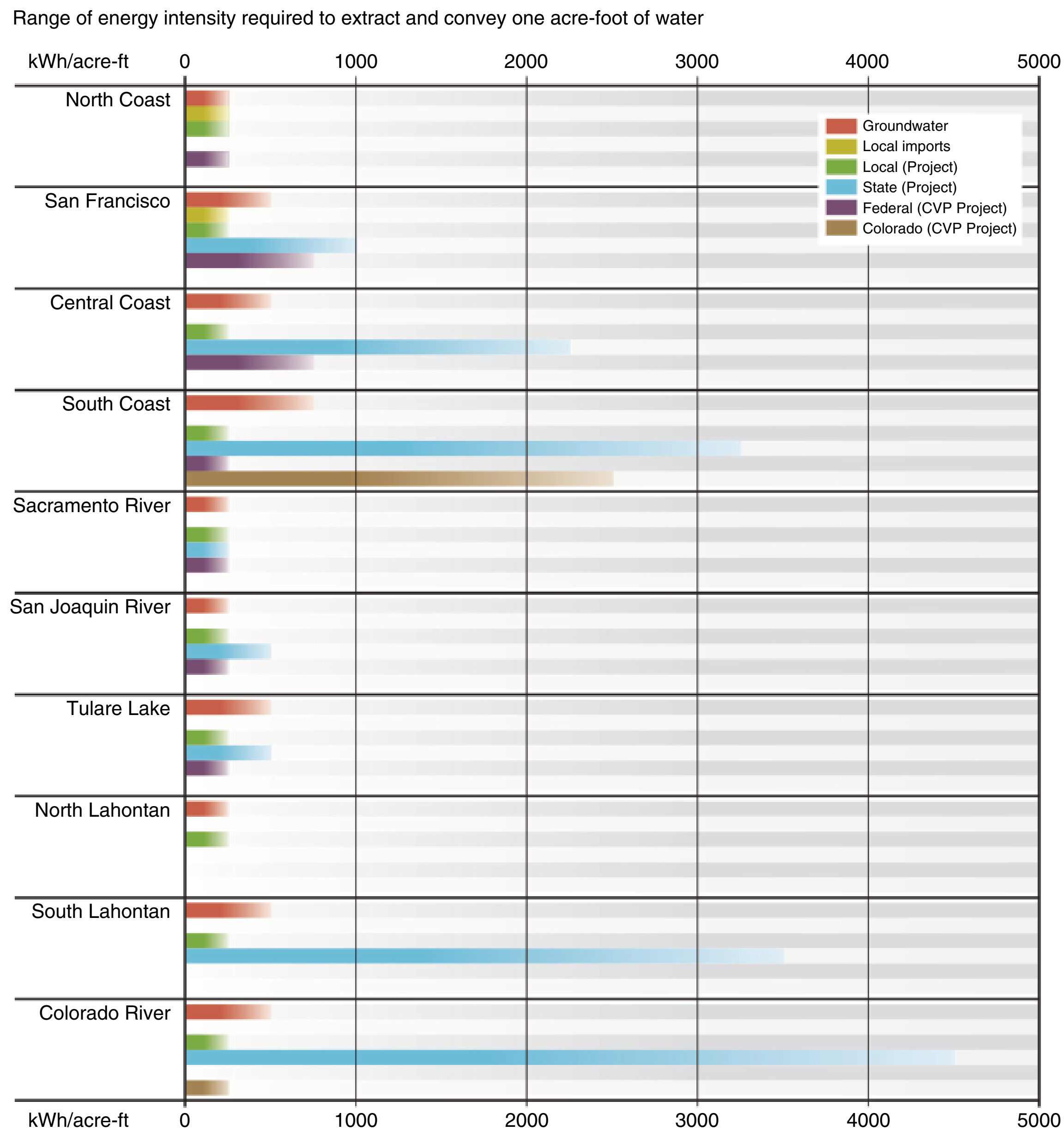
14.3.5. Energy Intensity of Regional Water Supply

Energy intensity at the regional scale (Figure 14.4) was estimated in the 10 hydrological regions shown on the California water system map (Figure 14.1) using a methodology described in *CWPU* [2013], Volume 5, Technical Guide, and with data from numerous sources [*California Department of Water Resources*, 2017]. These values in the figure reflect only the amount of energy needed to move water from a supply source to a centralized delivery location, not to the point of use. The approximate energy intensities were estimated for different types of water supplies (e.g., groundwater, and supplies from federal, state, and local agencies). The results showed a large variation in energy intensities for groundwater and federal, state, and local water supplies, both within each hydrological region and among the ten hydrological regions in California. For example, the South Coast region has relatively high energy intensity from the State Water Project supply compared with other regions; the energy intensities for local water projects are relatively low compared with other water supplies in this region. The results indicated regional decisions were critically important for addressing water-energy conflicts and meeting local CC challenges, including drought, multiple benefits in saving water and energy, a reduced carbon footprint, and better water quality and habitat values.

The energy intensity comparisons based on the hydrological regions provide local planners with an estimate of the energy required to extract and convey various types of water supply. The regional energy intensity of water varies greatly depending on the water source, conveyance method and efficiency, regional topography, and delivery location. Water in Northern California tends to have lower energy requirements due to less pumped imported water being needed when compared with the drier though more populous and agricultural southern portion of the state. Generally, the further water travels from Northern to Southern California through high elevation, the more energy is needed (with the exception of groundwater, which could require large amounts of energy to travel only several hundred feet to the surface). However, the regional energy intensity estimates do not show energy used in the other parts of the water cycle (e.g., energy for water treatment, distribution, and end use) due to incomplete data. For detailed evaluations at a project level, energy intensity can be gained by using other tools, which would allow water managers to model their water systems and simulate outcomes for energy, GHGs, and other metrics of water supply information [*Cooley et al.*, 2012].

These regional energy intensity values can be an effective tool for cost-effective investment plans for regional water and energy efficiency programs. Such a tool could be useful for regional water supply portfolio management including utilizing water from various sources, such as the State Water Project (SWP), groundwater, local water projects, and transfers or exchange agreements. When making water management choices, the energy intensity of individual supplies should be a part of the decision-making process in portfolio management. However, for each water source in the portfolio, there should be considerations of several factors such as water quality, environmental impacts, energy requirements, reliability, costs, CC impacts, and others.

Understanding the energy intensity of the water supply at a regional scale will enable local planners to make decisions on energy use related to their water supply options. It could help evaluate how much energy could be saved by water conservation and/or water use efficiency measures, perhaps showing the possible benefits of reducing water demands and GHGs. It can also help better inform public decision making on water, energy, and food choice issues so that limited natural resources are used efficiently with regard to saving energy, thereby reducing GHG emissions and meeting future demands. In some cases, the energy intensity information may help address water-energy conflicts in places with similar climatic conditions like the states in the American West.



Energy intensity in this figure is the estimated range of energy required to move one acre-foot (af) of water from the supply source to a centralized delivery point. All water sources are presumed to have a minimum energy intensity greater than zero, but not all water sources in a region may be listed. The goal of this figure is to provide a general idea of the energy required to deliver water to a particular region to aid water managers who wish to include energy intensity as a factor in their management decisions. The regional energy intensity compiled in this figure is provided in the *California Water Plan, Update* 2013, *Volume* 2, *Regional Reports* and in the Water-Energy Nexus. For detailed descriptions of the methodology used to calculate energy intensity in this figure,see the *California Water Plan, Update* 2013, *Volume* 5, *Technical Guide, Energy-Intensity of Regional Water Supplies.*

Figure 14.4 Estimated regional energy intensity range for hydrological regions in California. Source: *CWPU* [2013]. (*See insert for color representation of the figure.*)

14.3.6. Drought Impacts on the Nexus Components in California

Droughts significantly affect water supply for energy and food production, including reduced delivery of water and less hydropower generation from surface water projects in dry and critical years. Many groundwater basins in California have been over-pumped for the last few decades, especially during drought years. This not only threatens California's water supply resources in the future but has also brought many other negative impacts, such as land subsidence, groundwater level decline, water quality deterioration, aquifer capacity reduction, and foundation damage to infrastructures such as houses, buildings, streets, highways, aqueducts, and others. Another result of groundwater is the increased energy consumption as well water must be pumped from ever-increasing depths, which could also increase GHG emissions.

California's current multiyear drought since 2012 has had significant effects on the food and agricultural industry [*California Department of Water Resources*, 2015b]. More than 400,000 acres of farmland have been fallowed by farmers in response to the drought and other factors. Crop, dairy, and livestock revenue losses, plus the additional costs of groundwater pumping, have incurred a total direct cost to agriculture of approximately $1.5 billion, with the majority of these losses occurring in the San Joaquin Valley. Potentially, even greater economic losses may be incurred at the regional and state levels if the drought continues [*California Department of Water Resources*, 2017].

If groundwater pumping continues at its present rate or increases, water tables will continue to drop, which will increase pumping and energy costs and land subsidence. While droughts are a natural part of California's environment, CC exacerbates drought conditions as increasing temperatures drive up water demand, and droughts may become longer, more intense, and/or more frequent [*California Department of Water Resources*, 2015b, 2017]. Current drought conditions highlight the importance of sustainable groundwater management for California's reliance on groundwater for food production. California agriculture continues to adapt the current drought challenges by efficient irrigation practices and water conservation measures. The energy consumption and GHG emissions related to groundwater pumping have drawn attention recently. Complex information is essential to estimate the total energy consumption and GHG emissions, including the groundwater volumes, the total dynamic heads (TDH) in wells, and the pump efficiency. Integrated water management is used to address multiyear drought issues, including urban water management plans, agricultural water management plans, the California Statewide Groundwater Elevation Monitoring, and the Sustainable Groundwater Management Act programs with groundwater sustainability plans based on a regional scale.

14.4. INFORMATION GAPS AND RESEARCH NEEDS

Understanding the WEF nexus with CC implication is vital to inform decision making and to develop resource management strategies in order to use limited water and energy supplies efficiently for meeting increasing food demands. The complex and dynamic nexus links between these sectors should be kept in mind when making resource and planning decisions. Understanding the water-energy nexus used in our food systems also requires consideration of complicated interlinks. Every step in the food system requires tapping into the water-energy nexus, such as the water needed to grow, process, and transport the hundreds of specialty or commodity crops in California and the world. Dairy and livestock industries face similar energy needs and even greater water needs. Meat and dairy products account for more than 40% of California's consumed water, mostly from growing feed [*Fulton et al.*, 2012] and the energy used during milking, cooling, feeding, watering, and cleaning animals.

There are limited research and data on California agricultural water use [*Cooley*, 2015; Department of Water Resources, http://www.water.ca.gov/landwateruse/]. The Department of Water Resources developed agricultural water use models to estimate crop evapotranspiration, evapotranspiration of applied water, and applied water for 20 crop categories in California each year. As for the irrigated crop, acreages are estimated from the Department of Water Resources Crop Survey and reports of California's County Agricultural Commissioner, and are used as inputs in the models (http://www.water.ca.gov/landwateruse/models.cfm). Applied water is used to estimate water demand of agricultural crops, which is applied over the land surface by various application techniques to meet individual crop water requirements. There are large variations for applied water uses in different crops ranging from the lowest for potato, fresh tomato, safflower, sugar beet with 0.1 million acre-feet to the highest for alfalfa with 5.2 million acre-feet [*Cooley*, 2015]. The water intensity is also evaluated for the function of plant water requirements under weather conditions, including crops that may need less water under cool, wet conditions and more water under hot, dry conditions. For example, rice is the most water-intensive crop with the highest water intensity and safflower is the least water-intensive crop with the lowest water intensity. However, only limited study reported energy intensity of agriculture and food systems in developing countries [*Pelletier et al.*, 2011]. Lack of research and data for energy intensity in California's agricultural crops makes it very difficult to quantify the related WEF nexus at this point.

Often it is difficult to get a clear picture of the true cost of water and energy for food systems because of the complex production and process in the food life cycle that are broken up categorically with water, energy, and transportation, all being considered separate and unassociated with each other. The food life cycle (from "farm to fork") includes complex processes in food production, processing, distribution, marketing, consumption, and waste disposal. Water and energy are used for growing and harvesting crops, processing food in the food industry, food distribution (including imported food consumed by

Californians and food export outside of California) and marketing (including restaurants and grocery stores), food consumption, and food waste disposal. There is limited research in California linking food production to water and energy saving. For example, water-energy nexus assessments have been completed at a Campbell's Soup tomato-processing facility. This study has identified sustainability opportunities to improve energy and operational efficiency using combined heat and power as well as hot water conservation. Related environmental and economic benefits were also evaluated, including reduced energy costs, conserved groundwater resources, and reduced GHG emissions and wastewater discharge [*Amón et al.*, 2012]. Research information gaps still need to be addressed to determine water and energy implications of our food, and every associated cost within the food production and process in the complex life cycle. These information gaps and research needs are identified in Table 14.3.

End users are critical to the food life cycle process where a huge portion of water and energy is consumed. Consumers use energy and water to wash and cook food at home, restaurants, and other food facilities. Hot water uses have higher energy needs in relation to other food processes. Finally, one of the most forgotten portions in this cycle is the energy and water used in waste and disposal of food. Food waste must be collected and processed for disposal. Understanding the true costs of water-energy in our food should also make us acknowledge it is important to create food systems that are more efficient, but also the wasting of food is the wasting of all the resources used to produce those items.

It is critical to identify information gaps in models, data, and tools for completing integrated assessments. Bridging these gaps is essential to assess the water-energy-food nexus related to CC for integrated water management. There are limited assessments with integrated research to study the complex dynamics and the connections between CC, water, energy, and land/food related to agriculture [*Skaggs et al.*, 2012]. Different interdisciplinary approaches have been designed to begin assessing the WEF nexus in case studies among 32 Asia-Pacific countries [*Taniguchi et al.*, 2013]. Qualitative and quantitative methods and tools have been developed to address the WEF nexus using interdisciplinary and transdisciplinary research approaches [*Endo et al.*, 2015]. Data and model systems can improve our understanding of the interactions between CC, water, energy, food, and ecosystems, leading to better informed decision making. Application of integrated models could help quantify the relationships and trade-offs among a comprehensive set of WEF components. For example, two of California's water-energy modeling platforms are interlinked in order to quantify the water-energy relationships and trade-offs by using the Water Evaluation and Planning (WEAP) and the Long-Range Energy Alternatives Planning (LEAP) software [*Stockholm Environment Institute*, 2012]. Related GHG emission from energy use can also be evaluated in these integrated modeling platforms. Water and electricity elements are represented and analyzed within the WEAP-LEAP integrated model. Hydropower generation could be evaluated by LEAP while its water availability is simulated in WEAP at the same time. Thermal cooling requirements are based on electricity demand from LEAP, but the amount of water available could be estimated by WEAP. In addition, a national Water-Economy Database has been established, which is a coupled system's map of water connecting to food and energy [*NWEP*, 2015]. However, interdisciplinary research is still limited with respect to coordinated data collection and integrated model system development as well as integrated assessment to evaluate interactions of water, energy, and food in a changing climate. This makes it difficult to understand the dynamic interactions and related implications

Table 14.3 Water-energy-food nexus information gaps and research needs

Food production and process life cycle	Research needs to bridge information gaps
Irrigation of crops	Evaluate water and energy used in the irrigation of crops: conveyance, treatment, pumping, pressurizing
Growing crops	Evaluate water and energy used in fertilizers, herbicides, pesticides for growing crops
Food harvesting and processing	Evaluate water and energy used in food harvesting and processing: cooling, washing, sorting, packaging
Food industry	Evaluate water and energy used in the food industry including dairy and livestock as well as fishery industries
Transportation for food production and life cycle	Assess energy (fuel) used in transportation including growing and harvesting crops, and shipping food from field to processing, processing to distribution, food import and export, and distribution to market
Food waste	Evaluate embedded water and energy in food waste; assesse water and energy used in collecting and processing for food disposal

in integrated water resource management. The funding, policy, and management support for interdisciplinary research projects could contribute to best management practices in water and energy efficiency and food production efficiency related to GHG reduction for sustainability and security of water, energy, and food at both regional and global scales.

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Water, Energy, and Food Security Nexus in the West Asian Region

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ABSTRACT

The water, energy, and food nexus has complex interconnections and dimensions and is essential for human well-being, poverty reduction, and sustainable development in West Asia. Water is required to produce energy, while energy is needed for water extraction, treatment, and distribution. The food sector requires water and energy to produce food products, while fertilizer and pesticide from farmland use have negative impact on water quality. Understanding these interconnections helps to determine the framework that synergizes all these elements. The West Asian population was about 51 million in 1950, and increased to 319.55 million in 2012 and is projected to reach 560 million by 2050. Agriculture accounts for 73% of freshwater withdrawals, making it the largest user of water in West Asia. The food production and supply chain consumes about 32% of total energy consumed in the region. Energy is required to produce, transport, and distribute food as well as to extract, pump, lift, collect, transport, and treat/desalinate water. This situation is expected to be exacerbated in the near future as 64% more food will need to be produced in order to feed the region's population and 52% more energy in 2050. This study indicates that a sustainable future is possible in West Asia within the range of the available resources if efforts are made to manage these resources properly.

15.1. INTRODUCTION

The West Asian region can be classified according to freshwater resource availability, population growth, land resources, and economic activities into two distinct subregions: (i) the Mashriq and Yemen (including Jordan, Lebanon, Iraq, Syria, the Occupied Palestinian Territories (OPT), and Yemen); and (ii) the Gulf Cooperation Council (GCC) countries (including Kuwait, Bahrain, Qatar, Saudi Arabia, United Arab Emirates (UAE), and Oman) as shown in Figure 15.1. The two subregions have different levels of freshwater resource capacity and reserve, land resources, income disparities, and different rates of socioeconomic developments; however, in both subregions, freshwater availability is essential for achieving the desired socioeconomic, social, and environmental developments. Both subregions are also highly vulnerable to external natural and human-made threats and challenges, such as rainfall intensity, frequency, and variability; population growth, pollution loads and levels; and freshwater resources management practices [*UN-ESCWA*, 2006a]. The West Asian region has diverse incomes, which can be characterized by high-, middle-, and low-income countries; and highly diversified economies including agriculture, forestry, industrial, and several other service sectors. Countries in the West Asian region differ widely in land area, available natural resources including freshwater, land, population, income, and level of socioeconomic development.

The West Asian region is facing major challenges due to scarcity of its natural renewable freshwater resources, which affects the region's ability to produce enough

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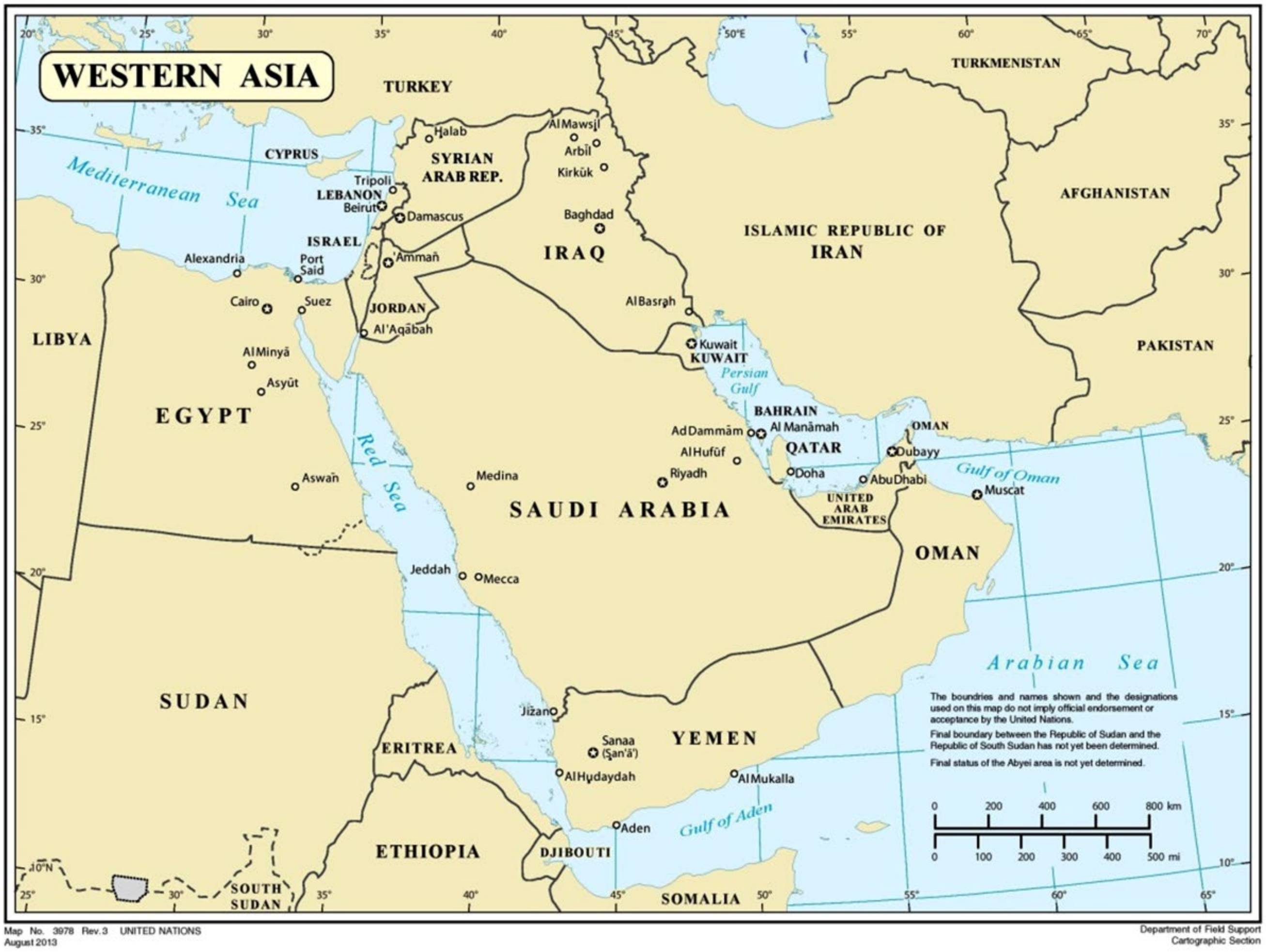

Figure 15.1 Location map for West Asia.

required food to meet the growing demand resulting from rapid population growth. Water production requires energy due to the GCC countries' reliance on desalination, and food production requires water and energy. The nexus therefore critically affects the region's social and political security and stability. The region's strategic decision and substantial investment to improve its water, energy, and food supply have been driven by legitimate motives to ensure the continued rapid growth of the region's economy and enhance the overall security of the nexus. The population of the West Asian region was estimated at 413.9 million in 2012, and is projected to be about 571 million by 2030, with an estimated value of 422.91 million as of 2015, which is about 4% of the total world population as shown in Table 15.1. The annual population growth rate in the region is 1.4%, which is above the world average of 0.9%.

The increase in population growth rate in the West Asian region was accompanied by high urbanization rates resulting from increased socioeconomic activities, migration from rural areas, and an influx of foreign laborers to some oil countries such as the GCC countries. The factors affecting the increasing rate of urbanization in the region include decreases in water availability due to depletion, and frequent droughts, land degradation due to salinization, deterioration of range capacity, and frequent drought cycles [*UNDP*, 2006; *UN-ESCWA*, 2009]. About 73% of the population in West Asia was living in urban areas in 2012 and this increased to about 75% by 2015 as shown in Table 15.2.

Rapid urbanization can also hinder the development of adequate water supply and sanitation infrastructure, such as efficient and smart distribution methods, effective sewage systems, and regulatory mechanisms. The high urbanization rate is overstretching the urban water infrastructure, creating water shortages and unhealthy living conditions, mainly in Mashriq countries [*UN-ESCWA*, 2009]. The urban population in West Asia that accounted for 23.7% of the total population in 1950 rose to 55% in 1980, 66.5% in 1995, and reached 69% in 2000 [*UNEP*, 2007]. In 2005, it accounted for 85% of the total population in the GCC countries and 71.6% in

Table 15.1 Economic Statistics of West Asia (2015)

No	Country	Area	Population (2015)		GDP (2015), US$	
			Number (million)	Density/km²	Nominal (billion)	Per capita
1	Armenia	29,800	3.26	109	10.77	3,304
2	Azerbaijan	86,600	9.8	113	35.14	3,586
3	Bahrain	665	1.23	1,850	30.09	24,463
4	Cyprus	9,250	1.09	118	22.995	21,096
5	Egypt	1,000,000	90.1	90	262.26	2,911
6	Georgia	69,700	3.73	54	15.847	4,249
7	Iran	1,648,195	78.87	48	396.9	5,032
8	Iraq	438,317	36	82	165.1	4,586
9	Israel	20,770	8.3	400	298.8	36,000
10	Jordan	92,300	6.32	68	38.21	6,046
11	Kuwait	17,820	3.69	207	123.23	33,396
12	Lebanon	10,452	4.46	427	54.4	12,197
13	Oman	212,460	2.77	13	60.18	21,726
14	Palestine	6,220	4.26	685	6.6	1,549
15	Qatar	11,437	1.8	157	192.4	106,889
16	Saudi Arabia	2,149,690	30.77	14	632.1	20,543
17	Syria	185,180	23.7	128	n/a	n/a
18	Turkey	783,562	78.5	100	788.1	10,039
19	UAE	82,880	8.26	100	339.1	41,053
20	Yemen	527,970	26	49	34.93	1,343
	Total	**7,383,268**	**422.91**		**3507.152**	

Source: *UNSD* [2016].

Table 15.2 Urban and rural population in West Asia (2012–2015)

No	Country	2012 (million)			2015 (million)		
		Urban population	Rural population	% Urban	Urban population	Rural population	% Urban
1	Armenia	1.61	1.40	53.60	1.80	1.46	55.20
2	Azerbaijan	5.25	4.36	54.60	5.66	4.14	57.80
3	Bahrain	1.21	0.15	88.80	1.10	0.13	89.50
4	Cyprus	0.78	0.39	66.90	0.73	0.36	66.80
5	Egypt	48.80	36.86	57.00	51.81	38.29	57.50
6	Georgia	2.31	2.00	53.60	2.09	1.64	56.10
7	Iran	52.62	21.18	71.30	57.73	21.14	73.20
8	Iraq	24.85	10.92	69.50	25.63	10.37	71.20
9	Israel	7.30	0.62	92.10	7.70	0.60	92.80
10	Jordan	6.43	1.26	83.70	5.42	0.90	85.70
11	Kuwait	3.52	0.06	98.30	3.63	0.06	98.50
12	Lebanon	4.44	0.62	87.80	3.97	0.49	89.00
13	Oman	3.23	0.93	77.60	2.25	0.52	81.40
14	Saudi Arabia	24.85	5.04	83.10	3.62	0.64	85.00
15	Palestine	3.42	1.13	75.30	1.40	0.40	77.60
16	Qatar	2.33	0.02	99.20	30.68	0.09	99.70
17	Syria	12.84	9.43	57.70	14.65	9.05	61.80
18	Turkey	56.29	20.40	73.40	60.99	17.51	77.70
19	UAE	8.19	1.38	85.50	7.24	1.02	87.70
20	Yemen	8.84	16.70	34.6	10.50	15.50	40.4
	Total	**279.1094**	**134.8506**	**73.1**	**298.62**	**124.29**	**75.4**

Source: *United Nations* [2016].

the Mashriq subregion [*UNDP*, 2009]. Moreover, increasing urbanization in the region has led to changes in consumption patterns, resulting in a per capita increase of water, food, and energy consumption and the generation of more waste. This urbanization has created many urban centers, which are home to more than 1 million people, putting more pressure on government budgets to meet the water supply, sanitation, and energy infrastructure needs of these newly built settlements.

The interrelated nature of West Asia's natural resources system is best described by the nexus of water, energy, and food. West Asia faces major challenges due to aridity and scarcity of natural renewable water resources, which affects its ability to produce enough food to meet the growing demand resulting from the rapid growth of its population. Water production also requires energy due to the use of desalination by West Asia. Therefore, the water, food, and energy nexus now critically affects West Asia's national security. West Asia's strategic decision and substantial investment to improve its water, food, and energy nexus has been driven by legitimate motives to ensure the continued rapid growth of the country's economy and to enhance the overall security of its water, food, and energy. This chapter will explore how West Asia could best ensure the long-term sustainability of its water, food, and energy.

15.2. PRESENT AND FUTURE SUPPLY AND DEMANDS: WATER, FOOD, AND ENERGY IN WEST ASIA

15.2.1. Water Resources Supply and Demand

Natural water scarcity, exacerbated by population growth in West Asia, combined with aspirations for higher standard of living, and expounded by increased influxes of refugees and displaced communities to countries within the region has resulted in exponentially increased water demand. Climate change impacts and conflicts over transboundary water resources have also added to the challenges facing freshwater availability in West Asia. Competing water demand between sectors and between users within the same sector, overlap of responsibilities, lack of enforcement of regulations, and absence of agreement on shared water resources, as well as pollution of water bodies, complicate water resources management in the region, resulting in food security issues, human health risks, and socioeconomic instability. Due to the annual population growth and economic development in West Asia, available freshwater resources are pushed to their natural renewable limits. The ability of urban and rural areas in these countries to grow, attract the needed investment, meet the fundamental needs of populations, and ensure environmental protection will be increasingly threatened if these scarce freshwater resources are not smartly and sustainably managed. Most of the West Asian countries suffer from renewable water resources scarcity. The annual renewable water resources in West Asia include 60 billion m^3, which is about 34% of green water (used by rainfed agriculture, forests, and pasture land), and 115 billion m^3, which is about 66% of blue water (internal and external surface and groundwater). The region was a net importer of about 40 billion $m^3$of agricultural virtual water in 2012. The renewable green water resources typically consist of water for rainfed agriculture abstractions, natural pasture abstractions, and forest abstractions [*AbuZeid*, 2008], which when combined with the total renewable blue water resources in the countries will result in the total renewable water resources in the region. Figure 15.2 shows the significance of the most precise estimate of total annual renewable

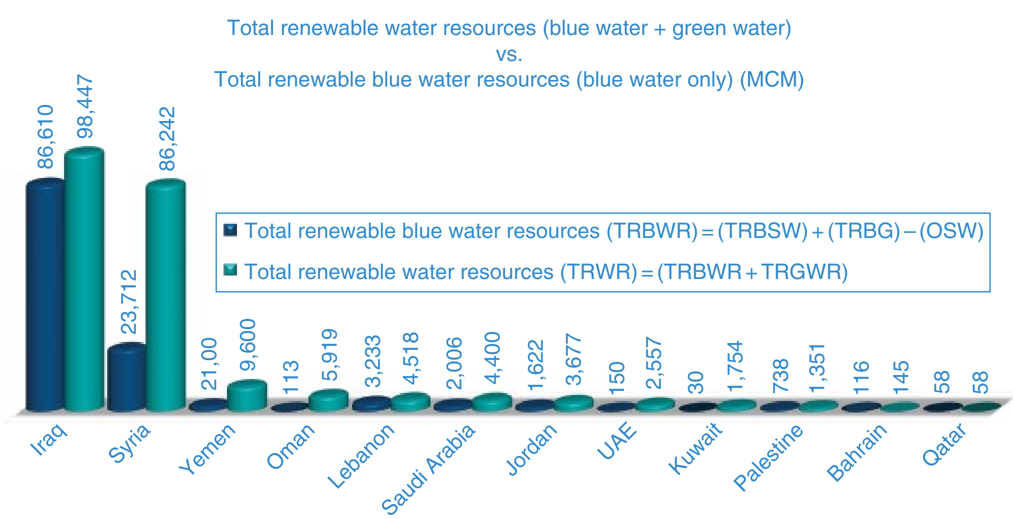

Figure 15.2 Total renewable water resources compared with renewable blue water resources.

water resources compared to the commonly used renewable "blue" water resources [*AWC and CEDARE*, 2014].

Accessibility to safe and clean water is considered a building block for future economic and social growth in the region. About 70% of the total population in West Asia was living in urban areas in 2015, and this increased to about 73% by 2015 as shown in Table 15.2. Rapid urbanization can also hinder the development of adequate water supply and sanitation infrastructure, such as efficient and smart distribution methods, effective sewage systems, and regulatory mechanisms. With the increase in population and urbanization, the annual per capita share of renewable freshwater resources in the region will fall from 850 m^3 in 2015 to 650 m^3 in 2025 and 425 m^3 in 2050 [*UNEP*, 2012b], as shown in Figure 15.3.

Due to the freshwater scarcity, most of the countries in West Asia rely on water desalination. Although the desalination industry has enabled population and economic growth, it comes with financial costs and environmental impacts. There is a need to improve the understanding of the impacts of desalination on ecosystems and deploy mitigation measures [*Dawoud*, 2012]. Additional responses for supply-side management include reusing treated wastewater and agricultural drainage, harvesting rainwater, cloud seeding, reducing distribution losses, and establishing emergency reserves through aquifer recharge. In parallel, demand-side management measures need to be strengthened through raising awareness programs, education, and capacity building; by increasing reliance on food imports; implementing new agriculture policies and legal and institutional framework reforms that aim to reduce abstractions and improve freshwater use efficiency [*Al-Zubari*, 2008]. Wastewater treatment in GCC constitutes an increasing freshwater source driven by escalating water consumption in urban areas and population growth. Existing sewerage treatment facilities and plants, which process primary wastewater and have a processing capability estimated at 921 million m^3 annually, can handle about 43% of all domestic wastewater. However, the reused treated wastewater, which does not exceed 395 million m^3 a year, is used mainly for irrigating fodder crops, public gardens, amenity plantations, recreational areas, highway landscapes, and parks [*Al-Zubari*, 1997]. The remainder is dumped at disposal areas into wadies to infiltrate shallow groundwater aquifers, or into the gulf or sea, which has some environmental impacts. In the Mashriq, wastewater, except in some large cities, is discharged into watercourses (mainly rivers and canals) and only part of it is reused legally or illegally for irrigation purposes. Recycled irrigation drainage water is not used much in the GCC countries since excess irrigation water infiltrates into the lower underlying soil horizons and ultimately reaches the shallow groundwater table; in Saudi Arabia and only in the Al-Hassa Oasis area, about 30 million m^3 of irrigation drainage water a year is reused in date palm farms by mixing it with groundwater [*Al-Kuwaiti et al.*, 1999]. In the Mashriq subregion, only Syria exploits these drainage water resources, with some 1210 million m^3 being recycled and reused annually. This freshwater resource has, however, future potential given proper irrigation practices and technologies are applied. Other forms of nonconventional water sources, such as rainwater harvesting, fog harvesting, and weather modification, are not proven yet and are still in the research stage.

The present water demand comes largely from the agricultural sector, followed by consumption from the domestic and industrial sectors. The national economy of most countries of West Asia depends on oil and oil-related industries, commerce, light industries, and agricultural farming, in this descending order. Due to the growing population and urbanization development, domestic water and industry demands are increasing at rates with which available renewable freshwater resources cannot keep pace. Furthermore, the adopted policies of agriculture food self-sufficiency imposes continual constraints on the allocation of scarcely availed freshwater resources, which would otherwise reduce the freshwater use share

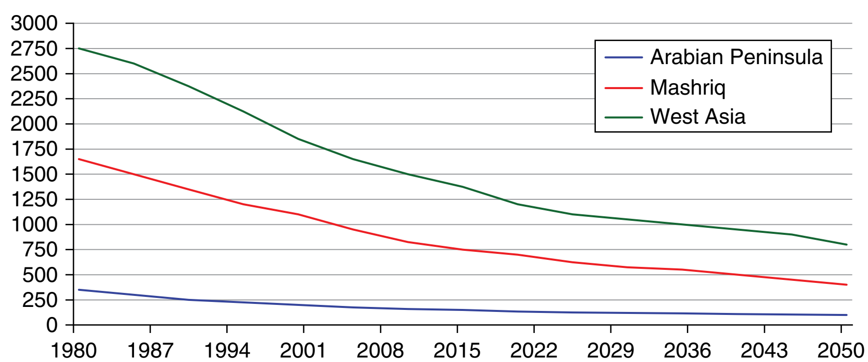

Figure 15.3 Per capita share of renewable water resources in West Asia (1980–2050). (*See insert for color representation of the figure.*)

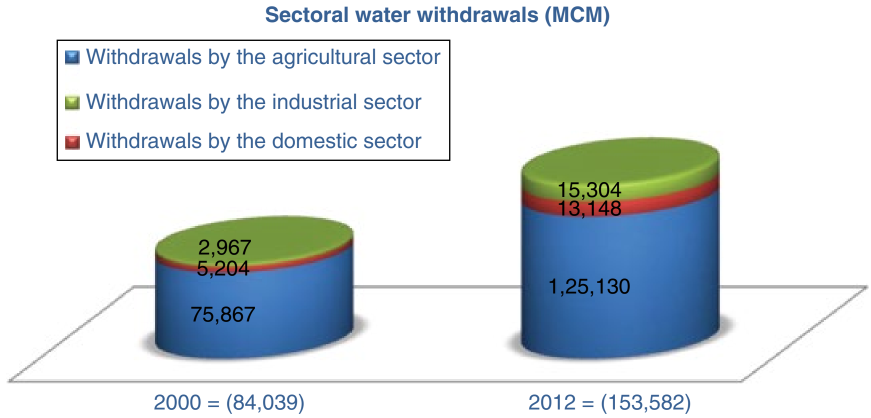

Figure 15.4 West Asia regional sectoral blue water withdrawals (2000 and 2012). (*See insert for color representation of the figure*.)

for agriculture in favor of increased domestic and industrial freshwater demands. Currently the agricultural sector uses about 85% of the total available freshwater resources in GCC countries and about 95% in the Mashriq, followed by domestic water use of 14 and 4%, respectively, with industry in both subregions accounting for less than 2%. Figure 15.4 shows an increase by about 82% in total blue water withdrawals for the three major sectors (agricultural, domestic, and industrial) between 2000 and 2012 in West Asia, reaching about 153 billion m^3 annually. It is clear from recently published studies that in almost all West Asian countries, the agricultural sector is by far the biggest freshwater user for food production [*UNEP*, 2012a].

Without freshwater, neither small businesses (e.g., private farms) nor major industries (e.g., major agribusinesses) in the region can function well. Also, poor water quality, or limited or unreliable access to freshwater resources means higher costs, challenges, and risks for both businesses and consumers. Scarcity of freshwater resources means greater risks for a community's long-term viability and negative impacts on their competitiveness. It also means that a community's ability to grow and create jobs will always face challenges and risks. If not properly managed, freshwater scarcity in West Asia will directly affect the local ability to grow and create jobs for future generation, which can also affect the political stability of these countries. In addition, the lack of access to sanitation and freshwater supply infrastructures constrict socioeconomic growth where it is needed the most. Generally, in West Asia, every US dollar spent to improve sanitation and water supply infrastructure can generate up to US$6 in returns [*UNEP*, 2016]. In 2015, 22% of the region's GDP was produced in water-scarce areas. At this rate, by 2050, this value will rise to about 45%, thus greatly challenging the West Asian ability to grow. In West Asia, recent studies indicated that poor access to good quality water will not only impact economic growth but will also completely stifle it, contributing to disease and malnutrition, and will keep women and youth out from education and the workforce [*Kushnir*, 2013].

15.2.2. Food Supply and Demand

Food security is defined as the condition in which "all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food, which meets their dietary needs and food preferences for an active and healthy life" [*FAO*, 2014]. Within this definition, food security consists of four dimensions, including food availability, economical and physical access to food, food utilization, and stability. Food security has continued to be the main concern of West Asian governments since the concept was introduced in the 1980s. The 2007 world food crisis, accompanied by the rapid increase in food prices, revitalized the need of some West Asian countries to become self-sufficient in certain food commodities, and especially to restrict the export of cereals and livestock feed [*AOAD*, 2009]. As a result, the region's national agricultural policies were revised and updated to increase agriculture and food production. Moreover, governmental control of farming systems was relaxed in favor of decentralization. To achieve food self-sufficiency, actions and incentives in the form of price controls, tax breaks and reductions, cereal and animal feed export restrictions, easy loans, and the introduction of new innovative and efficient techniques in reclamation and irrigation were explored.

In the West Asian countries, about 80% of available freshwater resources are used for irrigated agriculture for food production. However, the regional food self-sufficiency ratio was about 55.15% in 2011 and it is gradually decreasing to 54.65% in 2015 as shown in Table 15.3. Compared with Asia as a whole, the total food production in West Asia is very low as shown in Figure 15.5, mainly because of the changes in the land area under cereal production, the slow rate of economic growth, and the lack of new improved and innovative technologies in irrigation, agriculture, and food production. Despite these challenges and constraints, the food production can be increased in some West Asian countries, even in those having slow economic growth rates. Statistics indicate that food production in West Asia has not significantly increased compared to that in Asia, America, and Africa. Food production is low in GCC countries due to aridity and scarce freshwater resources and limited irrigation potential. West Asia is highly dependent on irrigated agriculture for food production and security. The region's import of wheat which was of 2.1 million tons in 1961 increased to 15.5 million ton in 2007 [*Ortas and Lal*, 2013]. Total food import also increased from 5.7 million tons in 1961 to 87.9 million tons in 2007 (by a factor of 15). Due to the gap between demand and production, food import increased and the net gap between import and export has widened in many West Asian countries to reach US$15.2 billion by 2009 and it is expected to increase to more than US$30 billion by 2050 as shown in Figure 15.6. Recent studies indicate that the yield of several crops has increased since the 1960s. This increase was slow in the period between 1960 and 1970, and then took on a relatively faster rate in the period between 1980 and 1990. However, grain yield has not increased since 1990. Despite a relative increase in the total production of wheat as shown in Table 15.4, the supply is lagging behind the demand in several regions and is exacerbating the food insecurity. With the projected increase in population, the food demand in West Asia is likely to increase in the near future. Wheat and maize are the staple food grains of West Asia. Yet, grain yield of these staples in this region is lower than that of the world average and is not enough to cover the future food demand in the region.

Table 15.3 Food self-sufficiency ratio in selected West Asian countries (2005, 2011, and 2015)

No	Country	2005 (%)	2011 (%)	2015 (%)
1	Armenia	58.91	60.80	61.12
2	Azerbaijan	90.00	92.10	93.00
3	Bahrain	12.96	12.81	12.75
4	Cyprus	73.00	72.00	71.10
5	Egypt	83.68	78.96	78.21
6	Georgia	65.00	64.00	63.50
7	Iran	76.00	77.20	78.10
8	Iraq	75.34	82.84	82.15
9	Israel	45.20	44.65	41.98
10	Jordan	56.26	53.09	52.89
11	Kuwait	28.38	21.68	20.57
12	Lebanon	73.23	61.03	61.00
13	Oman	45.21	34.52	33.45
14	Saudi Arabia	44.52	34.49	33.25
15	Palestine	81.55	72.26	72.10
16	Qatar	12.18	9.90	9.80
17	Syria	85.23	80.62	79.85
18	Turkey	100.00	100.00	100.00
19	UAE	21.10	18.60	17.98
20	Yemen	51.53	31.45	30.12
	Average for West Asia	**58.96**	**55.15**	**54.65**

Source: *FAO* [2016].

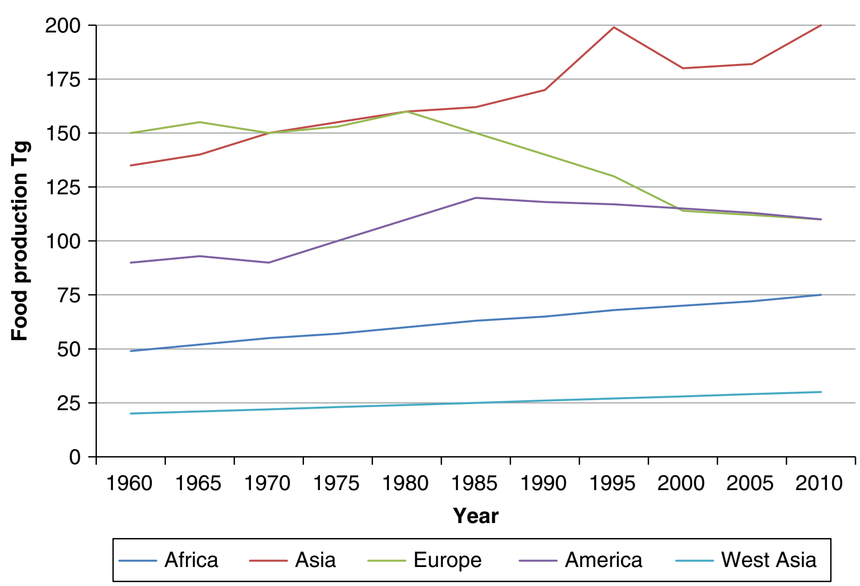

Figure 15.5 Global trend in food production (1960–2015). Source: *FAO* [2011]. (*See insert for color representation of the figure.*)

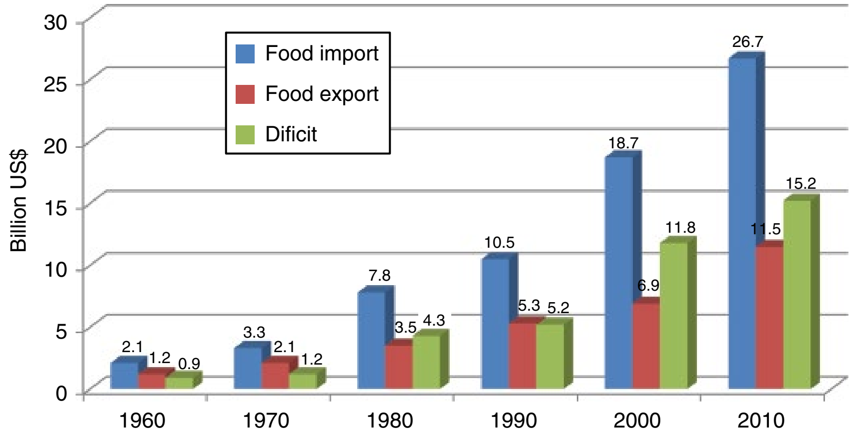

Figure 15.6 Deficit between food import and export in West Asia (1961–2007). (*See insert for color representation of the figure*.)

Table 15.4 Production trends of major crops in West Asia in million tons (1961, 1970, 1980, 1990, 2000, and 2007)

	1961	1970	1980	1990	2000	2007
Wheat	8.37	11.14	19.42	26.27	27.76	26.12
Barley	3.61	3.71	7.10	8.74	8.73	8.96
Maize	1.06	1.07	1.36	2.45	3.08	4.51
Cereals – beer + (total)	15.66	18.43	29.96	38.85	41.09	41.54
Cotton lint	0.35	0.59	0.70	0.87	1.29	0.98
Fruits, other	1.16	1.36	2.09	3.19	4.54	5.65
Tomatoes	1.60	2.49	5.10	8.25	13.03	14.57
Vegetables + (total)	8.90	11.65	19.06	25.83	37.88	39.79
Vegetables + (other)	6.77	8.31	12.70	15.69	21.91	22.53
Fruits – wine + (total)	6.82	9.55	12.23	15.49	19.51	22.34
Total	**54.32**	**68.30**	**109.70**	**145.63**	**178.81**	**186.99**

Source: *FAO* [2011].

To increase the food self-sufficiency ratio and due to limited land and freshwater resources, GCC countries started their plan for agro-investments abroad, mainly in some African and Asian countries in order to ensure privileged bilateral access to food productions. Most targeted countries have hitherto not been known for their food export capacities but have genuine food security concerns of their own such as Egypt, Sudan, Ethiopia, and Pakistan. These countries are logistically close and have established political and cultural ties with the GCC countries. Strategies and policies of increasing the food self-sufficiency ratio and foreign agro-investments are still challenges facing the West Asian countries. The political stabilities and high costs of agricultural investments in developing countries draw attention to the necessary infrastructure like roads and dams that would need to be ramped up first.

Recent studies recommended the buildup of strategic food reserves in West Asia. Such strategies and programs are now being realized in the GCC countries. However, the International Food Policy Research Institute (IFPRI) has contended that such national solutions could lead to unnecessary and expensive storage, an inefficient global production system, and tighter markets if practiced widely on a global level. They could cause the very problem they want to mitigate in the first place. Such a multilateral storage and information system could reduce volatility of markets by improving their transparency and predictability. By means of market intervention it could also prevent speculative overshooting of prices of agricultural commodities, which have been increasingly traded on international future exchanges. So, it's hoped that export restrictions like in 2008 could be avoided [*Joachim and Maximo*, 2009].

15.2.3. Energy Supply and Demand

West Asia is one of the major players in the global energy market, having about 52% of the world's oil reserves and 24.6% of the world's gas resources [*OAPEC*, 2009].

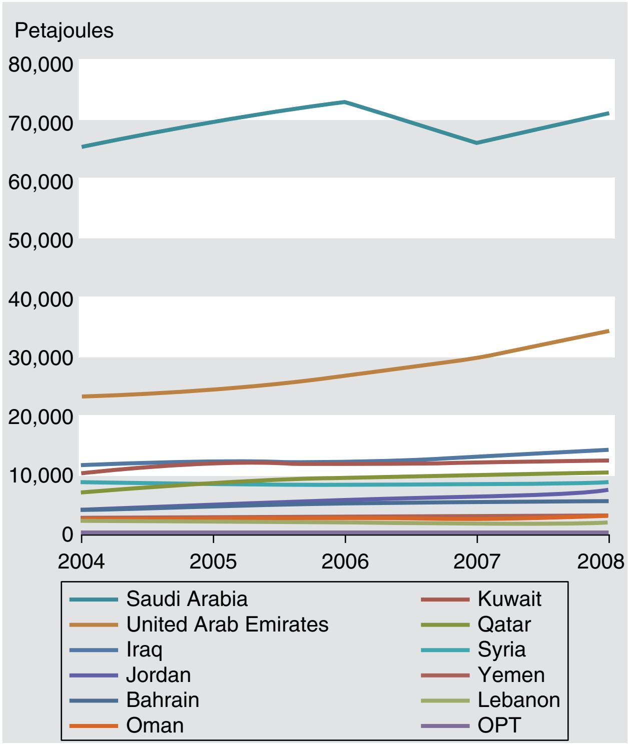

Figure 15.7 Energy consumption in West Asian countries (2004–2014). (*See insert for color representation of the figure*.)

The region produces about 17.3 million barrels of oil a day, which is 27.6% of the world's oil exports [*IEA*, 2010]. Rapid economic development, high population growth, urbanization, and changes in standards of living in the region have led to increases in energy demand as shown in Figure 15.7. Access to energy varies significantly across the region. High-income GCC countries produce, use, and export large quantities of oil and gas. In the GCC region, about 30% of energy production is used for producing water by the desalination industry. Low-income countries with no endogenous fossil fuel energy resources have high energy costs associated with water treatment and transportation. Countries in conflict or affected by sudden large influxes of displaced people face challenges to satisfy energy needs. Lack of access to energy not only hinders economic development but also creates pressures on the environment and public health. An example of this is the increase in deforestation in the region and the high exposure to air pollutants due to burning such materials as plastic, tyres, and other waste in uncontrolled conditions for heating purposes.

Competing demands and the international interests in energy resources have played an important role in the political, social, and environmental stability of West Asia. Conflict has led to the destruction and damage of oil production and transport infrastructure, in turn resulting in environmental disasters. An emerging issue is the competing interest for access to and development of natural gas resources in the Mediterranean Sea. West Asia's high reliance on fossil fuels (oil and coal) leads to detrimental impacts on the region's socioeconomy, environment, and public health. Fluctuations in international oil prices exacerbate the challenge of energy access and the financial burden of governments in countries with high energy subsidies. Fossil fuel combustion generates greenhouse gas (GHG) emissions and associated environment and health problems. Oil spills and oil and gas operations can contaminate aquifers and the marine ecosystem environment with increased risks for public health. The West Asian countries will continue to be the main producers, users, and exporters of oil and gas resources. However, there is a push for improvement in energy efficiency and the diversification of the energy resources mix (both fossil and renewable) for national security, socioeconomy, and environmental and health reasons. In oil- and gas-producing countries there is an opportunity cost associated with increasing national domestic energy demand as less energy resources become available for export, which could also affect the national economy in these countries. Promoting renewable energy sources is perceived as potential economic growth and there are already several renewable energy projects (mainly solar energy) on the ground, for example in Egypt, Jordan, Qatar, Saudi Arabia, and the UAE. Growth in the renewable energy sources can be facilitated by the creation of a dynamic market with participation and investment from the private and public sectors. This can be achieved by addressing existing energy monopolies and by deploying policies and measures that reduce investment risks. Separating the role of regulators and operators is crucial for effective and efficient management of energy sources, with implications for public safety, related, for example, to nuclear energy facilities. Transport is another sector that requires improvement in energy efficiency, and this can be achieved through integrated urban transport planning and investment in public transportation services.

Some of the West Asian countries have adopted policies and plans to promote the use of renewable energy sources such as solar and wind energy technologies, including solar water heaters and photovoltaic cells for energy generation on building tops, taking advantage of the area's abundance of natural solar energy. These policies and plans particularly address and target the demand of remote and rural areas with only an unreliable conventional energy supply or none at all. This has been done in parallel with the adoption of performance standards for solar water heating and street lighting systems and awareness campaigns that demonstrate their economic, social, and environmental benefits [*UNEP*, 2012b].

Successful energy policies in West Asian countries focus on two main areas:

1. Energy efficiency in the building and transportation sectors including systems for space heating and cooling, measures for promoting the use of renewable energy resources in street lighting, and using public transportation services
2. Energy generation mixes and targets for clean energy production, which require governmental commitment and advanced legislation and regulation

Indicators for measuring the progress and enforcement of selected energy policies in West Asia include the following:

1. Energy savings in percentage terms or cost terms, toward reduced air-conditioning system sizes and impacts on local markets
2. Total surface areas of solar water heaters installed (market penetration)
3. Diversification of energy sources as part of West Asian countries' future plans, and renewable energy sources capacity as a proportion of total capacity in the future

Energy efficiency plans and use of renewable energy sources in the building and construction sector have been a primary national target for the West Asian region. Thermal guidelines and green building codes have been developed and implemented in most of the West Asian countries. More recent building codes in the region tackle green building design and performance.

15.3. INTERACTION BETWEEN WATER, ENERGY, AND FOOD SECTORS

Many countries in West Asia often have to produce their food at the expense of exhausting their scarce renewable freshwater resources or producing freshwater at the expense of heavy energy utilization rates. The water, energy, and food nexus describes the complex and interrelated nature of West Asian countries' natural resources systems. In GCC countries, they have to produce freshwater using energy with the help of the desalination industry. Recent studies indicate that about 30% of the energy consumption in GCC countries used for desalinated water production has cost and environmental implications. Energy is also used for groundwater abstraction and surface water transmission in West Asia. In West Asian countries, about 80% of the region's available freshwater resources are used in the agricultural sector for food production. This has been oriented toward food self-sufficiency in certain commodities and overall food security in light of increasing food prices, rural development, and rising incomes. In West Asia, the agricultural sector employs about 35% of the domestic population, while in the GCC countries it depends on expat labor [*UNEP*, 2010]. The increasing use of oil and gas products in West Asia has secondary impacts on food prices through increased costs of energy and fertilizers, while some agricultural productions have been diverted toward producing biofuel.

Sustainably securing water, food, and energy requires unified political wells and efforts that promote a multilateral, collaborative approach and plans [*Hoff*, 2011]. The focus must be on finding sustainable solutions and alternatives that holistically tackle these issues, such as boosting production, tempering demand, and allowing for greater access to the entire energy, food, and water spectrum. We must also commit to finding solutions that minimize our carbon footprint, and ensure natural resources security in a manner that is mindful of the nations' sovereignty. Most readily, global policy measures are needed to take advantage of the opportunities to ensure the sustainable use of natural resources and the continued socioeconomic prosperity of nations.

15.4. CHALLENGES FACING THE WATER, FOOD, AND ENERGY NEXUS

The global risks, challenges, and opportunities around water, food, and energy resources are shared risks and opportunities including for the West Asia region. The vital challenge for policy-makers is how to put in place a water, food, and energy nexus framework in which those risks, challenges, and opportunities are engaged in collaborative plans by all who have a role to play in the region. The alternative, competition to control these resources, is one feature of today's incoherent responses to the water-food-energy nexus, which undermines resilience. Some of the West Asian countries have clearly built a development strategy on a sound understanding of the risks, challenges, and opportunities defined by their resources endowments [*Mohtar and Daher*, 2012]. Others have appeared to pursue strategies in tension with those fundamental constraints. Particularly where a country has used trade to avoid confronting the risks inherent in its nexus resource availability, increasing global interdependence warrants a review of whether that kind of development strategy can be pursued indefinitely. Figure 15.8 shows the features of the challenges facing the three current resources and where room for future improvement exists [*World Business Council for Sustainable Development*, 2014].

15.4.1. High Population Growth Rate

The high population growth in West Asia is a major constraint affecting all other sustainable socioeconomic developments within the region. The estimated population in this region was 86.5 million in 1995 [*UNSPD*, 1997] with

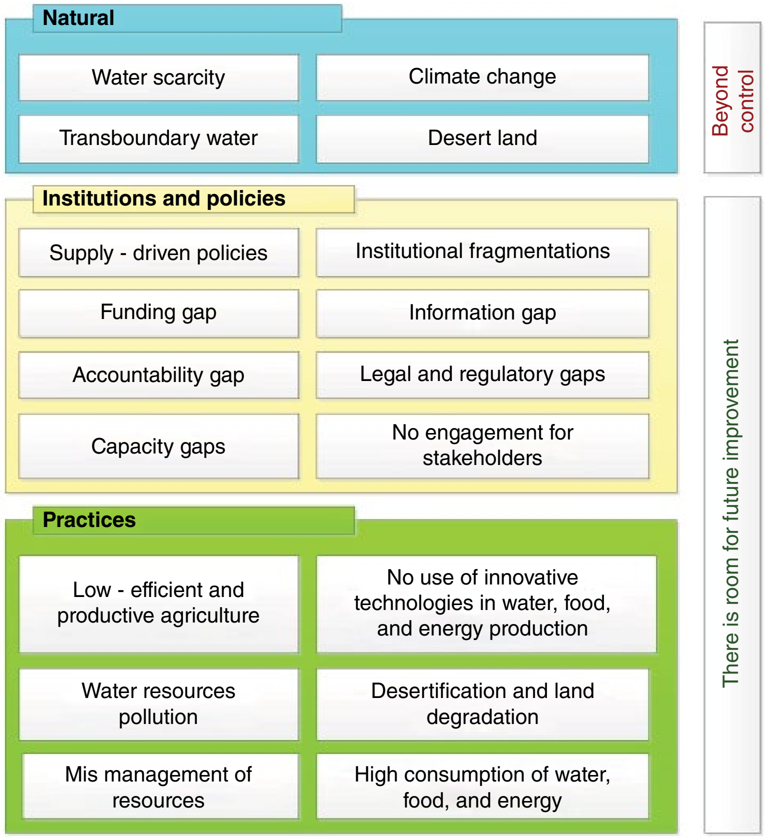

Figure 15.8 Features of current water, food, and energy nexus challenges in West Asia.

an average growth rate of 3.8% for GCC countries and 3% for the Mashriq countries. Due to the increasing rate of population growth, the annual per capita share of renewable freshwater resources is decreasing. At present, five countries in West Asia have a shared per capita water use of less than 500 m^3 a year, half the benchmark of 1000 m^3 a year, which indicates chronic water scarcity. Only two countries, Iraq and Syria, actually exceed the 1000 m^3 a year benchmark; Saudi Arabia, Bahrain, Qatar, Oman, and the UAE have done so only by mining their groundwater reserves.

15.4.2. Shared Freshwater Resources and Water Politics

One of the most challenging issues facing the freshwater sector in West Asian countries is the shared water resources from either surface water sheds and basins or groundwater aquifers. The region's shared surface water sheds and basins are well studied and known. Most of these have been subject to discussions and negotiations between riparian countries, and some, most notably the Jordan River Basin, have been overshadowed by sustained political conflict. In West Asia, there are seven shared river basins, as shown in Table 15.5. Surface freshwater resources, mainly from river annual flows, are estimated at 93.1 billion m^3 concentrated mainly in the Mashriq subregion, with 80.1 billion m^3 available from the major shared rivers and the remaining 13 billion m^3 from small rivers, springs, and intermittent wadi flow [*UN-ESCWA*, 2013]. The Mashriq countries, such as Iraq, Turkey, Lebanon, and Syria, rely on river flows supplemented by limited groundwater resources, while the remaining countries rely on floods and shallow and deep groundwater resources. Total annual internal renewable freshwater resources account for only 6.3% of their average annual precipitation, against a world average of 40.6%, due to the high rate of evaporation and evapotranspiration. The region has two shared rivers originating from outside it (the Euphrates and the Tigris) and many smaller ones. The GCC countries are characterized by arid climate conditions with annual rainfall of less than 100 mm, with no permanent surface water bodies, and depend mainly on nonrenewable groundwater aquifers and desalinated water to meet their increasing water demands for socioeconomic development [*UNEP*, 2007].

Renewable groundwater resources in West Asia are generally shallow alluvial aquifer systems recharged by the main rivers, excess irrigation water, and wadi surface

Table 15.5 Shared surface water basins in West Asia

Shared basin	River	Countries	Main shared tributaries
Euphrates-Tigris Shatt al Arab Basin	Euphrates River	• Iraq • Syria • Turkey	• Sajur River Jallab • Balikh River • Khabour River
	Tigris River	• Iran • Iraq • Syria • Turkey	• Feesh Khabour River • Greater Zab River • Lesser Zab River • Diyala River
	Shatt al Arab River	• Iran • Iraq	• Karkheh River • Karun River
Jordan River Basin	Jordan River	• Israel • Jordan • Lebanon • Palestine • Syria	• Hasbani River • Banias River • Yarmouk River
Orontes River Basin	Orontes River	• Lebanon • Syria • Turkey	• Afrin River • Karasu River
Nahr el Kabir Basin	Nahr el Kabir	• Lebanon • Syria	—
Qweik River Basin	Qweik River	• Syria • Turkey	—

Source: *UN-ESCWA* [2013].

flow, especially during major floods, and directly from rainfall at aquifer outcrop areas. Renewable groundwater resources, or the amount of groundwater recharge, are estimated at 15,500 million m^3. In the Mashriq subregion, the amount and frequency of recharge is much greater than in GCC countries, due to the higher volume and frequency of rainfall. The degree of groundwater exploitation in most West Asian countries is much higher than the amount of natural recharge, which leads to continuous and sharp declines in groundwater levels, extensive depletion of groundwater reserves, and increased salinity [*UNEP, LAS, and CEDARE*, 2010]. In some countries such as the UAE, the present abstraction from groundwater aquifers is 15 times the recharge from natural aquifers. There are shared surface basins and nonrenewable groundwater resources lying within and beyond many countries of the region. There are extensive groundwater reserves of varying quality available in shared deep nonrenewable aquifers covering most countries of GCC countries, such as Turkey, Jordan, Iraq, and Syria. The major shared deep groundwater sources are the Eastern Arabian aquifers (Um Err Raduma, Dammam, and Wajeed), located in the GCC countries, the Shaq aquifer between Saudi Arabia and Jordan, and the Basalt aquifer between Jordan and Syria [*UN-ESCWA*, 2013]. There are 18 shared groundwater aquifer systems within the region, as shown in Table 15.6.

Shared surface water basins remains a sensitive topic in West Asia and data sharing between riparian countries is very limited and considered confidential in most cases. As a result, there is no common understanding of the state and development of these freshwater bodies, water availability, water losses, water use, and flow trends. On a national level, data are often lacking, incomplete, or inaccessible, particularly when it comes to water use from shared resources, which is rarely measured in the riparian countries. Regionally, data obtained from different countries can be contradictory and fragmented, often because there are no unified standards for measuring flows and hydrological changes. The fact that cooperation between shared water basins of riparian countries is limited further impedes the development of a common vision on shared water resources management plans. Long-standing political instability in West Asia has hampered successful shared basin-wide conventions and cooperation [*UN-ESCWA*, 2006b]. There is not a single basin-wide agreement on shared water resources in West Asia. Existing bilateral agreements center on water allocation and use, with an emphasis on infrastructure development and management. Mostly, water quality is not even addressed in these agreements. While there are no river basin associations in place, bilateral cooperation over surface water does take place only through technical committees and local projects or bilateral agreements between two or more countries. At present, there are no agreements or conventions on shared groundwater aquifer systems, though in a few cases bilateral agreements include groundwater-related provisions. Cooperation over shared groundwater aquifer

Table 15.6 Shared groundwater aquifer systems in West Asia

Shared groundwater aquifer system	Shared countries
Saq-Ram Aquifer System (West)	Jordan, Saudi Arabia
Wajid Aquifer System	Saudi Arabia, Yemen
Wasia-Biyadh-Aruma Aquifer System (South)	Saudi Arabia, Yemen
Wasia-Biyadh-Aruma Aquifer System (North): Sakaka-Rutba	Iraq, Saudi Arabia
Umm er Radhuma-Dammam Aquifer System (South)	Oman, Saudi Arabia, UAE, Yemen
Umm er Radhuma-Dammam Aquifer System (Center)	Bahrain, Qatar, Saudi Arabia
Umm er Radhuma-Dammam Aquifer System (North)	Iraq, Kuwait, Saudi Arabia
Tawil-Quaternary Aquifer System	Jordan, Saudi Arabia
Ga'ara Aquifer System	Iraq, Jordan, Saudi Arabia, Syria
Anti-Lebanon	Lebanon, Syria
Western Aquifer Basin	Egypt, Israel, Palestine
Central Hammad Basin	Jordan, Syria
Eastern Aquifer Basin	Israel, Palestine
Coastal Aquifer Basin	Egypt, Israel, Palestine
North-Eastern Aquifer Basin	Israel, Palestine
Basalt Aquifer System (West)	Jordan, Syria
Basalt Aquifer System (South)	Jordan, Syria
Western Galilee Basin	Israel, Lebanon
Taurus-Zagros	Iran, Iraq, Turkey
Jezira Tertiary Limestone Aquifer System	Syria, Turkey
Neogene Aquifer System (North-West)	Iraq, Syria
Neogene Aquifer System (South-East)	Iraq, Kuwait, Saudi Arabia

Source: *UN-ESCWA* [2013].

systems is rare as resources are often not clearly delineated and may therefore not be recognized as shared by riparian countries.

15.4.3. Climate Change

The climate scenarios were produced by the five selected general circulation models (GCMs) which generated daily temperature and precipitation data sets for 2011–2050 using the delta change method for West Asia. The results indicated the likelihood of increasing temperature and precipitation and rise in seawater level, which would then have impacts on the region's water resources available for future use. The impact of climate change coupled with mismanagement of water resource can accelerate the impacts on scarce water resources. Although the Arab region as a whole does not contribute more than 5% of total GHG emissions, the impact of climate change on the region is substantial [*AFED*, 2014], with GCC countries shouldering the biggest share. Recent studies indicate that the degree of expected impacts will vary among countries of West Asia, and GCC countries will be particularly affected. The climate change global index study developed by Maplecroft classified countries in different parts of the world according to the degree of exposure to climate change [*Abdel Hamid*, 2009]. The study indicates that some West Asian countries may experience different degrees of vulnerability to impacts of climate change ranging from extreme to significant to highly vulnerable. This index classified Iraq as the fifth most vulnerable country in the world which experienced impacts in the form of decreased water and food availability and extreme temperatures and associated health problems. Bahrain and Qatar were ranked eleventh and are projected to suffer significant impacts because of their small area and low elevation with their coastal zones exposed to sea level rise. The rest of the GCC counties are rated as highly vulnerable and Yemen as extremely vulnerable [*Abdel Hamid*, 2009]. Reduced water availability due to climate change and environmental degradation coupled with high population growth could threaten the progress made toward achieving the sustainable development goals (SDGs). Studies on the impacts of climate change on West Asia are very limited due to poor data availability coverage and dissemination.

The change in precipitation patterns (amount, intensity, duration, distribution, and seasonality) will influence the availability and dependability of water resources due to the unpredictability of weather events. Future projections suggest a decrease in rainfall in the region according to most global climate models [*Meslemani*, 2008]. Rainfall is projected to decrease by 20% over the next 50 years [*Khordagui*, 2007]. In the Mashriq subregion, rainfall may decrease by 25% at the regional level and at some locations by 40% [*Shindell*, 2007]. Results from a European Union project on the Mediterranean region supported these projections and indicated that there will be general and continuous drought conditions with increases in water deficits in the Mediterranean region [*Hanson et al.*, 2007]. The project also suggested that Lebanon, Syria, Jordan, and GCC countries may experience significant reduction in rainfall due to the expected changes in the general weather system pattern [*Hanson et al.*, 2007]. Temperature increases could influence the quality of surface water in terms of dissolved oxygen, stratification, mixing ratio, self-purification, and biological content and growth, especially algal bloom, bacterial content, and fungal levels [*Khordagui*, 2007]. Increases in temperature may result in heat waves with impacts on health, higher water and energy consumptions, and increased incidence of disease.

The agricultural sector, being a major water consumer and faced with the challenge of producing enough food, is expected to be impacted by these changes in temperature and precipitation patterns. This will also have an impact on food security. The region imports about 70% of its total food. Attempts to achieve food security will force many countries to assess their requirements by focusing on food availability, accessibility, utilization, and system stability, thus intensifying food production. Food shortages will force many countries to depend on foreign imports. Climate changes could impact production from rainfed agriculture and decrease productivity per hectare due to variable and reduced rainfall and soil moisture. Table 15.7 shows the overview of the main

Table 15.7 Climate changes impacts on water, food, and energy nexus

No	Factor	Impacts
1	Increased demand for food	• Food demand is expected to increase by 60% in 2050 over the 2005/2007 baseline. • Increased food demand is caused by population growth and by higher per capita calorie intake and change in diets. • Annual West Asian agricultural production needs to increase by some 73%.
2	Increased demand for biofuels	• The global demand for biofuels (biodiesel and ethanol) is expected to increase by threefold by 2050. • Globally, the area needed to meet biofuel demand in 2030 is estimated to be between 2.5 and 20 times the current area designated for biofuel production, depending on sources of biofuel and the development of second-generation biofuels.
3	Impact on land	• The major increase in food production has to come from intensification on existing land through higher yields and cropping intensity, whereas extensification plays a minor role. • By 2050, global arable land will increase by 4.5%, of which 107 million ha will be in developing countries. In developed countries, arable land will decrease by 40 million ha. • The area available for rainfed agriculture is potentially enough to meet global demand, but it is risky to bank only on this. Investments in irrigated agriculture are also needed.
4	Impact on water	• By 2050, irrigated agriculture on 16% of the total cultivated area is expected to be responsible for 44% of total crop production. • By 2050, the area equipped for irrigation will expand by 6.6% over the base 2005/2007. • Most of the expansion in irrigated land will be achieved by converting rainfed agriculture into irrigated land. • Sharp increases in domestic and industrial water use will increase competition over water with agriculture. • Competition over water resources could cause a 22% reduction in the availability of water for agriculture by 2050.
5	Impact on agriculture	• Higher temperature increases water demand of crops and livestock. • Increased temperature will cause annual variation in crop and livestock production due to extreme weather events and animal stress, and also decrease the productivity. • There will be risks in rainfed agriculture production in areas vulnerable to drought. • Crop yields will go down due to temperature increases. • Energy consumption and costs rise for temperature regulation. • Extreme weather events could affect soil and soil water availability.
6	Impact on energy	• The food sector currently accounts for about 30% of West Asia's total energy consumption. • The region's energy demand is projected to increase by 80% in 2050. • The region's agricultural commodity prices are sensitive to increased energy.
7	Greenhouse gas emissions	• The region's greenhouse gas emissions are expected to grow by 50% between 2015 and 2050, mostly driven by energy demand and economic growth. • Agriculture, food, and water production within the region is responsible for 18% of total greenhouse gas emissions.

Table 15.7 (Continued)

No	Factor	Impacts
8	Agricultural commodity markets	• Regional commodity prices are likely to remain high. • With increased food demands in West Asia, there will be more regional food trade and with it more price volatility. • Rising oil prices will have an impact on agricultural production costs (in 2016 there was a drop in oil price). • Food trade needs to buffer fluctuations in food production.
9	Impact on water quality	• Increase in temperature will translate to increase in water demand and withdrawal, which will lead to water deterioration and salinity increase, especially in groundwater resources. • Increasing salinity and water pollution will impact the productivity of agricultural crops. • Regionally at least 1.5–2 million ha of land are irrigated with either untreated wastewater or polluted water. • Regionally about 8 million ha are currently affected by salinity.

Source: *World Business Council for Sustainable Development* [2014].

projections for food, feed, fiber, and biofuels, and implications for land, water, energy, markets, and the climate.

15.4.4. Legal and Institutional Fragmentation

Integration of legal and institutional frameworks refers to the need for cross-sectoral interconnectivity so as to minimize the potential conflicts between the various legal, policy, and institutional frameworks that apply to the management of the water, food, and energy nexus or of each of these resources. Integrated water resources management in the water sector expresses the idea that water resources should be managed and allocated in a holistic way, coordinating and integrating all aspects of water and land management, so as to bring sustainable and equitable benefit to those sectors dependent on water resources. The close links between water, food, and energy and all other socioeconomic development should be reflected in law and in the overarching legal and institutional frameworks that cover all activities under the management of these three resources toward achieving and improving the nexus. Integration should take into account the uniqueness of the environment, and the economic and social characteristics. Interlinked challenges of land degradation, food security, ecosystem decline, water quality, water flow depletion, and energy demand stand in the way of improving the water, food, and energy nexus, which will lead to poverty reduction and sustainable development.

15.4.5. Desertification and Land Degradation

Land degradation and desertification continue to be the most significant challenges for the water, food, and energy nexus in West Asia, especially in countries where the agricultural sector contributes significantly to these countries' national economy. There are extensive desert areas in the region, ranging from about 10% of total country area in Syria to nearly 100% in Bahrain, Kuwait, Qatar, and the UAE. Desertification has also affected wide areas of rangelands in Iraq, Jordan, Syria, Egypt, Yemen, and GCC countries. The causes include a combination of climate change impacts, high population growth rates, and intensive agriculture in the region. Poverty and inappropriate government policies and plans exacerbate the problem. Political and social instabilities in and around the West Asian countries have persuaded governments to adopt policies aimed at achieving national food security. These policies have been accompanied by agricultural protection, erection of trade barriers, and government subsidies for agricultural and food inputs. Subsidies, together with free (or cheap) irrigation water resources, have had severe impacts on land and scarce freshwater resources, and have contributed to the unsustainability of the agricultural sector in West Asia. As a result, land degradation has become widespread over the region, and it has accelerated as more rangelands were reclaimed and put under cultivation. Forest fires and forest removal are two of the main factors affecting vegetation cover loss and soil erosion. Between 1985 and 1993, forest fires destroyed more than 8000 ha of forests and affected another 20,000 ha or more of coastal forests in Syria, resulting in an annual soil erosion of more than 20 tons/ha. During the same period, about 2440 ha of forests were removed and cleared for agricultural purposes [*UNDP/World Bank*, 1998]. High population growth and other demographic changes have led to losses of land due to the increase in urbanization, industrialization, and nonagricultural activities.

Insufficient development and services in the rural areas of Mashriq subregion, Egypt, and Yemen has resulted in a rural influx to urban areas, spreading illegal settlements and squatter houses on the peripheries of major cities at the expense of fertile agricultural lands. As well as encouraging intensification of agriculture, national policies aimed at achieving higher levels of food self-sufficiency ratio also resulted in a more than twofold increase in irrigated area between 1972 and 1999, from 2991 to 7191 million ha. The largest increase occurred in Saudi Arabia, from 0.437 million ha in 1980 to 1.6 million ha in 1993 [*Al-Tukhais*, 1999]. However, despite the large increase in the irrigated agricultural areas and new reclaimed lands (Egypt and the UAE for example), the increase in food production has not kept pace with population growth.

Poor management, inefficient use of irrigation water, using brackish and saline groundwater, and poor drainage systems have resulted in salinization, alkalization, water logging, and nutrient depletion in large fertile agricultural areas within the region. Salinization and waterlogging, which are the most important causes of degradation of irrigated agriculture lands, have affected about 52% of the desert area in West Asia. In addition, about 2.1 million ha of the cultivated land area in Saudi Arabia, 33.6% in Bahrain, and 38.5% in the UAE are moderately salinized. Salinity and waterlogging have affected 8.5 million hectors or 64% of the total arable land in Iraq, while 20–30% of irrigated land has been abandoned due to salinization.

15.5. INVESTING IN A WATER-FOOD-ENERGY-SECURE FUTURE IN WEST ASIA

Governmental investments and policies must help to encourage private investments in technologies and management practices that enhance the sustainable production of crops, livestock, fish, and energy by both smallholders and large-scale producers in West Asia. Continuous investment is essential in research and development to adopt new innovative technologies that will intensify smallholder crops, livestock, and fish production, as well as water and energy supply. In the food production sector, improvements should be made in crop and livestock genetics, and in production techniques that will permit farmers to feasibly increase their food productions using less land and water resources. These resources must be made available to smallholders, together with supporting investments in education, training, outreach, technology and knowledge transfer. Private sector investments and public-private partnerships will increase the pace at which new technologies can be developed and implemented. Investments are also needed in programs that enhance risk management in rainfed and irrigated agriculture. Investments and programs that enhance the management of agricultural and food production risks, particularly for smallholders, will be critical in enabling farm households to adopt new innovative technologies, diversify their activities, and sustain food security during periods of high input prices, low crop yields, and major weather events. Investments are also needed in infrastructures that help to enhance the availability and transport of farm inputs, crops, and livestock products, and to reduce the transaction costs of marketing farm productions. Such investments will increase the value generated by farmers using scarce renewable freshwater resources, while improving food security. Investments in water supply and water quality are essential to ensure arability of freshwater to enhance food production. Innovations in water supply and governance will be needed in many areas, partly because of the increasing competition for limited freshwater supplies. Given the future increase in competition for water demands across different development sectors, innovative systems will be required for water rights, allocation, governance, development, and management.

15.6. SUMMARY

Understanding water, food, and energy interconnections could help to determine the framework that synergizes all of these resources together. Regional projections indicate that demand for freshwater resources, energy, and food will increase significantly over the next decades in West Asia under the pressure of the growing population, economic development, urbanization, cultural and technological changes, and climate change. This study indicates that a sustainable future is possible in West Asia within the range of the available resources if efforts are focused on managing these resources properly. The inventory and evaluation of the best available water, food, and energy technologies show that there is room for improvement in human development aspirations that are compatible with reversing natural degradation trends and with the building up of a more adaptable and more resilient society. However, the relative optimism of this conclusion cannot shade the magnitude of the challenge of transforming the promise into a reality. A particular emphasis has to be placed on increasing the water use efficiency in agriculture and energy productions and also on increasing the energy use efficiency in water and food productions. Legal and intuitional reform is essential to minimize the fragmentation in responsibilities and resources wastage. Political wells are needed to develop new perspectives on the water, food, and energy nexus in the region to ensure the linkages between the nexus and sustainable economic growth; how the nexus is integrated into national planning; incorporating the nexus into economic, finance, and development policies; how nexus risks are considered by private and public investors; and the role of the nexus in the future development agenda of the region.

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16

Assessment of Water, Energy, and Carbon Footprints of Crop Production: A Case Study from Southeast Nepal

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ABSTRACT

This study aims to assess the water, energy, and carbon footprint of crop production under the groundwater irrigation system in Nepal. The productivity of cereal crops was found to be better than the national average in Raniganj, although their yields are still below potential either due to insufficient resource inputs or because of inefficient use of it. The maize and rice production showed relatively better yields per unit of water and energy inputs, whereas wheat showed poor performance. The wheat crop required the largest quantity of water (1938 m^3) and energy (3734 MJ) resources to produce 1 ton of wheat. The carbon emission rate was also the highest (153.8 kg/ton). Maize production seems to be the most water- and energy-efficient farm business; it requires almost half of the resources used in wheat production for each ton of yield. Also the carbon emission per ton of maize yield showed a significantly low value of 65.7 kg/ton. However, rice is the most water-intensive crop but requires the least irrigation water and associated energy input due to excess water from monsoon rainfall during the season.

16.1. INTRODUCTION

Of all the natural resources, water, energy, and food are most needed to sustain life on earth. These three strategic resources are facing constraints on a global scale due to rapid growth in their demand [*FAO*, 2011]. Moreover, the global water cycle, carbon energy cycle, and food production are inseparably linked. Since they are essential to maintain functioning of any society, they represent a deep issue for resources conservation [*UNESCAP*, 2013].

Water and energy are the primary components of any production process, and the appropriate management of these resources significantly impacts on the total yield and benefits. Global crop production has expanded threefold over the past 50 years, largely through higher yields per unit of land and crop intensification [*FAO*, 2011]. Cereal crops occupy more than half of the world's harvested area and are the most important food source for human consumption. Irrigated agriculture plays a crucial role in the global food production system, accounting for more than 40% of the world's production on less than 20% of the cultivated land [*Rothausen and Conway*, 2011; *Soto-García et al.*, 2013]. Evidence has shown that irrigated crop yields are about 2.7 times higher than those from rainfed farming on a worldwide scale [*WWAP*, 2012].

Energy consumption is the essential component for any agricultural production process, either in the form of direct mechanical operation or indirect energy input. The increasing use of energy resources (machinery and fertilizer) has boosted agriculture productivity, hence resulting also in higher greenhouse gas (GHG) emissions from these sectors [*Eurostat*, 2012]. Agricultural farms emitted 6 billion tons of GHGs in 2011, or about 13% of total global emissions, which makes the agricultural sector the world's second largest emitter, after the energy sector [*Russell*, 2014].

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In developing countries, the energy and water use for agriculture largely remains inefficient [*Chen et al.*, 2008; *Jackson et al.*, 2011]. The tendency toward inefficient input systems and current levels of energy inefficiency in agricultural systems may be due to a lack of awareness and low energy costs. However, this scenario has been changing under current circumstances, where energy and water costs are becoming prime factors for producers and one of the fastest-growing costs [*Chen et al.*, 2008]. The energy-yield relationship is becoming increasingly important with enhanced mechanization and agricultural intensification, considered to be the only means of boosting agricultural production in land-limited situations [*Mushtaq et al.*, 2009].

In many instances, the management of resources is considered separately and can improve one sector in particular but could create problems in others. To avoid unwanted consequences, the nexus approach can be a guiding tool for policy- and decision-makers. The nexus approach basically focuses on the interdependence of resources (water-energy-food) by understanding the challenges and finding opportunities. The general principle behind this approach is to produce more with less water and energy; and cutting down the associated GHG emission.

The agriculture sector in Nepal is the prime means of livelihood of the people and also the basis of national economy. It provides employment to two thirds of the population and contributes to one third of the gross domestic product (GDP) [*NPC*, 2010]. The agricultural productivity of Nepal is still very poor compared to neighboring countries due to several constraints. In comparison to many other countries, the energy consumption pattern in Nepalese agriculture is also poor both in terms of quantity and quality [*Panta and Palikhe*, 2011]. The total energy consumption in the agriculture sector of Nepal in 2011/2012 was about 4.4 million GJ, of which almost one third was used for irrigation, mainly for pumping activities [*WECS*, 2014].

The conventional approach to studying agricultural production processes is largely limited to analyzing cropping intensity, crop yields, and economic impacts [*ADB*, 2012]. There has been a lack of comprehensive study considering the issues of water and energy resource use performances and associated carbon emissions. Groundwater abstraction is one of the energy-intensive farm operations and has become an important contributor of GHG emissions [*Devi*, 2009; *Wang et al.*, 2012]. Currently more than 0.363 million hectares (M ha) of agricultural land in Nepal is undergoing irrigation from nearly 104,000 shallow tubewells (STWs) and some 900 deep tubewells (DTWs), and there is still a huge potential to expand the irrigation over 1 M ha in Terai by increasing the number of tubewells [*GRDB*, 2012]. A small change in the water-energy nexus can bring about big savings of water and energy and reduction in associated GHG emissions on the national scale. Therefore, this study aims to assess the water, energy, and carbon footprint of crop production under groundwater irrigation systems in Southeast Nepal.

16.2. STUDY AREA

16.2.1. Study Site and Its Climate

The study area is located in Raniganj Village Development Committee (VDC), Sarlahi district, in the southeast region of Nepal, at a latitude of 27°2′N and longitude of 85°39′E, and an average elevation of 125–180 m above sea level (Figure 16.1). The VDC is situated at the base of Churiya hill, stretching from north to south covering a total area of 18.1 km^2. The general topography is flat terrain in between the two intermittent rivers Phuljor and Kalinjor that gently slopes toward the south.

The climate in the study area is subtropical with reasonably hotter summers and mild winters. The maximum mean annual temperature is 31°C and minimum is 20°C. The mean annual rainfall of the study area is 1780 mm [*DHM*, 2012]. There is concentrated rainfall of nearly 80% during the monsoon period from June to October.

16.2.2. Land Use and Soil Type

The land cover of Raniganj is distributed among agriculture, forest, settlement, and river sands, with the largest share comprised of the agriculture sector. At the foothill of Churiya hill in the northern are, about 20% of the total area (i.e., about 4 km^2) is covered by shrub forest. Agricultural land is concentrated in the middle and southern parts covering almost 65% of the total area.

The soil texture in the study area is of a mixed type. There is coarse-textured soil with fine gravel in the northern part and relatively alluvial medium to fine-textured soil in the southern part. The nutrient content of alluvial soil in the study area is fair to medium and is suitable for almost all kinds of cereal crops and vegetables [*DADO*, 2012].

16.2.3. Agriculture and Irrigation System

Agriculture is the main occupation of the people in Raniganj, with almost 80% of the population involved in it. The study area is suitable for all kinds of cereal crops and vegetables: primarily rice, maize, wheat, legumes, oilseeds, and sugarcane are the major commodities grown [*DADO*, 2012]. There are basically two main seasons for agriculture: the wet season (*Kharif*) and the cool dry season (*Rabi*).

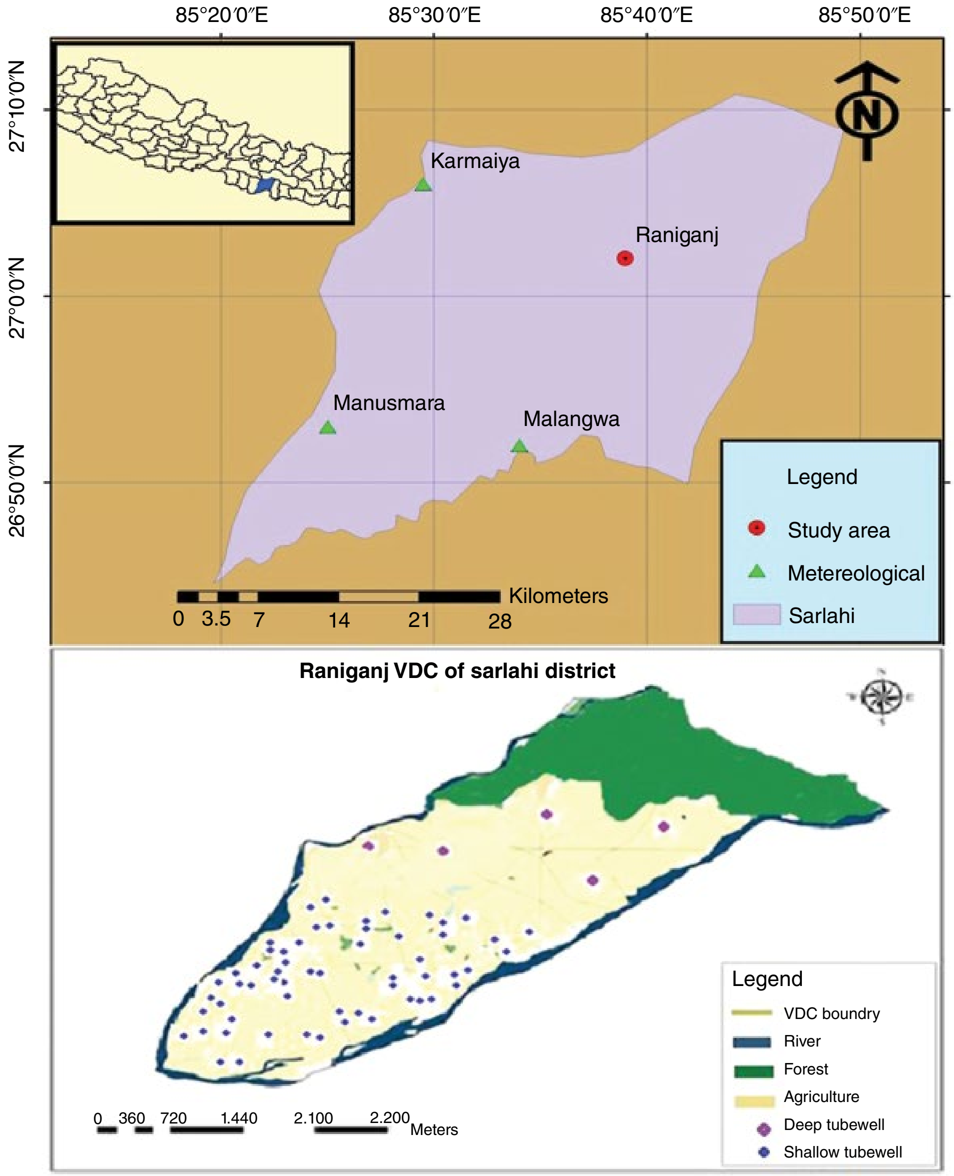


Figure 16.1 Location of Raniganj VDC in Sarlahi district, Nepal. (*See insert for color representation of the figure*.)

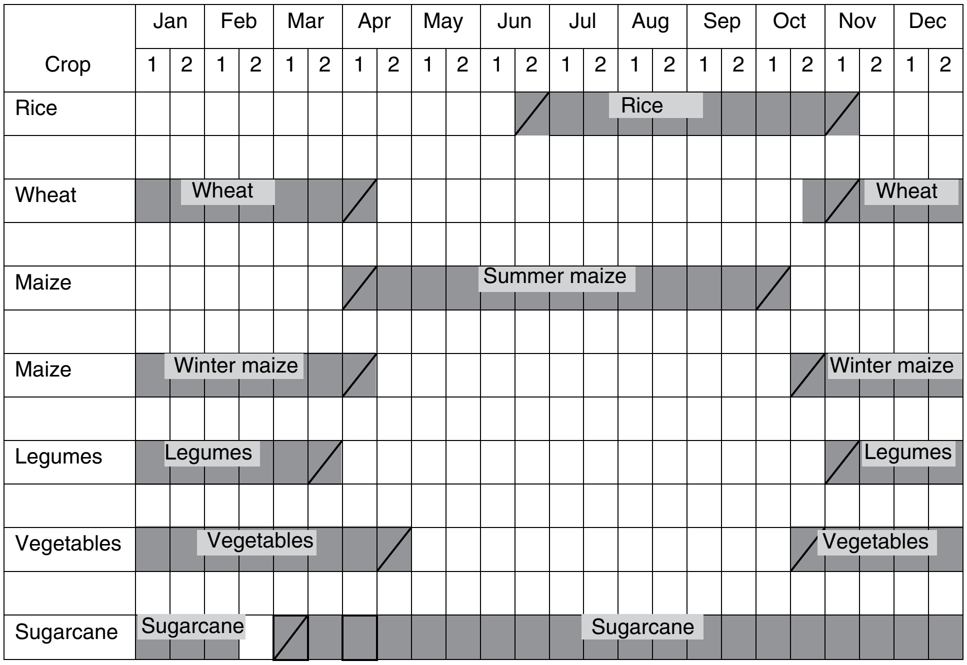
Rice and summer maize are primarily grown in the wet season whereas wheat, winter maize, oilseeds, legumes, and vegetables are grown in the dry season. In the irrigated farms, maize is cultivated in both seasons. The cropping calendar of the major crops grown in Raniganj is shown in Table 16.1. Seed bed preparation, planting, weeding, fertilizer application, irrigation, and harvesting are the major agricultural activities performed to complete the cropping calendar of Raniganj.

Due to geographical constraints, the development of a surface irrigation system has not been possible, and groundwater is the only source of irrigation water in Raniganj. So far, 5 DTWs and 46 STWs have been developed and used solely for irrigation in Raniganj. The total tubewell system covers 25% of the agricultural land and farmers are still bound to conduct rainfed farming in the remaining area.

However, both kinds of tubewells for irrigation exist in Raniganj. Farmers usually prefer DTWs because of their reliability. DTWs tap groundwater from more than one aquifer, and usually have a depth of 90–150 m. They are characterized by their depths (100–150 m), big tubewell size (12–14 inch), and large command area (30–40 ha) in the study site.

Farmers practice traditional flooding methods of irrigation on cereal crops and furrow methods on

Table 16.1 Cropping calendar of major crops in the study area



Source: *Field Survey* [2012].

some vegetables. This supplies 3–4 irrigations for maize, 2–3 for wheat, and 1–2 for rice. A minimum amount of irrigation is required for rice due to available excess rainfall during the season.

16.3. METHODS AND DATA

16.3.1. Sample Selection and Field Survey

The methodology adopted in this study is structured into several steps. First, a set of field-level data were collected in November 2013 through a designed survey approach. The survey design includes a selection of tubewells and farmer households based on a random sampling approach, a questionnaire, and an analysis of survey data. The energy and carbon auditing approach was used to examine the energy use efficiency and environmental footprints of major crop production. Two DTWs having different capacity of pumps and the most commonly grown crops (i.e., rice, wheat, and maize) were selected and the detailed methodology adopted for the study is presented in Figure 16.2.

16.3.2. Water, Energy, and Carbon Emission Budget

The monthly and seasonal irrigation supply rates reported by the farmers were used as baseline data. The irrigation volume was determined based on the pump discharge and total irrigation hours. The average irrigation efficiency for the tubewell system was assumed to be 50% as suggested by the Agriculture Development Project Janakpur (ADPJ). The energy data used for pumping units were collected as per the monthly records of their energy (electricity and diesel) bills as reported by the pump operators.

In addition, the total energy inputs for crop production at farm level were quantified based on the energy audit method used by *Hatirli et al.* [2006] and *Khan et al.* [2008]. Resource inputs used at the farm level from land preparation to harvesting were quantified based on the information provided by the farmers. Crop cultivation, irrigation supply, fertilizer application, and harvesting are the major agricultural activities requiring energy inputs. The equivalent energy contents of the farm inputs were reviewed from the previous studies and used for the accounting method (Table 16.2).

Each type of farm inputs is responsible for direct or indirect carbon emissions. The equivalent CO_2 emission is estimated from the total amount of energy associated with an input (Mega Joule) and by multiplying it with equivalent emissions factors ($CO_{2\text{-e}}$). This method has been used in several previous studies [*Barber*, 2004; *Khan et al.*, 2008; *Jackson et al.*, 2011]. Animal and human labor was not included in the emission budget. The equivalent emission resources used for this study are given in Table 16.3.

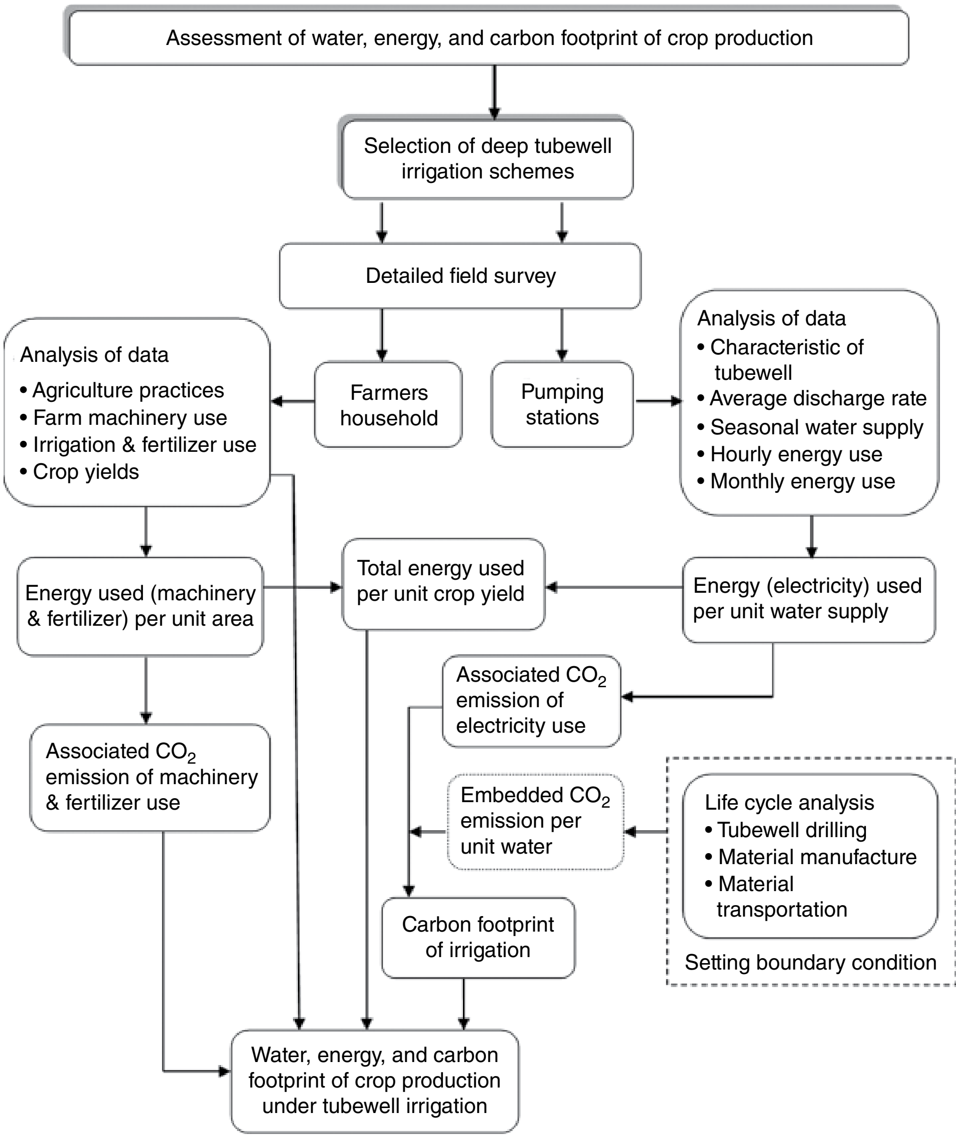


Figure 16.2 Methodological framework for the assessment of water supply, energy, and carbon footprints of crop production under deep tubewell scheme of Raniganj.

Table 16.2 Energy content of various farm inputs relevant to this study

Resources	Energy equivalent	Reference
Machinery	62.7 MJ/ha	*Mushtaq et al.* [2009]
Diesel	38.6 MJ/L	*Jackson et al.* [2010]
Animal (Ox)	10 MJ/day	*FAO* [2000]
Human	1.96 MJ/day	*Ozkan et al.* [2004]
Urea	23.93 MJ/kg	*Ledgard et al.* [2010]
DAP	12.35 MJ/kg	*Ledgard et al.* [2010]
Nitrogen	65.0 MJ/kg	*FAO* [2000]
Phosphate	9.0 MJ/kg	*FAO* [2000]
Seed	14.0 MJ/kg	*FAO* [2000]
Insecticides	200 MJ/kg	*FAO* [2000]

Table 16.3 Established CO_2 emission factors of various farm inputs relevant to this study

Resources	Energy equivalent	Reference
Machinery	62.7 MJ/ha	*Mushtaq et al.* [2009]
Diesel	2.679 kg $CO_{2\text{-}e}$/L	*Carbon Trust* [2008]
Electricity	0.004 kg $CO_{2\text{-}e}$/kW	*Defra* [2010]
Nitrogen	3.25 kg $CO_{2\text{-}e}$/kg	*Barber* [2004]
Urea	0.93 kg $CO_{2\text{-}e}$/kg	*CSE* [2009]
DAP	1.79 kg $CO_{2\text{-}e}$/kg	*Wood and Cowie* [2004]
Phosphate	1.94 kg $CO_{2\text{-}e}$/kg	*Wood and Cowie* [2004]
Potash	0.16 kg $CO_{2\text{-}e}$/kg	*Wood and Cowie* [2004]

16.4. RESULTS AND DISCUSSION

16.4.1. Direct Energy Resources Used for Agriculture

Rice, wheat, and maize are the most commonly grown cereal crops in Raniganj using groundwater. As identified earlier, energy consumption is the essential component for any agricultural production process; the total energy inputs/ha/year of cultivation was estimated for these three major crops grown. This study primarily considers the resources used for crop cultivation, harvesting, irrigation, and fertilizer use. The energy resources used for different farm activities of crop production have been considered as average value of the selected two DTWs. The type and quantity of resources used per hectare of cultivation in Raniganj are shown in Table 16.4.

The resource inputs for agriculture consist of diesel fuel, electricity, animal power, human labor, fertilizer, and manures. Diesel fuel is used in tractor and machinery operation for land preparation and threshing of crops and electricity is used for groundwater pumping. The use of animal power in the farm is limited but human labor is vital in every activity. Fertilizer and farm machinery have indirect use of energy. Manure use is not regular and is decreasing in trend, so its values are not considered in total resource inputs. The energy inputs to various agricultural operations were found to be similar to those at the farm level.

16.4.2. Indirect Energy Resources Used in Agriculture

Energy resources associated with irrigation water, chemical fertilizer, and pesticides are considered as indirect uses of energy to agriculture. Since farmers make occasional use of pesticides on cereal crops in Raniganj, only irrigation water and fertilizer have been considered as components of indirect use of energy resources. In general, farmers apply 100 mm of irrigation and 80 kg/ha of nitrogen fertilizer as average farm inputs to rice fields. Similarly, on average, 110 mm of irrigation and 80 kg/ha of N fertilizer for wheat and 170 mm of irrigation and 100 kg/ha of N fertilizer for maize crops are used. Table 16.5 shows the indirect energy use in terms of irrigation and fertilizer application for major crops and the resulting yields.

The comparative figures in Table 16.5 indicate that maize crop required the largest volume of irrigation water (6055 m^3) and associated energy (3084 MJ) per hectare of cultivation. The lowest quantity of water (3114 m^3/ha) and energy (1627 MJ/ha) were used for rice crop because of excess rainfall during the rice season in Raniganj. Similarly, energy inputs through fertilizer application were the highest for maize crop. Along with these resource inputs maize had the highest yield of 7.5 ton/ha while wheat had almost one third the yield of maize.

16.4.3. Total Energy Inputs to Various Farm Operations

Broadly, cultivation, irrigation, fertilizer application, and harvesting were identified as the four major farm operations requiring energy inputs. For a given crop, cultivation and harvesting operations were almost identical at the farm level, consuming almost the same energy inputs. The rate of fertilizer and irrigation applications was found to vary significantly from one farm to another.

Table 16.4 Energy resources used per hectare of cultivated land for different farm activities in Raniganj

	Rice			Wheat			Maize		
Activities	Labor (No)	Diesel (L)	Animal (No)	Labor (No)	Diesel (L)	Animal (No)	Labor (No)	Animal (No)	Diesel (L)
Cultivation	5	28		4	22		4	4	22
Planting	40			5			12	6	
Weeding	30						30		
Irrigation	4			6			6		
Fertilizer	—	—	—	—	—	—	—	—	—
Harvesting	30			25			25		
Threshing	6	12		8	12		8		11
Total	**115**	**40**		**48**	**34**		**85**	**10**	**33**

L is liters; No is numbers.

Table 16.5 Indirect energy use (irrigation and fertilizer) for crop production in Raniganj

Crops	Irrigation water used (m^3/ha)	Irrigation energy used (kWh/ha)	Nitrogen fertilizer used (kg/ha)	Fertilizer energy used (MJ/ha)	Crop yield (ton/ha)
Rice	3114	1627	80	5200	4.25
Wheat	4844	1995	80	5200	2.5
Maize	6055	3084	100	6500	7.5

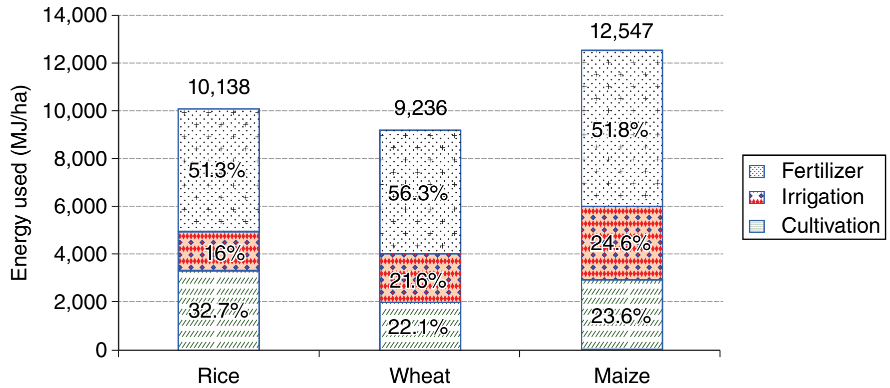


Figure 16.3 Proportion of energy used for different agricultural operations of rice, wheat, and maize production in Raniganj.

The crop production process of Raniganj was evaluated in terms of energy inputs to cultivation, irrigation, and fertilizer use. Here cultivation includes both cultivation and harvesting operations. Figure 16.3 presents farmers' existing practice of energy resources through different agricultural activities of cereal crop production. It shows that the highest energy input per hectare of cultivated land was required by the maize crop (12,547 MJ/ha) followed by rice (10,138 MJ/ha) and wheat (9236 MJ/ha).

Indirect energy inputs through the application of fertilizer represent the highest proportion of total energy inputs for all crops. The current application rates of fertilizer amount to almost 56% of total energy inputs to wheat and 51% to rice and maize. The cultivation and harvesting operations together comprise the second largest energy-consuming farm operations, with a minimum value of 2041 MJ/ha for wheat and a maximum of 3311 MJ/ha for rice. The highest use of cultivation energy is in the rice field because of specialized requirement of land preparation and labor-intensive planting and weeding operations. The lowest share of energy inputs (16–25%) were for irrigation.

16.4.4. Carbon Emission Associated with Crop Production

Since every level of energy resource use is associated with certain units of GHG emission, the equivalent carbon emission from crop production was estimated using the established emission factors of the resources used. The equivalent carbon emissions associated with crop production are directly related to the energy inputs, mainly diesel fuel for farm machinery operations, pumping irrigation water, and application of chemical fertilizer. The diesel fuel for machinery operation and chemical fertilizer for application are the major carbon contributors. The electricity used for pumping irrigation water was fully obtained from hydropower and no direct emission was considered from it.

Table 16.6 Energy input per hectare of crop cultivation and associated carbon emission in Raniganj

Crop	Total energy used (MJ/ha)	Equivalent carbon emission (kg $CO_{2\text{-}e}$/ha)	Equivalent carbon intensity (kg $CO_{2\text{-}e}$/ton)
Rice	10,138	400.2	94.2
Wheat	9,236	384.4	153.8
Maize	12,547	499.6	65.7

Table 16.6 indicates that the total carbon emission (kg $CO_{2\text{-}e}$/ha) is directly proportional to the total energy inputs. As with energy consumption, maize cultivation showed the largest equivalent CO_2 emissions of 499.6 kg/ha followed by rice (400.2 kg/ha) and wheat (384.4 kg/ha). But the emission rate per ton of crop production is the lowest for maize and almost double for wheat. Methane emissions from the flooded paddy field were not considered here.

16.4.5. Water, Energy, and Carbon Footprints of Crop Productions

Water and energy resources required per ton of crop production and the associated carbon emission were further estimated for a comparative understanding of resource use benefits and compared with the results of similar studies conducted in other parts of the world. Table 16.7 shows the water, energy, and carbon intensity of rice, wheat, and maize production in the Raniganj area.

The comparative figures indicate that wheat crop required the largest quantity of water (1938 m^3) and energy (3734 MJ) resources to produce 1 ton of wheat. The carbon emission rate was also the highest (153.8 kg/ton). Maize production seems to be the most water- and energy-efficient business; it requires almost half of the resources used in wheat production for each ton of yield. The environmental footprint per ton of grain produced is

Table 16.7 Water, energy and carbon footprints of crop production in Raniganj

Crop	Crop yield (Mt/ha)	Irrigation water intensity (m^3/ton)	Energy use intensity (MJ/ton)	Equivalent carbon intensity (kg $CO_{2\text{-}e}$/ton)
Rice	4.25	733	2385	94.2
Wheat	2.5	1938	3734	153.8
Maize	7.6	797	1651	65.7

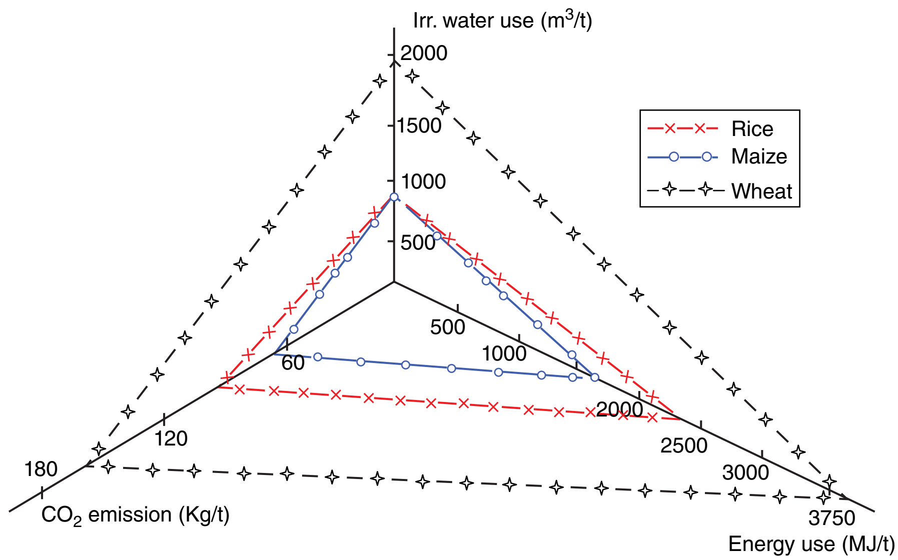


Figure 16.4 Web diagram, showing the comparative use of irrigation water, energy, and associated carbon emission to produce 1 ton of rice, maize, and wheat in Raniganj.

significantly low for maize (65.7 kg/ton) and rice (94.2 kg/ton) compared to that for wheat. The reason that rice needs the least irrigation water intensity and associated energy inputs, in spite of being one of the most water-intensive crops, is because of its cropping calendar. As it is cropped during the rainy season, most of its water requirements are met by rainfall, and therefore less irrigation water is required. The lesser requirement of water intensity for maize is also attributed to its cropping season, which mostly spans across the rainy season.

Figure 16.4 also illustrates a comparative study of water, energy, and carbon footprints of crop production in Raniganj. It indicates that the irrigation water required was almost the same for producing 1 ton of rice or maize, but for wheat it was almost 2.5 times that of maize. However, there is no significant difference of energy requirement and associated carbon emission per ton of rice or maize produced but for wheat both values seem to be significantly high.

Khan et al. [2009] evaluated the quantity of energy required to produce 1 ton of rice and wheat as 2436 and 2240 MJ, respectively, in South Australia. The energy intensity of rice produced in Raniganj (2385 MJ) seems to be very similar to that of South Australian farms, but it showed significantly higher value (1.5 times) for wheat (3734 MJ/ton). This indicates that there exists a large scope for improvement in energy efficiency and in cutting down the carbon emission per unit of wheat production in Raniganj. *Pathak and Aggarwal* [2012] estimated the CO_2 emissions per ton of rice (26.7–54.7 kg) and wheat (51–67 kg) produced in the Indogangetic plain of India. These figures are much less (one third) in comparison to Raniganj's emission rates because the researcher did not consider the separate groundwater-irrigated farms of the Indogangetic plain. This gives a clear picture that wheat production under current practices in Raniganj is highly water, energy and carbon intensive, giving the least benefit, in comparison, to rice and maize. It would be wise to shift from wheat to maize cultivation in Raniganj, because it would not only increase the resources use efficiency but also reduce the total carbon emission from the production processes.

16.5. SUMMARY AND CONCLUSION

Water and energy are the primary components for any agricultural production process. The agriculture sector consumes energy resources through both direct and indirect modes and each unit of consumption is responsible for an equivalent carbon emission in the atmosphere. Due to high energy requirements and various biological processes, the agriculture sector has become the second largest GHG emitter after the energy sector.

Farmers in this study area are making use of all types of energy resources (fossil fuel, electricity, chemical fertilizer, human labor, animal power) to drive their farm business. Rice, wheat, and maize are the commonly grown cereal crops in Raniganj. However, although the productivity of cereal crops was found to be better than the national average in Raniganj, their yields are still below potential either due to insufficient resource inputs or inefficient use of it. Maize and rice production showed relatively better yields per unit of water and energy inputs, whereas wheat showed poor performance.

Wheat crop required the largest quantity of water (1938 m^3) and energy (3734 MJ) resources to produce 1 ton of wheat. The carbon emission rate was also the highest (153.8 kg/ton). Maize production seems to be the most water- and energy-efficient farm business; it requires almost half of the resources used in wheat production for each ton of yield. Also the carbon emission per ton of maize yield showed a significantly low value of 65.7 kg/ton. However, rice is the most water-intensive crop but requires the least irrigation water and associated energy input due to excess water from monsoon rainfall during the cropping season.

The lower values of water, energy, and carbon footprints of maize produced in Raniganj indicate it has good resources use efficiency whereas for wheat production resources use efficiency is very poor. The productivity of irrigation water and energy inputs of Raniganj's agriculture system can be increased either by introducing a high yielding variety of wheat or shifting from wheat to maize crop.

The energy content and embedded carbon emission associated with farm machineries manufacturing and transportation were not considered in this study due to unavailability of reliable data. Also the water from rainfall and soil moisture was not counted. It is recommended to further study these two factors of machinery and natural water use to estimate more accurate values of water, energy, and carbon footprints of crop production of any region.

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17

The Food-Water-Energy Nexus in Modern Rice Cultivation in Bangladesh and Competing Discourses of Rice Research Institutions

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ABSTRACT

In Bangladesh, rice is the staple food and a primary source of renewable energy in rural regions. This chapter examines dominant discourses within public rice research institutes in Bangladesh and internationally, namely of the Bangladesh Rice Research Institute (BRRI) and of the International Rice Research Institute (IRRI), expressed in text published by such institutions between 1971 and 2015, primarily to investigate how rice modernization has been framed by them, and whether this has been beneficial for Bangladesh, in particular for rice farmers. It also investigates rice farming using a "food-water-energy" nexus, and tries to understand whether such discourses are prevalent in BRRI and IRRI. It suggests that the approach of these two institutes has not been holistic but focused on rice production, and has ignored the full relevance of rice to rural communities.

17.1. INTRODUCTION

Since the 1960s, rice modernization has been practiced in Bangladesh as a solution to rice scarcity, and yet, very little critical scholarship focuses on how rice farmers have been impacted by modern rice and farming methods in Bangladesh, and on how these types of farming were introduced by leading public policy institutes. This chapter explores the matter by asking how discourses about rice modernization and farming have affected rice production and farmers in Bangladesh, and how a food-water-energy nexus weighs in as a form of discourse within leading public policy research institutes in Bangladesh.

Crop modernization was first introduced to East Pakistan (previous name of Bangladesh) in the 1960s as a requirement of the Lyndon B. Johnson administration in the United States which restricted aid to population control and agricultural modernization programs only, and at the request of President Ayub Khan of Pakistan [*Wilcox*, 1965; *Cleaver*, 1972, p. 179; *Khan*, 1996]. It was endorsed by the Government of Bangladesh after the 1971 War of Independence from Pakistan. Since then, food trade and food aid have also been introduced to increase the circulation of food in Bangladesh, typically when there was scarcity [*Davis*, 2001, p. 88]. In the 1970s, 1980s, and 1990s, trade and capital liberalization were prescriptions to the Third World by the World Bank (WB) and the International Monetary Fund (IMF) [*Tabb*, 2004]. Addressing scarcity by increasing circulation of goods is, however, a much older idea that originated in Europe in the writings of Abeille and other physiocrats, while Thomas Malthus argued for increasing food production to combat overpopulation [*Malthus*, 1798; *Foucault*, 2009]. Using redistribution to address food scarcity was also a state practice within ancient Indian civilization and argued for by Kautilya in Arthashastra [*Sen*, 1997, pp. 20–21].

To develop modern high-yield varieties of rice, the East Pakistan Rice Research Institution was established in

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Dhaka in 1970, as an autonomous institution, and later renamed the Bangladesh Rice Research Institute (BBRI) in 1973, and the Bangladesh Agricultural University was established in 1961 in Mymensingh [*Chandler*, 2000, p. 188; *BRRI*, 2015, p. 2]. At the same time, in the Philippines, the International Rice Research Institute was established in the 1960s, with a grant from the Ford and Rockefeller Foundations [*IRRI*, 2015a]. IRRI became the central rice research institute in the world after its scientists introduced "IR8" rice, a type of modern rice which was said to be able to withstand floods, a common problem in Asia [*Chandler*, 1992, p. 51; *Ashikari and Matsuoka*, 2002, pp. 1–11]. Between 1973 and 2015, 317 scholars and 781 short-term trainees from BRRI and other rice research organizations received training at *IRRI* [2015b].

Foreign aid to Bangladesh also allowed for development of private seed and agricultural input markets. The USAID and other donors provide funds to the Bangladesh government to create local companies that became distributors of high-tech farming equipment and chemical fertilizers [*Hossain et al.*, 2006]. By the 1990s, Bangladesh was able to produce urea for local consumption and for export to India [*Economist*, 1995]. As of 2014, the USAID and other donors began promoting seed companies in major agricultural conferences in Bangladesh, where Paul Dorosh and others spoke.

However, these methods are not without problems. Imports and food aid are increasingly seen as inadequate measures, especially after the 2005–2008 speculative shocks to crop prices that led to rice-exporting nations like India to consider banning rice exports to neighbors such as Bangladesh [*Lewis*, 2008; *Management Today*, 2008; *Dorosh and Rashid*, 2012]. The argument that increasing rice production could solve food scarcity has also been dismissed by *Dreze and Sen* [1989, pp. 1–20], who showed that the famine of 1974–1975 in Bangladesh and the Bengal Famine of 1943–1944 were caused by problems of food distribution and in fact occurred during bumper-crop years. Rehman Sobhan has argued that food aid from the United States was used to garner political votes from Bangladesh during the Organization of the Petroleum Exporting Countries (OPEC) price hike of 1975, and failure to follow through resulted in food aid being delayed [*Sobhan*, 1979, pp. 1973–1974]. Other problems included matters of food aid distribution, such as theft of grains and delays [*Dorosh and Rashid*, 2012].

In the 1990s, a subfield emerged within the social sciences to investigate "hidden" social and ecological costs in policy decisions, such as in food and agriculture, which resulted in questioning both trade and bioengineering of rice. Within this framework, scholars began investigating various "nexuses" or "connections" between food, water, and energy, such as in the extraction, distribution, and consumption phases, to understand the impact of public policies. They urged the use of a "systems thinking" to examine the larger impact of public policies and, as such, to be more inclusive of communities affected, to consider ecological impacts, and also to be critical of technology and trade/markets [*Bazilian et al.*, 2011, p. 7897]. "Nexus" scholars are thus concerned with examining food, energy, and water securities as a totality.

Terms such as "ecological footprint" coined by *Wackernagel and Rees* [1996] and "carbon footprint" have emerged from this discourse of "hidden costs" of resource use [*Allan*, 2003, p. 8; *Wiedmann and Minx*, 2008, p. 2]. Some scholars use the term "virtual water" to make explicit the hidden levels of water use in the production of food that is for consumption or export [*Allan*, 2003, p. 5]. Others such as *Wiedmann and Minx* [2008, p. 2] show that there is a lack of consensus on measures of indicators in the field related to hidden costs. *T. Allan* [1997, pp. 2, 12] suggests that scholars have faced pressure from world governing agencies such as the World Bank to not use the term "virtual water," thus suggesting a close relationship between discourse and power. Environmental activists, such as Vandana Shiva, have articulated hidden costs to farmers from the privatization of seed, such as from patenting of genetically modified seed that is protected by the World Trade Organization and that is distributed by Monsanto and other seed companies. Farmers in the United States and internationally have filed lawsuits against Monsanto and others whose seed has genetically infected farmers' crops from neighborhood fields, and many farmers were sued by Monsanto for using seed without paying royalties [*Shiva*, 2001]. Shiva discursively connects seed privatization and patents on seed to the broader context of world capitalism, colonialism, and patriarchy [*Shiva*, 1988, pp. 1–20].

Our chapter thus investigates (i) dominant discourses employed by BRRI and IRRI, and (ii) whether BRRI and/or IRRI conceptualize rice farming using a *food-water-energy nexus*. We do so by examining (i) the role of water as a threat to rice farming and the consequent development of so-called water-suitable modern rice varieties; (ii) the use of water and modern irrigation methods as an input in rice farming; (iii) the role of rice in rural energy security; (iv) the role of energy and chemical inputs in rice farming; and (v) the total impact of rice modernization on rice farmers in Bangladesh.

17.2. APPROACH

We use "critical discourse analysis" as our main approach, and follow with simple quantitative analysis. Using critical discourse analysis we uncover the dominant ideas conveyed in the "text" of IRRI and BRRI regarding rice modernization and the agricultural policies of the "state" that affect farmers and rice production. Here, "text" is any spoken, written, or visual representation that conveys attitudes of dominant groups or institutions toward a particular group or on a social issue. Comparative analysis of "text" is used to understand the leading ideas and attitudes or the "discourse" [*Phillips and Hardy*, 2002, pp. 4–5]. The discourse is understood in conjunction with the social practices that IRRI and BRRI encourage with respect to rice farming and their impact on rice farmers, leading to a "critical analysis."

The goal of critical discourse analysis is to show the relationship between knowledge and power. It is an approach in social sciences inspired by the writings of social philosophers such as Michel Foucault, Antonio Gramsci, and Karl Marx, who proposed a relationship between group or institutional power and knowledge about "multiplicities" or populations that such groups or institutions create. Some, such as Foucault, stress the importance of exposing dominant discourses of institutions, and understanding how they came about, and also how they changed over time [*Foucault*, 1972, pp. 1–15; *Fairclough*, 2013, pp. 1–10]. Others, such as Edward Said, investigate the relationship between discourse and forms of oppression [*Said*, 2003; *Chowdhry*, 2007].

For this chapter, primary documents from the 1971 to 2016 time frame served as "text" of IRRI and BRRI, usually from their web sites or from journal-published articles. Recent documents on the BRRI web site were mainly marketing manuals and guides to its farming methods, and offered statistics on rice varieties and methods. Journal articles of scholars employed by BRRI and IRRI were also used to understand how BRRI promoted these methods. Quantitative data from the Bangladesh Bureau of Statistics (BBS) publication, *Statistical Pocketbook of Bangladesh 2006*, *2010* and *2013*, were additional data sources on rice farming in Bangladesh. BBS is a government agency in Bangladesh in charge of major statistical surveys, such as the census.

Much of the data collection was part of earlier research conducted by Sophia Barkat during 2007–2009, and was updated recently. Over time, BRRI and IRRI web sites have changed, requiring information to be updated. The particular web sites used were www.irri.org (IRRI) and www.brri.gov.bd (BRRI). Until 2009, the BRRI web site was http://www.brribd.org, which no longer exists. BRRI web pages had to be translated from Bangla to English.

17.3. FINDINGS

17.3.1. Water as a Threat

This section explores dominant discourses of both IRRI and BRRI that have closely shaped rice modernization in Bangladesh. IRRI and BRRI both discursively connect water and rice in particular ways which frame their institutional goals of rice modernization and portray scientists and engineers as the saviors of rice farmers. Water is said to play the dual role of "destroyer" and "savior" in the context of agriculture in many parts of Asia, not just Bangladesh. According to IRRI, food scarcity is a matter that scientists and engineers (and not farmers) can solve, because only they can make crops "water suitable" or "water resistant." Thus, in a 1984 publication on terminologies for rice farming, most scientists mention that they have limited knowledge about rice but also propose that they must develop such knowledge. M. S. Swaminathan of IRRI stated: "Rice must be developed that are adapted to drought and/or flooding, very high or low temperatures, and to salinity and other soil problems" [*Swaminathan*, 1984]. In the document, G. S. Khush showed the large variety of rice-growing environments in Bangladesh and other regions of Asia, and listed specific types of rice desired for those regions, some of which are shown in Table 17.1 [*Khush*, 1984, pp. 6–10].

Table 17.1 Type of water-terrains in Bangladesh and desired rice seed qualities

Type of terrain	Region description	Type of seed and rice plant desired
Irrigated, low temperature, tropical zone	Northern areas of Bangladesh	Boro rice. Cold tolerance at seeding stage, blast tolerance
Rain-fed shallow, drought prone	6–7 million ha in India and Bangladesh; plants are broadcast and then transplanted to the field	Aus crop: photoperiod-insensitive varieties with shorter maturity (90–105 days), medium height, and drought tolerant
Rain-fed shallow, submergence prone	Floods can submerge rice for up to 10 days at a time; rainy season lasts for 5–6 months	Rice must survive submergence
Rain-fed medium deep, waterlogged	Low-lying lands: water stagnates up to 2–5 months; has poor drainage; water depth is 25–50 cm	Semi-dwarf rice: height 110–120 cm, photoperiod insensitive
Deep water	Water depth is 50–100 cm	Tall rice: drought tolerant at seeding; can survive stagnant water; has photoperiod sensitivity

Source: Data from *IRRI* [1984, pp. 6–10].

Terms like "photoperiod sensitive" and "blast tolerance" are scientific terms, and not used by farmers in Bangladesh. In the same publication, D. P. Garrity stated that rain-fed rice varieties are to be developed [*Garrity*, 1984, 12]. In the 1990s, when IRRI added "integrated pest management" to its goals, the emphasis on using engineering and science, as opposed to indigenous technologies and knowledge, remained the same. Nowhere was it considered that local farmers might already grow such rice varieties.

By the 1990s, IRRI had developed a sense that its scientists and engineers have superior understanding of rice than farmers. In 1993, an IRRI report used the word "primitive" to describe indigenous farming techniques [*Juliano*, 1993, p. 8; *Barkat*, 2009, p. 97]. In a 1998 document, *Bell et al.* [1998, p. 3] state as follows:

> Environmental concerns call for technologies to be developed to prevent or reverse the negative effects of agriculture and industrialization. In particular, diminishing soil and water resources can be more effectively managed through better engineering interventions to reduce erosion and contamination (pollution) and maintain adequate water quality…

They recommend "better management skills" for farmers [*IRRI A*, p. 2; *Barkat*, 2009, pp. 97–98]. *Juliano* [1993, p. 12] raises the matter that scholars such as *Feldstein and Poats* [1990, p. 12] have shown that female agricultural workers in rice farming lack appropriate technology for postharvest work, leading to poor rice yields [*Barkat*, 2009, p. 98].

As mentioned earlier, IRRI itself rose to prominence as the central rice research organization in the world after developing the first so-called water-resistant hybrid variety of rice, called IR-8-288-3, which was seen as a blessing in Asia [*Chandler*, 1992, pp. 51, 107–108; *Ashikari and Matsuoka*, 2002, pp. 1–11]. The quest to produce water-"resistant" or water-"suitable" IR8 derivatives in Bangladesh began when the BRRI received the gift of IR8 from IRRI. IR8 was, however, a short-stemmed rice variety and was not suitable for flood-prone and rain-fed regions, which is the case of two thirds of Bangladesh, and so BRRI could not release IR8 in its original form [*Herdt and Capule*, 1983, p. 2]. BRRI had to develop IR8 hybrids with Indica rice, which is indigenous to South Asia [*Ahmed*, 2007; *IRRI*, 2007].

In Bangladesh, farmers had grown rice to match local environments. About 24% of Bangladesh is completely flood prone. Various types of rice called "Aman" are grown in flood plains after floods subside by local farmers. On another 43.1% of the land which is rain-fed lowlands, only "Aus" rice and jute are typically grown by local farmers [*The Economist*, 2004, p. 76; *Swain et al.*, 2005; *World Bank*, 2008, p. 60]. "Boro" is the name for crop grown in winter and dry climates by local farmers. So local farmers have some kind of historical knowledge about the types of rice they grow and they don't grow them in the wrong time or place.

BRRI, however, developed hybrids between local Indica varieties and IR8, typically named, BR rice, BRRI dhan, and BRRI hybrid dhan ("dhan" is Bangla for "unhusked rice") [*BRRI*, 2015]. Over time, BRRI scientists developed modern rice varieties that were said to be "saline water resistant," "cold resistant," "drought tolerant," "best for rain-fed areas," "suitable for low-depression areas," and "photoperiod sensitive," all terms used by IRRI (see Table 17.1). In particular, BR8, BR17, BR18, and BR19 are modern varieties of rice that are said to be "suitable" for Boro-growing areas in the Northeast (for "haors" or depressed basins) [*BRRI*, 2014a, 2015, pp. 3–8]. BR20 and BR 21 are for Aus-growing areas or rain-fed upland regions [*BRRI*, 2015, pp. 3–8; *BRRI A*, pp. 3, 5]. BR11, BR22, and BR23 are said to be "photosensitive" [*BRRI*, 2015, pp. 3–8]. BRRI dhan 30, 31, 32, 33, 34, 37, 38, 39, 40, 41, 42, and 46 are for Aman-growing or "flood-prone regions" [*BRRI*, 2015, pp. 3–8; *BRRI A*, pp. 3, 5]. BRRI dhan27 was developed that is supposedly "suitable for non-saline tidal regions," while BRRI dhan30, BRRI dhan31, and BRRI dhan32 are suitable for "rain-fed lowlands" [*BRRI*, 2015, pp. 3–8; *BRRI A*, pp. 3, 5].

Of these, some rice varieties have high yields too. Between 1970 and 1998, ten rice varieties were developed by BRRI (BR3, BR8, BR9, BR14, BR16, BR17, BR18, BR19, and BRRI dhan 28 and 29) that were said to have "high yield" or "uncha fashal" (between 6 and 7.5 ton/ha) but had long cultivation cycles (155–170 days, or 5–6 months) [*BRRI*, 2014a, 2015, pp. 3–8; *BRRI A*, pp. 3, 5]. And between 1999 and 2014, 16 rice varieties were developed by BRRI that were said to have "high yield" (between 6 and 9 tons/ha), but much shorter cultivation cycles of 140–155 days [*BRRI*, 2015, pp. 3–8]. Today, about 50% of Aman, 33% of Aus, and 95% of Boro are modern rice varieties, and 79% of all rice in Bangladesh is modern or hybrid [*BRRI*, 2014b]. Increasingly, other rice research institutes, such as the Bangladesh Institute of Nuclear Agriculture (BINA), are being developed to grow modern rice varieties. IRRI recently stated that 73 high-yield rice varieties originated in Bangladesh including various submergence-tolerant, drought-tolerant, salinity-tolerant rice and some from research institutes other than *BRRI* [2015].

In the end, it is debatable how environmentally suitable or water sustainable such modern rice varieties are. Most of Bangladesh is prone to flooding. Rice grown in Aman and Aus seasons and regions cannot escape flooding. *Shankar and Barr* [2005, pp. 1–3] show that even in parts of northeast and north-central Bangladesh, where Boro rice is grown, floods are common during June and July. As Boro is a semi-dwarf rice variety and is not water-resistant, it cannot withstand floods.

Throughout Bangladesh, during the monsoon, the water depth usually exceeds 5 m, though dykes have reduced this to 1–3 m, and BRRI claims that 0.8–2.5 m is enough to flood a region [*Juliano*, 1993, p. 10]. The modern varieties that were popular in Bangladesh in the 1990s were usually medium-stemmed (between 0.95 and 1.20 m) and could not withstand floods. The only tall rice variety was BR3. In fact, between 1970 and 2014, the six tallest rice varieties of BRRI were only between 1.25 and 1.40 m, and most varieties that have been developed originate from Boro rice. These are BR4, BR5, BR7, BR8, BR9, and BRRI dhan 27.

With the exception of BRRI dhan 27, none became popular. BRRI dhan 27 had the longest height of 140 cm, and the shortest cultivation cycle (115 days), and is also an Aus type, that is, grown in highlands that need rainfall, but it can also be grown in drier and colder seasons like Boro rice although it has a lower yield of 4 tons/ha [*BRRI*, 2014b, 2015, pp. 3–8].

As BRRI rice has often not solved the problem created by floods, rice farmers have been wary of adopting a small variety of modern rice crops. Studies suggest that questions of "environmental sustainability" and "suitability" are important to rice farmers in Bangladesh. *Zimmerer and Douches* [1991], *Benin et al*. [2004], *Hossain* [2012, p. 7], and *Hossain and Jaim* [2012] all suggest that farmers in Bangladesh prefer rice that has high yield and is environmentally sustainable.

In fact, studies suggest that indigenous rice varieties are preferred over modern rice varieties by farmers in flood-prone regions. A 2004–2005 study of rice farming in 62 out of 64 districts in Bangladesh conducted by IRRI shows that over 1000 varieties of indigenous rice were still grown in Bangladesh, despite loss of biodiversity from rice modernization, and typically in flood-prone regions [*Hossain and Jaim*, 2012, p. 15; *Hossain*, 2012, pp. 1, 2, 10]. Also, the most popular mix of modern and local rice grown today includes 535 varieties of Aman rice, 261 varieties of Boro rice (all modern), and 295 varieties of Aus rice, despite IRRI's emphasis on Boro rice cultivation [*Hossain*, 2012, p. 2].

IRRI itself maintains a genetic bank of over 8000 indigenous varieties from Bangladesh, and it is not sure why, as it doesn't seem to promote such rice [*Hossain et al*., 2013, p. 1]. IRRI's and BRRI's newer interest is in developing and popularizing transgenic/genetically modified rice such as Golden Rice, in which Monsanto, Syngenta, and other private seed companies have become collaborators. With monetary interests of such seed companies at stake, it is likely that IRRI and BRRI have become pawns to the private seed industry, though there is denial of any motive for profit by the companies. Monsanto and Syngenta have shared patented information about seed freely in the collaboration, but no one can say how this will affect farmers in the long run [*IRRI C*].

17.3.2. Water as an Input

In this section, we try to show that BRRI and IRRI have argued for modernizing rice but mainly developed Boro rice, which can be grown in drier and cooler regions, and so have not really addressed the rice security issues for Bangladesh, which is prone to flooding. Boro rice requires ample irrigation, which in turn requires ample access to agricultural credit, which has not been provided consistently in Bangladesh.

Irrigation modernization was started during the mid to late 1970s during the administration of President Ziaur Rahman in Bangladesh, when renting of public irrigation was subsidized for farmers. At the time, Ziaur Rahman's budget for agriculture was one third of the development budget, and led to the IMF imposing restrictions on the government [*Mahmud et al*., 2008, pp. 232, 235]. The irrigation subsidies were discontinued after Ziaur Rahman's assassination, and restarted only in 2000 during the period of democratization in Bangladesh [*Zohir*, 2001]. In between, however, farmers did not have access to subsidies. Even micro-credit organizations such as Grameen Krishi Bank admitted to discontinuing credit to farmers in the 1980s, and focused instead on nonagricultural credit to women, though Grameen has reintroduced agricultural credit to small landholders since then [*Braverman and Gausch*, 1989; *Fugelsang and Chandler*, 1993, pp. 9, 38, 44–45; *GDRC*, 2014, pp. 1–5].

Thus, dictates to modernize rice and farming methods in Bangladesh have not been supported by foreign donor commitments to help farmers implement rice modernization, and, as Table 17.2 shows, modern rice varieties have only grown fast between 1967 and 1991 and between 2001 and 2010. As a result of increased irrigation, the area planted with modern rice crops rose sharply from 0.6% in 1961 to 47.4% in 1991, and from 53.6% in 2001 to 81.7% in 2010, as shown in Table 17.2, while there was a slower pace of adoption between 1991 and 2001.

Table 17.2 Area planted (or harvested) under modern rice varieties (MV) and as percentage of area of all rice, 1965–2010

Year	Area under modern rice varieties (1000 ha)	Percentage of all rice area (%)
1967	63	0.6
1971	624	6.7
1981	2324	22.2
1991	4857	47.4
1995	5194	52.2
2001	5710	53.6
2010	9421	81.7

Source: Data from *IRRI* [2015c], percentage calculated from Table 17.3 area data.

Tables 17.3 and 17.4 show how Boro rice used most modern irrigation and multiplied the fastest in Bangladesh. In fact, the rise in Boro production matched the rise in Boro area irrigation. Among the rice crops cultivated, Boro production has increased more than 10 times from 1971 to 2010, while Aman has doubled, and Aus has remained the same, according to Table 17.3. Part of this was achieved by increasing the area cultivated with each crop, in which the Boro area has multiplied five times, while Aman has remained constant, and Aus has reduced to one third, as Table 17.3 shows. Table 17.3 suggests that rice varieties grown in Bangladesh have had poor yields, between 0.8 and 4 tons/ha; however, this raises questions once again as to whether rice modernization has been successful.

Modern irrigation has a slight lead in Bangladesh, but irrigation usage as a whole is not high. Table 17.5 shows that land irrigated by power pumps and tube-wells has risen between 2000 and 2012 to just 16%, while traditional irrigation equipment/methods have remained low at 7.3% during 2000–2001, and 4.6% during 2011–2012. This suggests that modern irrigation is either not in demand or too expensive. The table also shows that the use of indigenous sources of irrigation, such as buffalo-driven irrigation, has fallen by 78%, as has the use of human labor by 25%, suggesting that farmers either don't need such services or cannot afford such services and animals [*Hossain et al*., 2006]. A 2005 survey by the micro-finance institution in Bangladesh, BRAC, shows that only 28% of farmers owned irrigation machines in Bangladesh, while the rest bought irrigated water from machine owners, suggesting that irrigation machines were too expensive for most farmers. Finally, irrigation machines were most popular in drier regions where 92% of farmers used such machines, compared to only 47% in saline-water regions [*Hossain et al*., 2013, p. 13].

Tables 17.3, 17.4, and 17.5 thus suggest that the impact of modern irrigation has mostly been on regions that grow Aus and Boro rice, namely that most regions previously growing Aus now grow Boro rice, and that this has led to a rise in the production of rice between 1971 and

Table 17.3 Approximate data on total rice production in Bangladesh over time and by area, production, and yield for Aus, Aman, and Boro rice

	Area (10^4 ha)			Production (10^4 tons)		
Year	Aus	Aman	Boro	Aus	Aman	Boro
1971–1972	30	54	9	23	57	17
1975–1976	34	57	11	33	70	23
1980–1981	31	60	12	33	80	26
1985–1986	28	60	15	28	85	37
1990–1991	21	58	25	23	92	64
1995–1996	15	56	28	17	88	72
2000–2001	13	57	38	19	112	120
2005–2006	10	54	41	17	108	140
2010–2011	11	56	47	21	128	186

Source: Data from *BRRI* [2015].
"Area" and "production" statistics were approximated to nearest hundred thousand units and based on data provided in *BRRI* [2015], which were in turn based on statistics from the Bangladesh Bureau of Statistics and the Department of Agricultural Extension, of the Government of Bangladesh.

Table 17.4 Irrigated land by type of rice

	2000–2001	2011–2012
Irrigated Boro area as percentage of total Boro area	85	97
Irrigated Aman area as percentage of total Aman area	5.5	13.8
Irrigated Aus area as percentage of total Aus area	6	—
Boro irrigated area as percentage of all irrigated rice area	88.8	87.3
Aman area as percentage of all irrigated rice area	8.7	12.3
Aus area as percentage of all irrigated rice area	2.2	—

Sources: *BBS Statistical Pocketbook Bangladesh* [2013, p. 210], *BBS Statistical Pocketbook Bangladesh* [2007, pp. 177, 196, 214], and data from *BRRI* [2015].

Table 17.5 Irrigated area by type of method (in millions of acres)

Year	Irrigated by modern methods	Irrigated by power pump	Irrigated by tube-wells	Irrigated by traditional means	Total irrigated rice area
2000–2001	10.1	1.87	7.8	0.8	10.9
2002–2003	10.9	1.93	8.6	0.8	11.7
2004–2005	11.2	1.98	9.3	1.2	12.4
2007–2008	14.2	2.6	11.6	1	15.1
2009–2010	15.3	2.7	12.6	0.9	16.2
2011–2012	16.6	2.9	13.6	0.8	17.4

Source: Data from *BBS Statistical Pocketbook of Bangladesh* [2014, p. 210] and *BBS Statistical Pocketbook of Bangladesh* [2007, p. 213].

2015 from about 10,000 tons to some 33,500 tons, mainly in Aman and Boro rice. A rise in production seems like a victory, if one considers raising production levels as the only goal of agriculture, and neglects other kinds of ecological matters or an analysis of how such rice production was achieved and the impact on farmers.

17.3.3. Rice Security as Energy Security

As suggested earlier, IRRI and BRRI primarily seem to treat rice production as "food production." However, rice is used in other ways in rural Bangladesh. In this section, we show that IRRI and BRRI do not consider "food-water-energy" security as a totality.

In rural regions, rice paddy is used as cooking and heating fuel for domestic use, and is a primary form of cattle fodder, and also roofing material for homes [*BRRI*, 2003a; *Jashimuddin et al.*, 2006]. Rice serves as food not only for humans, but also for farm animals, which provide part of the labor for rice farming, and thus it reduces dependence on other sources of animal fodder. In rural areas, using rice and other agricultural residues as cooking fuel also lowers energy dependence on fossil fuels. In fact, rice-based agricultural residues are the most efficient forms of energy in rural Bangladesh. When burned, rice hull releases $2000–2200 \times 10^3$ Mt of energy, compared to cow dung at $1600 - 2200 \times 10^3$ Mt, rice straw at $1400 - 1500 \times 10^3$ Mt, and leaves at $1000 - 1300 \times 10^3$ Mt [*Sarkar and Islam*, 1998, p. 786].

Almost all rural energy is derived from burning wood, branches, leaves, agricultural residues, and cow dung. Rice paddy, husk, bran, straw, bagasse, and jute stick constitute "agriculture residues," which provide 30–67% of rural energy, depending on where one is located in the rural parts of Bangladesh [*Sarkar et al.*, 1995; *Sarkar and Islam*, 1998, pp. 785, 787; *Miah et al.*, 2003, p. 277; *Jashimuddin et al.*, 2006]. About 87–89% of rural energy is used for cooking (either in homes or at tea shops), and 20% is for parboiling, a step in rice preparation before selling it to the market [*Sarkar et al.*, 1995, *Sarkar and Islam*, 1998, p. 785; *Jashimuddin et al.*, 2006].

The heavy reliance on rice also shows the desperation of rice farmers in Bangladesh with little means to diversify food and energy use. Farmers make daily choices between whether to use paddy as fuel or for roofing or for feeding their livestock, all of which can be difficult in the long run. BRRI has, however, failed to adequately connect the relevance of rice paddy to energy security in rural Bangladesh. Instead, it conceptualizes rice as "the main source of energy for Bangladesh," where energy is connected only to human food consumption [*BRRI*, 2015, p. 2].

IRRI studies, however, seem to acknowledge that paddy is used as a heating fuel and was "cheap" and "CO_2 neutral" when compared to other fuels, but also points out that such heating systems were "labor-intensive" and the fuel was bulky and not easy to commercialize [*IRRI B*, p. 2]. Other IRRI documents suggest that rice paddy is a source of pollution, releasing methane while still in the water, and also when burnt as fuel [*Ferrer*, 2013, pp. 1–2; *IRRI*, 2016, p. 2]. Paula B. Ferrer of IRRI states that rice husk and straw could become more energy efficient when liquefied, as well as "an extra source of income" for farmers, implying that such energy is in the initial phases of being developed in Bangladesh. Ferrer claims that 1 ha of rice area could produce 12 tons of husk and straw per year, equivalent to 1800 L of diesel [*Ferrer*, 2013, pp. 1–2]. Such commercialization of rice paddy fuel could, however, reduce rural farmers' abilities to manage their own food-fuel needs, and push them into energy dependence on commercial fuels, such as liquefied paddy fuel and fossil fuels.

As suggested, agricultural residue is used more by the poorest rural households, and mostly in areas that are deforested, while the richer households cook with wood [*Miah et al.*, 2003, pp. 279–282]. Historically, fuel wood consumption per capita in Bangladesh has been the lowest in the world, at just $0.043\,m^3$, but a greater share of energy for 2003–2013 was expected to come from fuel wood [*Miah et al.*, 2003, p. 278]. In comparison, natural gas consumption has been negligible in rural Bangladesh, and is used mainly in cities. Other commercial fuels such as diesel, petrol, and electricity were used for irrigation pumps, boat engines, in homes, and in agricultural industries [*Sarkar and Islam*, 1998, p. 788].

In the last two decades, cell phone use has boomed, even in rural regions, increasing rural-urban connectivity and speeding up money transactions and trade between rural regions and cities. This has increased demand for electricity in rural areas. The government of Bangladesh, under Prime Minister Sheikh Hasina, has launched the "Digital Bangladesh" program, which is supposed to increase telecommunication between rural and urban regions [*Karim*, 2010]. Solar and wind panels are now being placed, which will reduce dependence on electricity providers. Roads and highways have also improved connectivity between rural regions and urban markets, and this is pushing rural Bangladesh away from a rice-based system, and somewhat away from a self-reliant energy model, as far as transport fuel is considered. It is not known whether the rice-based liquid fuel will replace fossil fuels for transportation as solar and wind turbines start to power rural homes.

17.3.4. Energy and Chemicals as Farming Input

While rice itself has become a fuel for rural regions and food for livestock, rice farming requires energy and chemical inputs. IRRI has valued using engineering above indigenous farming methods. In 1998, Kenneth Fischer, Deputy Director General of Research in IRRI, stated that developing modern rice was not enough, and that IRRI's research and outreach would evolve to food processing and market development also [*Bell et al.*, 1998, p. v]:

> Engineering is a critical component for helping to meet the challenges facing increased rice production… The opportunity is for contributing to an integrated system from field preparation all the way through the chain to end users.

In Bangladesh, however, mechanization has been gradual, and rice cultivation is still a labor-intensive business. Planting and harvesting of rice are still done using manual labor of animals and humans, while some modern technology is also used. This is suggested from pictures in BRRI manuals on rice production [*BRRI A*, pp. 4, 6, 8). This could well be due to a lack of agricultural credit to help farmers to modernize, and also because the bulk of rice is still grown in rainfed and flood-prone regions, where the same kind of industrial model doesn't work.

In 2008, 30 million people out of a population of some 144 million were employed in the agriculture sector in Bangladesh, as both farm and non-farm workers, and 99% were in rural regions. Of these, 22 million were directly engaged in farming. The agricultural labor force was also two thirds male, with women mostly tending to post-harvest work [*BBS*, 2011, p. 8]. Such percentages represent a shrinkage in the population of rice farmers in Bangladesh since the 1970s, when 95% of the population was rural. BRRI states that only 55–60% of the labor force today are involved in rice cultivation [*BRRI*, 2015, p. 2].

Historically, mechanization was used in women's work, that is, in post-harvest activities. Women's labor is typically operating rice dehusking machines called "dheki," though increasingly this is now done by machines, such as the automated Engelberg machine [*Fugelsang and Chandler*, 1993, pp. 24–26; *Sarkar and Islam*, 1998]. Today, there are some 100,000 traditional mills, against 500 semiautomatic mills and 50 automatic mills [*Farouk and Zaman*, 2002; *Jaim and Hossain*, 2012, pp. 78–79]. Women's labor has been diverted to non-farm labor, through micro-finance organizations such as BRAC and Grameen, and many village women now work in the cities as maids and in the garments sector, although both sectors offer very little pay. Garment factory workers get paid approximately Taka 3500 per month (about US$50) for working 12 hs a day, often 6 days a week. Maids in cities get comparable salaries, and some also receive food, boarding, and clothing.

As suggested earlier, while machines have been used increasingly to dehusk, animal labor is still used in transportation and in plowing fields, though ownership of animals has fallen. In 2008, there were only 0.87 buffaloes per landholding, and the number of cattle was just 0.26 cattle per landholding used in agriculture, down from 1.6 in 1983–1984 [*Rahman and Rahman*, 2009, p. 96; *BBS*, 2014, p. 183]. In 1999, rice farms with 2 ha or more of land owned the most bullocks (33% of the share), while those with 0–0.5 ha owned only 5% and used human labor [*Ramsey and Andrews*, 1999]. In 2008, smaller farms collectively owned more cattle than large farms, but small farms also comprised 87% of all farms [*BBS*, 2014, p. 182].

IRRI data suggest that in 2006 only 3000 tractors existed in farms in Bangladesh, against 900 tractors in 2001, 2050 tractors in 1991, and 3350 tractors in 1981, suggesting a "comeback" for tractors [*IRRI*, 2015c]. More recent data from IRRI suggest that 600,000 two-wheeled tractors were distributed to farmers in Bangladesh, though it is not known how equitably [*IRRI*, 2015b]. BRRI did not have statistics on such tractors, however.

A study performed in 2004–2005 suggested that for Aman rice cultivation in flood-prone regions, BRRI promoted new varieties of rice, namely, BRRI dhan 28, 29, 30, 31, 36, and 41. Alongside, it promoted particular technologies such as drum seeding, supposedly aimed at reducing human labor during seed-planting season, which can lead to backache in farmers. Drum seeding is said to increase rice yields by 10–20% and decrease days of cultivation by 10–12 days. Drum seeding requires that the soil be totally leveled and all water be removed before seed planting, and is a completely new way of planting seeds [*BRRI*, 2013a, 2013b]. Another technology promoted was "soil solarization," a way to increase solar energy use in rice farming in which soil with seed was covered by a polythene sheet to capture sunlight during drier seasons, and in the seeding stages of the plant [*BRRI*, 2013c]. It was not clear from BRRI what percentage of rice farmers used any of the modern methods, and how successful they were in "water-rich" regions.

As far as consumption of chemical energy is concerned, farmers in Bangladesh have been using large amounts of chemical fertilizers and pesticides. In 1957, the first wave of chemical pesticides were introduced into Bangladesh in the form of DDT and BHC, and were distributed for free to farmers, but the subsidy was cut to 50% in 1974 and stopped finally in 1979 [*Parveen and Nakagoshi*, 2001, p. 109]. Studies suggest that in the 1980s and 1990s farmers received free chemical pesticides with purchase of chemical fertilizers from distributors [*Dasgupta et al.*, 2007; *Robinson et al.*, 2007]. Subsidies for chemical fertilizers were started in the late 1970s but discontinued by 1979 and restarted in 2010 [*Mahmud et al.*, 2008; *Hossain et al.*, 2013, pp. 2–3]. To help farmers pay for increased costs, as of 2010, the Government of Bangladesh had started subsidizing fuel costs for irrigation pumps and for chemical fertilizers, at a rate of US$11.51–14.40 per farmer, and was also distributing rice and wheat through food rations and as wages in food-for-work programs; some 9 million farmers are supposedly covered by the state program, though this level of outreach may be insufficient [*Tobias et al.*, 2012, pp. 2–3].

In sharp contrast, IRRI is said to have promoted the use of organic fertilizers and pesticides under the Integrated Pest Management (IPM) program, which was originated by the UN Food and Agriculture Organization, though it did not rule out all chemical use, such as of fertilizers and pesticides, herbicides and insecticides [*IRRI D*]. In the organic method, animals and insects are used for pest management, such as in "rice-duck" farming, introduced by BRRI [*Khan et al.*, 2005, p. 144]. What both IRRI and BRRI propose is that more chemical use is necessary with modern rice varieties. However IRRI also disclosed some harmful effects from overuse of chemicals [*IRRI E*]. Table 17.6 shows that chemical fertilizer and pesticide use has increased in Bangladesh, against IPM prescriptions. Table 17.6 suggests a sharp rise in chemical fertilizer use between 1971 and 1981, between 1981 and 1991, and between 1991 and 2001, tapering off after that.

Comparative data on chemical pesticides are missing from IRRI and BRRI. Scholars have suggested that total chemical pesticide use rose in Bangladesh from 6200 tons in 1991 to 14,000 tons in 1999 [*Parveen and Nakagoshi*, 2001, p. 109]. A 1996 study by S. Rahman suggests that modern rice used four times the level of chemical pesticides as indigenous varieties of rice [*Rahman*, 2003, p. 245]. A 2005 study by BRAC suggests that the latest popular modern rice varieties such as BRRI dhan 29 used far more urea, TSP, and MP than indigenous and older modern varieties, while use of urea varied widely by region, with farmers of some regions using up to 236–260 kg/ha, while others used 73–95 kg/ha [*Hossain et al.*, 2013, pp. 12–13].

All of this suggests that dependence of rice farmers on modern chemical-based fertilizers and machines is on the rise, and that a kind of modern rice-farming practice was used that wasn't too mechanized but that there was a considerable dependence on manufactured pesticides and fertilizers, which were expensive. In the next section we try to ascertain how all this has impacted rice farmers.

Table 17.6 Total Consumption (000 t) of fertilizers (N, P, K) from chemical sources, and fertilizer per acre of rice, 1961–2010

Year	Tonnage of fertilizer (1000 tons)	Chemical fertilizer/area (1000 tons/ha)
1961	23	0.003
1971	114	0.01
1981	400	0.04
1991	1004	0.1
2001	1449	0.14
2010	1427	0.12

Source: Data from *IRRI* [2015c] and Table 17.3 for total area.

17.3.5. The Impact of Input Costs on Farmers

Studies suggest that agricultural workers in Bangladesh are barely surviving and do not have the financial ability to engage in rice modernization at full scale, which is why subsidies are necessary. For one, rice farmers are typically poor and debt burdened. The average person employed in agriculture in Bangladesh has a debt-burden of Taka 39,000, half of which are institutional loans, and they also have fewer assets such as land, cattle, and other livestock that can be used as collateral, as has been shown [*BBS*, 2014, p. 196]. In 2008, the average number of farm landholdings per agricultural worker was about 0.5, that is, for every two workers one would have land, while the ratio was higher for "farm workers" at 0.67 [*BBS*, 2014, pp. 177, 200]. Actual landholding was about 0.12 ha per farmer [*Rahman and Rahman*, 2009, p. 95]. At the same time, the average number of cattle/buffalo per agricultural worker is 0.88, and the average number of cattle/buffalo per farm worker is 1.2 [*BBS*, 2014, pp. 196, 200].

Data from the Bangladesh Bureau of Statistics suggests that not just are there challenges in rice farming, which accounts for 75% of all agriculture in Bangladesh, but also that agriculture as a form of livelihood is fast diminishing in Bangladesh [*BBS*, 2014, p. 196]. Between 1983 and 2008, the number of farms had risen from 10 to 14.9 million, but in a country of some 144 million people, this is low (an estimated 50–75 million people). Meanwhile, 60–65% of the population is still rural, suggesting that many in rural regions no longer engage in rice farming [*BBS*, 2014, p. 177].

In addition, land ownership today is highly fragmented so that the average small farm is smaller than what it was in 1971. The number of small farms (0.5–2.49 acres) has risen from 70.34% in 1983–1984 to 84.3% in 2008, while the percentage of medium-sized farms has fallen from 24.7% to 14.2% during this time [*BBS*, 2014, p. 177]. The rise in the number of small farms and the fall in mid-sized farms can be explained to be due to inheritance and represents "fragmentation" of plots by siblings, and to some extent challenges to farming businesses, such as incidence of loans.

In this time, the number of farm holdings of any kind as a percentage of total land holdings has fallen from 72.7% to only 58.7%, and cultivated land area has fallen from 20.2 to 18.8 million acres. Finally, the total area of crops has fallen from 32.5 million acres in 1983–1984 to 28.6 million acres in 1996, but bounced back up to 30.1 million acres in 2008 [*BBS*, 2014, p. 177].

There also seem to be more small farmers with less claim to land than ever before, but the data are not reliable. Some reports suggest that land ownership itself is extremely low in Bangladesh. According to BBS reports, about 95.7% of the population claimed to own no land in 2008, against 96.52% in 1996 [*BBS*, 2014, p. 177].

However, Rehman *Sobhan* [1998] suggests that in 1995–1996, about 70% of the rural population in Bangladesh comprised wage laborers, 38% owned land, and 41% consisted of tenants [*Sobhan*, 1998, pp. 15–16].

The reduction in farm holdings coincides with the removal of agricultural subsidies for modern equipment and for renting of public irrigation. The reinstatement of partial subsidies to 9 million marginal farmers in 2010, as *Tobias et al*. [2012] show, came late and was not enough. Part of the loss of agricultural population has to do with perceived benefits of city life, a higher rate of literacy and migration to cities, as well as diversifying production to non-rice farming, such as in fruits, vegetables, and fisheries. Rural to urban migration has been high in Bangladesh since India's partition from Pakistan in 1947, and continues till today, leading to a rapid rise in the urban population. A simple cost-benefit analysis further reveals the kind of expenses a rice farmer has to bear today in Bangladesh.

While the emphasis of IRRI and BRRI has been to mechanize and modernize Boro rice regions, rice farming itself appears to be unprofitable for Boro cultivation, as Table 17.7 shows. "Profit per unit" is calculated by subtracting the "net unit cost" from the "price per output" for the listed crops. In 2000–2003, farmers in Bangladesh made less than Taka 1/kg of rice in profits (around $0.01/kg and $0.02/kg). However, this held true only when all chemical inputs were used by farmers in their proper amounts. Farmers probably did not use these required inputs, as costs were too high. Studies suggest that farmers in Bangladesh cope with high costs of rice farming by helping each other in their community, such as with labor during rice planting and harvesting, and with supplies of seed.

Finally, Table 17.8 shows how expensive each of the variable inputs is for Aman and Boro, and that a particular ratio of seed, chemical fertilizers, and pesticides, as well as irrigation and human labor, is prescribed for best results. More units of all inputs were required for Boro cultivation than for "high-yield variety" (HYV) Aman. It is not known why the latest data on costs to farmers are over 15 years old.

Studies suggest that in 2000, 60% of farming households rented modern agricultural machinery, such as tube-wells and electric pumps. The cost per acre for renting machines, hiring labor, and for chemical inputs ranged from US$40.4 to US$22 (Taka 1400 to 1165) between 1987 and 2000 [*Hossain et al*., 2006]. In 2000, US$1 was Taka 51, and in 1987 it was about Taka 35. However, these costs are still significant for farmers in Bangladesh, who are in the lowest quintile groups for wealth. The 2005 BRAC survey suggests that the burden on farmers went up with the latest forms of modern rice, for which they pay far more due to urea expenses than for older ones [*Hossain et al*., 2013, pp. 12–13].

The high cost of agriculture associated with modern varieties of rice can explain why farmers have chosen more indigenous rice varieties for cultivation in flood plains in Bangladesh, where the risk of loss is higher, as suggested by *Hossain* [2012] and *Hossain et al*. [2013], and why the yields of rice might be low for those regions/

Table 17.7 Output per acre of Aman and Boro Rice and profit margins

	Type of crop	2000–2001	2001–2002	2000–2003
Output per acre (in kg)	Aman (HYV) paddy	1,350	1,406	1,437
	Aman rice	917	962	983
	Boro paddy	2,020	1,990	2,016
	Boro rice	1,313	1,294	1,310
Total cost per acre (in Taka)	Aman (HYV) paddy	9,257	9,557	9,814
	Aman rice	9,257	9,557	10,285
	Boro paddy	13,552	14,237	14,442
	Boro rice	13,552	14,036	15,320
Net unit cost (Taka/kg)	Aman (HYV) paddy			6.6
	Aman rice			10.13
	Boro paddy			6.83
	Boro rice			11.03
Price per unit (Taka/kg)	Aman (HYV) paddy			7.33
	Aman rice			12
	Boro paddy			7.4
	Boro rice			11.5
Profits as percentage of cost	Aman (HYV) paddy			11.06%
	Aman rice			18.50%
	Boro paddy			8.30%
	Boro rice			4.30%

Source: Data from *BBS Statistical Pocketbook Bangladesh* [2007, pp. 216–219].

Table 17.8 Input ratios and cost per acre of Aman and Boro rice in 2000–2003

	HYV Aman Paddy and Rice		Boro Paddy and Rice	
Input	Required quantity per acre (in kg)	Cost per acre (in Taka)	Required quantity per acre (in kg)	Cost per acre (in Taka)
Seed		750		1300
Fertilizer				
Urea	52	304	90	522
TSP	32	394	50	570
MOP	13	119	25	233
Manure	1163	291	1500	375
Pesticides	1	175	0.6	240
Labor				
Family	30	1260	32	1312
Hired	35	2415	48	3312
Bullock	16	1120		
Land preparation			16	1000
Irrigation	10	350	50	3150
Interest on working capital		237		428
Rent		2400		2000

Source: Data from *BBS Statistical Pocketbook Bangladesh* [2007, pp. 216–219].

climates, as suggested in Table 17.3. Part of it may have to do with lack of outreach to farmers. When farmers lack access to credit or modern inputs and seed, they stick to what they know traditionally and from observing others. *Hossain* [1998] suggests that farmers' adoption of new technologies such as HYV rice and modern pesticides depended largely on the presence of strong social networks in villages that connect farmers to "block supervisors" or agricultural extension workers. The extent of agricultural extension programs in Bangladesh was, however, very limited. *Hossain* [2001, pp. 154–158] stated that in 2000 only 12% of farmers had connections with agricultural extension workers, but that connectivity was on the rise with Department of Agricultural Extension (DAE) programs [*Hossain et al.*, 2013, pp. 10–11]. Due to lack of credit and agricultural extension programs, farmers take up to 4–5 years to adopt new modern rice varieties that they like [*Hossain*, 2012, p. 7]. So, even with modernization and promotion of Boro rice, there has been little adoption of modern varieties.

A 2005 BRAC study revealed a lot of variation in modern seed adoption by region within Bangladesh. Areas near the Indian border tended to grow more "Indian" rice, while most regions tended to grow more modern rice during Boro season, and showed more genetic diversity in Aus and Aman seasons [*Hossain et al.*, 2013, pp. 23–39]. Studies suggest that outreach to farmers was poor in regions farther from urban centers, such as in the northern part of the country, and that this resulted in "mongas" or famines [*Mortimer et al.*, 2008; *Barclay*, 2009].

In Bangladesh, actual access to benefits from agricultural extension programs of the government depends not only on the availability of such benefits but also on the political environment within one's village and one's connection to local power elites. Scholars on rural political systems in Bangladesh suggest that government aid and other benefits are allocated based on "patron-client" relationships: if one votes for local politicians who win, one may have greater access to development aid. Blair proposes that micro-credit nongovernmental organizations (NGOs) have addressed some gaps from such dependencies [*Blair*, 2005, pp. 923–926]. However, it remains to be seen whether NGOs in Bangladesh are completely free of the influence of rural politics.

17.4. SUMMARY

In this chapter we have tried to shed some light on the major narratives of BRRI and IRRI on rice farming and how they have impacted rice production in Bangladesh. Through a food-water-energy nexus we have also tried to see if such a discourse was prevalent in BRRI and IRRI, but found that this is not the case. The emphasis is still on rice production as "food security," though there is a possibility that rural energy independence may be maintained in other ways, such as by introducing solar panels and wind turbines. However, it does seem that, overall, cultivation of modern varieties of Boro has pushed the rice farmers of Bangladesh into financial crises and that without agricultural credits and outreach programs, rice farmers find the sector to be unprofitable, even though Boro production has increased widely.

Our suggestions are to reverse the situation by listening to the needs of farmers and by alleviating their suffering, instead of only promoting rice modernization. Farmers have historical knowledge of rice and rice farming, which seems to be ignored by public policy makers and research scientists, even though IRRI is amassing a large share of that genetic bank. It is time to pay attention to the indigenous knowledge of rice farmers in Bangladesh.

This would also make it easier to alleviate the debt burden of farmers. The micro-credit sector can easily reduce their debt burden and offer easier farming credit terms, as some have begun to do. The state can offer subsidies for irrigation and increase access to agricultural extension programs. There is a need for some kind of farmer's insurance to protect farmers from weather and market fluctuations and for better storage facilities.

We hope that further research examining the food-water-energy nexus of crops will show the impact of agriculture policies on farming and rural communities, as these are the people whose lives are at stake.

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18

Riverbank Filtration Technology at the Nexus of Water-Energy-Food

Thomas B. Boving[1] and Kavita Patil[2]

ABSTRACT

Riverbank filtration (RBF) is a proven water treatment technology that permits the indirect abstraction and treatment of surface water, which can then be applied to cultivate land and produce high-value crops that currently cannot be grown with polluted river water. Field studies, one from Jordan and one from India, are discussed and evidence is presented illustrating the benefits of converting an RBF wellfield from a conventional, grid-operated system to a solar-energy-powered one. Further, the two studies demonstrate how an RBF treatment system enables farmers to irrigate with treated river water that otherwise would be too polluted to be used on crops and plants. The results of this analysis suggest that affordable RBF systems can be designed to meet the irrigation water needs of small farming communities, to increase both crop yields and quality, and to offer a degree of independence from the electrical grid.

18.1. INTRODUCTION

Water, food production, and energy are strongly interconnected and directly related to rising population numbers and economic growth. Historically, the accessibility and availability of water resources has given rise to civilization and has greatly influenced the evolution of agricultural practices globally. It is therefore not surprising that agriculture accounts for 70% of total global freshwater withdrawals, making it the largest user of water. Further, the total global water withdrawals for irrigation are projected to increase by 10% by 2050 [*FAO*, 2014]. In addition, nearly 15% of global freshwater withdrawals annually are linked to energy supply. In South Asia in particular, freshwater supplies are stressed because of increasing water demands in rural and urban areas, which raises questions relating to energy and food security [*Rasul*, 2014]. Many Asian countries (e.g., India, Nepal, Bangladesh, and Sri Lanka) already experience energy shortages due, in part, to a lack of nonconventional energy resource alternatives or deficient electrical grid infrastructure, particularly in rural areas. By some estimates, almost 30% of South Asia's 1.7 billion people do not have access to electricity [*Rasul*, 2014]. Energy is required to produce, transport, and distribute food, as well as to extract, deliver, and treat water. Hence, about 30% of total energy consumed globally is invested in the production of food and the agri-food supply chain [*FAO*, 2011]. These statistics clearly demonstrate that the water, food, and energy nexus is complex and dynamic and cannot be looked at in isolation from one another [*FAO*, 2014]. The challenge of meeting the growing demand for water, energy, and food is further compounded by climate change impacts. Already there is growing evidence of shifting precipitation patterns that have impacts across all three sectors [*IRENA*, 2015].

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The great majority of people in South Asia rely on agriculture for their livelihood. With the rising population and increasing demands on food quantity and quality, the agricultural sector has become resource and capital intensive, especially in terms of water, land, and energy. In addition, the farmers in this region are small landholders in a disconnected market, and are often unable to attain true value of their produce. In order to fortify the market linkage and further encourage farmer's involvement, there is a need to encourage collective action at the nexus of water, food, and energy [*REEEP*, 2015]. One such action is to train farmers to use treated, clean irrigation water rather than polluted water to increase food production and quality of the produce. Also, shifting from wasteful irrigation techniques, such as flood irrigation, toward more efficient techniques, like drip irrigation, can empower farming communities and enhance their competiveness in the marketplace.

While the need for clean water for food production is increasing, natural groundwater resources are rapidly depleting in many parts of the world. For example, in India, groundwater currently provides 85% of the country's domestic water, but in 20 years, about 60% of all of India's aquifers will be critically degraded [*Schiermeir*, 2014]. A strategy for making up for depleting groundwater resources is to use natural water treatment systems that permit a cost-effective treatment and reuse of polluted surface water resources, like rivers. One such treatment method is riverbank filtration (RBF).

18.2. ABOUT RIVERBANK FILTRATION (RBF) TECHNOLOGY

RBF is a water treatment technology that is based on extracting water indirectly from rivers by pumping wells located in the adjacent alluvial aquifer (Figure 18.1). Water is withdrawn from one or more RBF wells, which may either be vertical or horizontal [*Sandhu et al.*, 2011]. Generally, RBF wells are installed 30–50 m or more away from the river [*Grischek et al.*, 2002; *Boving et al.*, 2014]. During pumping, the water table is lowered and river water (together with some fraction of groundwater) is induced to flow through porous riverbed sediments [*Hiscock and Grischek*, 2002]. As the raw surface water travels toward the RBF well, dissolved and suspended contaminants, such as pathogens, are eliminated or significantly reduced. The treatment is achieved by physical, chemical, and biological processes that take place within the hyporheic zone, or the interface between surface and groundwater, and within the alluvial substrate [*Hubbs et al.*, 2004]. The removal of pathogenic material, like bacteria or viruses, is particularly effective, but other organic and inorganic pollutants are also attenuated. For instance, *Schmidt et al.* [2003] demonstrated that RBF systems can reduce total heavy metals concentrations of zinc, copper, lead, chromium, and cadmium by 82, 51, 75, 94, and 75%, respectively. Further, bacteria removal efficiencies of 3–4 log are common [*Kühn and Müller*, 2000; *Kumar and Mehrotra*, 2009; *Boving et al.*, 2010; *Cady et al.*, 2013]. *Grischek et al.* [2002] compiled available information

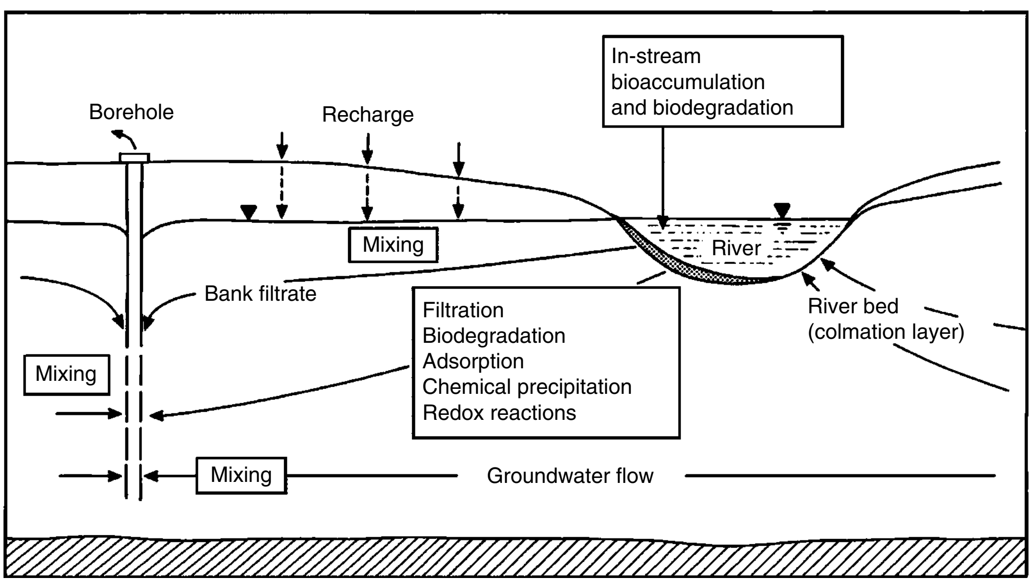

Figure 18.1 Schematic diagram of processes affecting water quality during bank filtration. The natural attenuation processes are strongly dependent on site-specific hydrogeological and hydrogeochemical conditions. Source: *Hiscock and Grischek* [2002]. Reproduced with permission of Elsevier.

from RBF systems in the United States and Europe, and concluded that the most important parameters for success during RBF treatment of pollutants are the flow path length, the thickness of the aquifer, and the infiltration area in the river.

In general, the degree of pollutant removal depends on the nature of the pollutants and on the properties of the materials through which the flow takes place. Removal processes include physical filtration, microbial and chemical degradation, ion exchange, precipitation, sorption, and dilution. Other factors that also contribute to the treatment include the river water and the groundwater quality, river hydrodynamics, the porosity and mineralogical makeup of the alluvial media, the water residence time in the aquifer, temperature and pH conditions of water, and oxygen concentrations [*Jaramillo*, 2011]. Further, there is evidence that much of the contaminant removal occurs at the interface between the river and the sediments [*Bellamy et al.*, 1985; *Albrechtsen et al.*, 1998]. This zone is known as the colmation zone, schmutzdecke, or biofilm layer and is characterized by high microbial activity and small grain size [*Wang et al.*, 1995]. It is thought that periodic scouring during flood events regenerates the treatment activity of the colmation layer [*Gupta et al.*, 2009]. Due to these auto-regenerative natural treatment processes, properly engineered RBF systems can maintain essentially unlimited treatment durations.

RBF offers a relatively inexpensive means to remove large amounts of contaminants and improve the quality of the water delivered for domestic or agricultural uses [*Schubert*, 2002]. Although typically considered as a pretreatment technology [*Ray*, 2002; *Schmidt et al.*, 2003; *Speth et al.*, 2003], RBF may in some cases prove adequate in reaching drinking water standards [*Dash et al.*, 2010]. The principal advantages of RBF use for water treatment are removal of particles and turbidity [*Dillon et al.*, 2002; *Dash et al.*, 2008, 2010]; attenuation of virial, bacterial, and parasitic loads [*Havelaar et al.*, 1995; *Berger*, 2002; *Schijven et al.*, 1998, 1999; *Tufenkji et al.*, 2002; *Wang*, 2002; *Gollnitz et al.*, 2003; *Weiss et al.*, 2003; *Boving et al.*, 2010; *Dash et al.*, 2010]; degradation of micro-pollutants, pesticides, and natural organic matter [*Massmann et al.*, 2003; *Ray et al.*, 2002; *Verstraeten et al.*, 2002; *Wang*, 2002; *Kühn and Müller*, 2000; *Doussan et al.*, 1997]; and disinfection of by-product precursors [*Weiss et al.*, 2002, 2003]. RBF technology is also recognized for dampening temperature and concentration variations and compensating for peak pollution and shock loads [*Jaramillo*, 2011].

Riverbed (alluvial) sediments are often highly permeable and the depth to groundwater in the vicinity of rivers is typically shallow because most rivers are commonly connected directly with the alluvial aquifer. These attributes make shallow RBF wells located near rivers highly productive, less costly to drill than typical groundwater resources [*Schubert*, 2002], and less prone to contamination than surface water resources [*Ray et al.*, 2002]. For these reasons, RBF technology is well suited for use in developing and industrial countries [*Boving et al.*, 2010, 2012, 2014; *Dash et al.*, 2010; *Sandhu et al.*, 2011]. Although the practice of RBF has been used in Europe for more than a century, the current understanding of the processes and mechanisms behind this technique, particularly in tropical areas and where the source water is highly contaminated, are still fairly empirical [*Jaramillo*, 2011]. Furthermore, limited data exist to evaluate the effectiveness of RBF technology in enhancing food production and reducing energy consumption. The results from selected case studies presented in this chapter may ignite discussions and initiatives toward bridging the knowledge gap.

18.3. RBF AT THE WATER-FOOD NEXUS

Most rivers in developing countries serve as wastewater conduits and therefore are contaminated with high loads of pathogenic microorganisms and toxic compounds, such as heavy metals or man-made organic chemicals [e.g., *Sikder et al.*, 2013]. When leafy crops, vegetables, or fruits are irrigated with untreated river water, disease-causing pathogens or toxins can enter the food chain via consumption of unwashed produce (leaves, roots, shoots, fruits, etc.) by humans. The risk posed by pathogens in irrigation water was recognized early in the last century [*Bewley and Buddin*, 1921; *Hong and Moorman*, 2005] and rules prohibit the use of untreated surface water for irrigation in some places.

Studies have shown that surface water treated with RBF technology can reach drinking water quality [e.g., *Cady et al.*, 2013]. However, a largely unexplored potential for RBF lies in the application of treated water via irrigation for growing high-value crops. This is because RBF can cost-effectively and sustainably treat pathogenic and other pollutant classes. The resulting filtrate is typically of higher quality than the original surface water, which makes RBF water superior to conventional irrigation water sources, such as untreated river water or dug wells. Hence, crops and vegetables irrigated with RBF water are likely of higher quality compared to river-water-irrigated plants [e.g., *Saha and Sharma*, 2006].

An example of a polluted river is the Zarqa River, which is the only river flowing entirely within the borders of Jordan. The Zarqa River is so polluted that both access and use of its water is restricted [*Abu-Taleb and Maher*, 1994; *IUCN*, 2009]. However, rules and restrictions are often ignored and contaminated produce can end up being sold in the marketplace. People who consume fruit or vegetables that were exposed to contaminated water are at risk of developing a foodborne illness [e.g., *Amoah et al.*, 2006].

Many farmers and customers are aware of the linkage between polluted irrigation water and food contamination. Not surprisingly, the affected produce often fetches much lower prices in local markets than produce grown with treated, clean water [*Saha and Sharma*, 2006]. Hence, farmers without access to treated irrigation water generate less income for the same amount of work and the same volume of (irrigation) water used. This situation is not only uneconomical but also wasteful. Therefore, those farmers would benefit from water treatment solutions that are appropriate, affordable, and provide an alternative to using irrigation water abstracted from polluted rivers. RBF treatment might be the only technology that meets these requirements [*Boving et al.*, 2012]. The potential for RBF as a source for clean water for agricultural uses is illustrated in the following case studies.

18.3.1. Case Study: Zarqa River

An RBF wellfield was installed at the Zarqa River in northern Jordan near the historic town of Jerash in 2009 (Figure 18.2). The study site is about half-way between the capital of Amman and the border to Syria to the north. One objective of this project was to encourage Jordanian farmers to use less of the rapidly depleting groundwater resources and switch over to river water. Since RBF water is water that only days earlier was flowing in the Zarqa River, it is not considered groundwater in the traditional sense.

In this area, the river slightly meanders and water enters and exits the river as it flows through the valley filled with alluvial sediments. The wellfield comprises six wells, which were drilled up to 25 m away from the river (Figure 18.2a). The aquifer consists of predominantly sandy and gravelly alluvial materials composed predominantly of carbonate rock fragments. Bedrock was encountered 21 m below ground level (mbgl). The depth of the wells ranged from 16.5 to 21.6 mbgl. Each well was encased in concrete and capped for protection. An electrical pump and a certified, calibrated flowmeter were installed. The pump was a Grundfos brand model 85S50 driven by a Franklin brand 5 horsepower motor model with a variable frequency drive.

A conservative tracer test [*Fetter et al.*, 2017] was conducted to determine the water travel times. A quantity of 20 L of a solution containing approximately 1 g/L of Fluorescein dye and 450 g/L of sodium chloride (NaCl) was injected into the riverbank immediately adjacent to the Zarqa River. The injection pit was dug into the riverbank. It was approximately 1.5 m deep and 0.5 m by 0.5 m in area and was separated from the river by a mud mound approximately 20 cm wide at its base. The mound prevented river water from entering the injection pit and flushing out the tracer. The bottom of the pit coincided with the river stage. The tracer solution was poured into the pit and

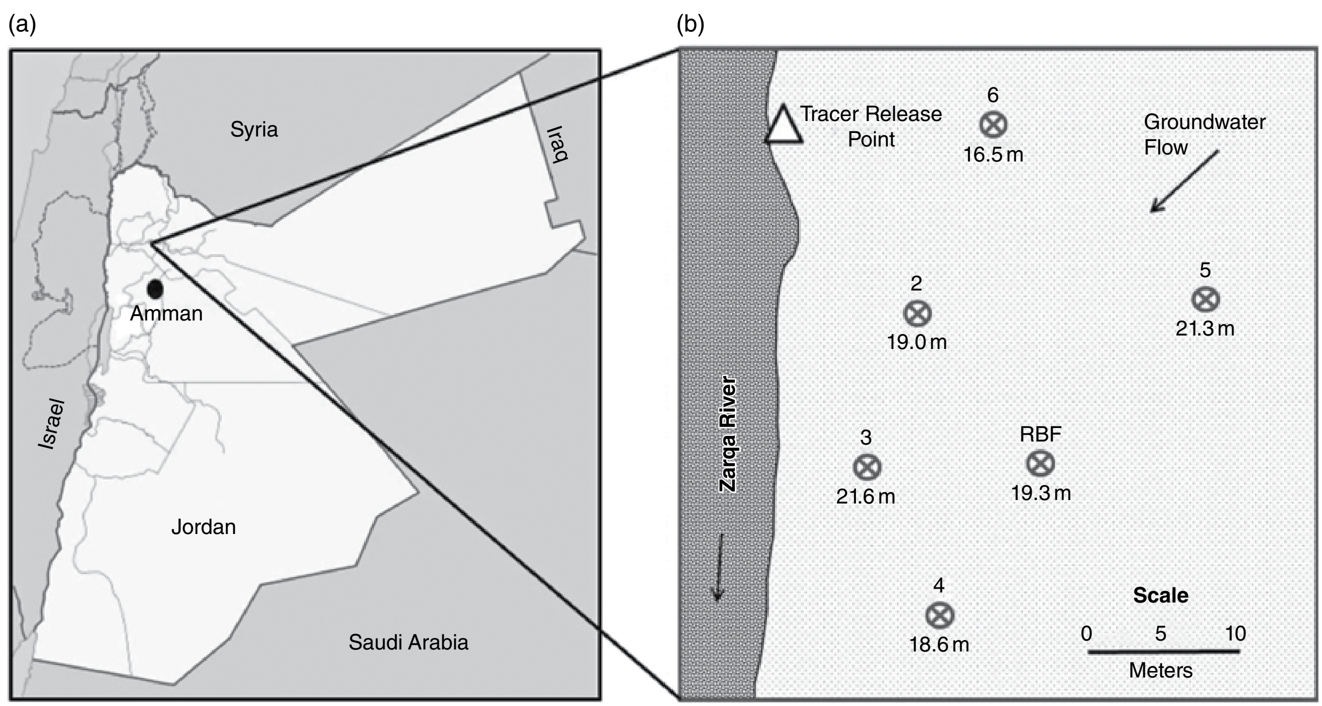

Figure 18.2 (a) The Zarqa River study site in northern Jordan near the town of Jerash. (b) The layout of the RBF wellfield adjacent to the Zarqa River. "RBF" is the principal production well. Observation wells are numbered 2 through 5. Values below the well symbol mark the depth of the well in meters. Source: Modified after Wikipedia.

infiltrated over the course of 30 min. At the time of injection, the RBF well had been pumping continuously for over 24 h at an average rate of 15.4 m^3/h. The tracer breakthrough in observation well 2, located 5 m away from the river (Figure 18.2b) was monitored with a YSI multisensor electronic data logger, which recorded the water's electrical conductivity (EC), pH, and temperature. In addition, water quality samples from the RBF well and Zarqa River were collected for *Escherichia coli*, Enterococci, somatic coliphages, somatic salmonella phages, and F-specific bacteriophages. The river samples served as a benchmark for comparison of the RBF water quality.

The tracer test data indicate that the RBF wellfield was hydraulically connected to the Zarqa River and that the travel time of the water is rapid, at 0.07 m/min, under pumping conditions. The fecal indicator bacteria and bacteriophage removals were 3.4–4.2 $\log_{10}$ and 2.7–3.3 $\log_{10}$ units, respectively (Table 18.1) [*Saadoun et al.*, 2008; *Boving et al.*, 2010]. These values indicate a high rate of microbe removal over a comparably short distance. The microbial activity of the well water relative to the river indicates a removal performance expected from the literature [*NRC*, 2012].

An RBF wellfield was installed on the property of a nursery plant business where a variety of plants were grown with untreated irrigation water pumped directly from the Zarqa River. A risk assessment analysis was performed based on the observed viral and bacterial removal rates. The results showed that public health risks from exposure to RBF water, like consumption of raw vegetables irrigated with this water, may be reduced by 2000–2500 times (3.3–3.4 $\log_{10}$) compared to using river water directly [*Boving et al.*, 2010]. While this study did not include an assessment of any socioeconomic changes caused by switching to RBF water, anecdotal evidence from the field site suggests that greater yields and healthier plants were produced in the years following the RBF installation. That is, once the RBF system was fully operational, the nursery plant business on which the study was conducted abandoned its river water supply and switched to RBF well water for all its irrigation needs. According to anecdotal evidence provided by the nursery plant owner, the plants irrigated with RBF water grew healthier and faster, which resulted in great profits in the years following the RBF well installation. In addition, the RBF well was more reliable and more protected than pumps directly installed in the river. Reliability and protection of irrigation equipment from thieves or floods are additional benefits of RBF technology and an important adaptation consideration for agro-business in general. However, future studies of these indirect benefits and a direct measurement of the impact of RBF irrigation water on the productivity and income of farmers in this area would be highly desirable.

Table 18.1 Log removal of *Escherichia coli*, Enterococci, somatic coliphages, somatic salmonella phages, and F-specific bacteriophages by riverbank filtration along the Zarqa River, Jordan

Indicator	Log_{10} removal
E. coli	>4.2
Enterococci	3.2
Somatic coliphages	3.3
Somatic salmonella phages	>2.7
F-specific bacteriophages	3.3

A one-log removal would indicate 90% removal whereas a 4-$\log_{10}$ removal indicates 99.99% removal [*Saadoun et al.*, 2008; *Boving et al.*, 2010]. The distance of the RBF well from the river was approximately 16 m.

18.4. RBF AT THE WATER-ENERGY NEXUS

While the study from Jordan is an example that illustrates the appropriateness of RBF as a water treatment alternative for farmers in areas where river water is too polluted to be used on crops and plants, the following example demonstrates how RBF is connected to the nexus of water and energy.

Most high-performance water pumps rely on electrical power. Although the electrification in developing countries has made great progress, in countries like India, more than 22% of the 1.3 billion people still remain without electricity [*World Bank*, 2015]. In the absence of an electrical connection, farmers often rely on diesel-powered electric generators, which burn fossil fuels and are expensive to operate. It is therefore of great interest to examine whether RBF systems can be supported by off-the-grid, decentralized electric power systems that do not rely on fossil fuel. While there are a number of case studies investigating the use of solar-powered pumping schemes for food production, such as field studies in Kenya and Ethiopia [*REEEP*, 2015], or the use of solar power to desalinate irrigation water [*Jain*, 2015], there are currently no published studies available describing solar-powered RBF systems. Yet, sources of alternative electrical power, such as photovoltaic (PV) cells, can potentially power RBF systems in remote, off-the-grid areas or in areas where farmers seek independence from the electrical grid or want to substitute petrol-powered pumps.

The following case study describes an RBF field study which is currently being conducted in the state of Goa, India (Figure 18.3). In this example, a single solar-powered RBF well was installed to serve the local farming community with treated water for the irrigation of vegetables. Herein, different RBF power supply scenarios are being evaluated, such as relying entirely on solar power or operating a hybrid RBF system using both solar and grid power.

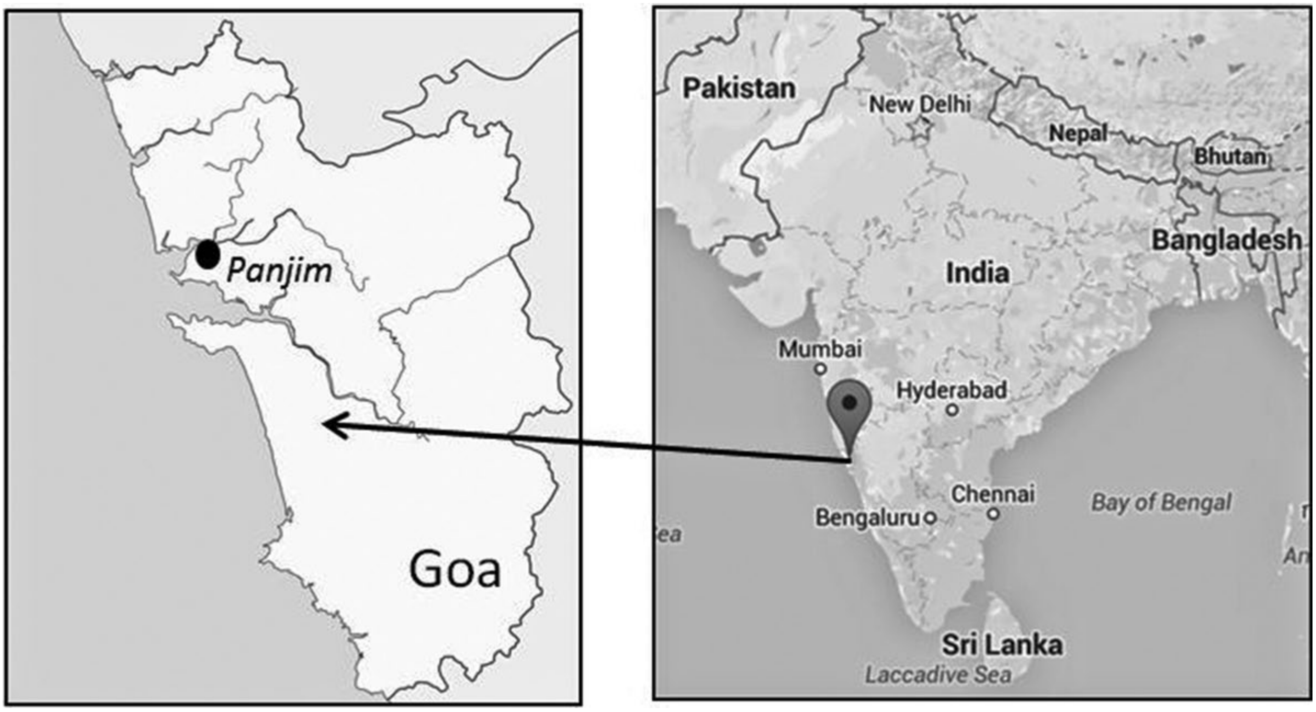

Figure 18.3 The RBF study site is located along the Sal River near the town of Margao in southern Goa, India. Source: Modified after Wikipedia.

18.4.1. Case Study: Sal River, Goa, India

An RBF wellfield was installed on a farm in the Mandopa village, on the eastern bank of the Sal River near the town of Margao, Goa, in India. The Sal River is Goa's third largest river in terms of length and basin size. The study area is dominated by small (<1 acre) farms growing rice in the monsoon season (June through September) and vegetables during the rest of the year. During the dry season, the fields are irrigated with untreated water directly extracted from the Sal River. The project was designed primarily to demonstrate that access to clean and reliable irrigation water directly benefits small-scale farmers by permitting them to grow high-value crops, such as cabbage, amaranth, or other leafy produce. Growing these crops with clean RBF water permits farmers to demand higher prices in the market compared to those farmers who must use polluted river water for irrigation. The project was also intended to investigate if a solar-powered RBF system can compete with a system hooked up to the electric grid.

Based on the hydrogeological information obtained from a drilling and exploration well, an RBF well was drilled in January 2016. The well penetrated 6 m of highly weathered, structured lateritic soil and 21 m of fractured gneissic bedrock. Water was encountered at approximately 1 mbgl. An 8 inch PVC casing was installed within the lateritic soil and about 1 m into the bedrock. The casing was screened approximately 1.5 m upward from the top of the bedrock. A 1 × 1 m concrete block was constructed to protect the well head and minimize contamination from the surface. Because the study area is prone to flooding during the monsoon season, the well head resides 2.5 m above ground level. The concrete block was raised to a height of 1 m above ground and outfitted with concrete stairs to permit access to the well head. During the growing season, a temporary fence protects the agricultural land and the RBF well from roaming livestock and possible bacteria contamination associated with manure.

Table 18.2 Technical specifications for the photovoltaic panels installed at the RBF site along the Sal River field in Goa, India

Parameter	Value per PV panel
Cell type	Multi-crystalline silicon
Manufacturer	Jain Irrigation Systems (Model JJ-M672)
Max. power (Pmax)	300 W
Rated current (Impp)	8.39 A
Rated voltage (Vmpp)	35.76 V
Dimensions	196.1 cm × 99.7 cm
Area	1.96 m^2
Controller	JFC1.4-V1 AC/DC float switch controller (Jain irrigation systems)

Source: Label on PV panel.

A solar-energy-powered, one horsepower (HP) Grundfos submersible electric pump was installed in the RBF well at approximately 10 mbgl and attached to a PV power system comprised of three PV panels. Technical specifications for the panels are provided in Table 18.2. The well yield is up to 3.7 m^3/h (16 gpm) depending on the time of day and weather conditions, which determine the power output of the solar system. Pipes were laid to distribute the RBF water to the parcels of farm land surrounding the well. The amount of water distributed to the surrounding fields is metered and the RBF water quality is monitored by sampling for *E. coli* bacteria, electric conductivity/salinity/total dissolved solids, pH, temperature, and dissolved oxygen content. The Sal River water quality is monitored monthly by the Goa State Pollution Control Board and the fecal coliform bacteria data in 2014 and 2015 are shown in Figure 18.4. The data indicate that the river is carrying high loads of bacteria year-round, particularly during the monsoon season. Further, the river's total dissolved solids load, as determined from electrical conductivity readings at the field site, was found to be equivalent to 141 mg/L of salt at 34°C on 23 January 2016. This compares to 2 mg/L in the water from the RBF well, indicating that some mixing with local groundwater is occurring. No RBF bacteria data are available at this time.

18.4.2. Alternative Energy Resources Assessment for RBF Wells

Sources of renewable energy include solar power, energy from biomass or wind, and others. For small RBF pumping systems of the scale described herein (1 HP), solar power is likely the most economical solution because PV energy offers an economic alternative to grid- or fuel-based pump sets. However, biogas reactors or wind energy schemes might be economical at field sites where these resources are readily available. Either way, renewable energy can provide access to sustainable, secure, and cost-competitive energy along different segments of the water supply chain, thereby reducing pressure on existing energy infrastructure [*IRENA*, 2015].

At sites where a connection to the electrical grid already exists, like the Sal River test site in Goa, it must be evaluated whether a hybrid alternative/conventional energy system is meaningful to bridge the transition period from conventional to alternative sources. Based on electric power generated by solar energy, this hybrid system and a system entirely based on solar power are being evaluated in the two scenarios presented in this section.

Elements of a Solar-Energy-Powered RBF System: A basic solar-energy-powered RBF system consists of PV panels connected to a charge controller and a water pump installed in the RBF well. PV panels with a range of capacities are offered by many manufactures. The type of panel to install largely depends on local availability and ultimately on cost. A number of studies provide guidance for sizing the solar-energy-powered pumping system based on project needs and local conditions [e.g., *Narvarte et al.*, 2000; *Ghoneim*, 2006]. As shown in Figure 18.5, the

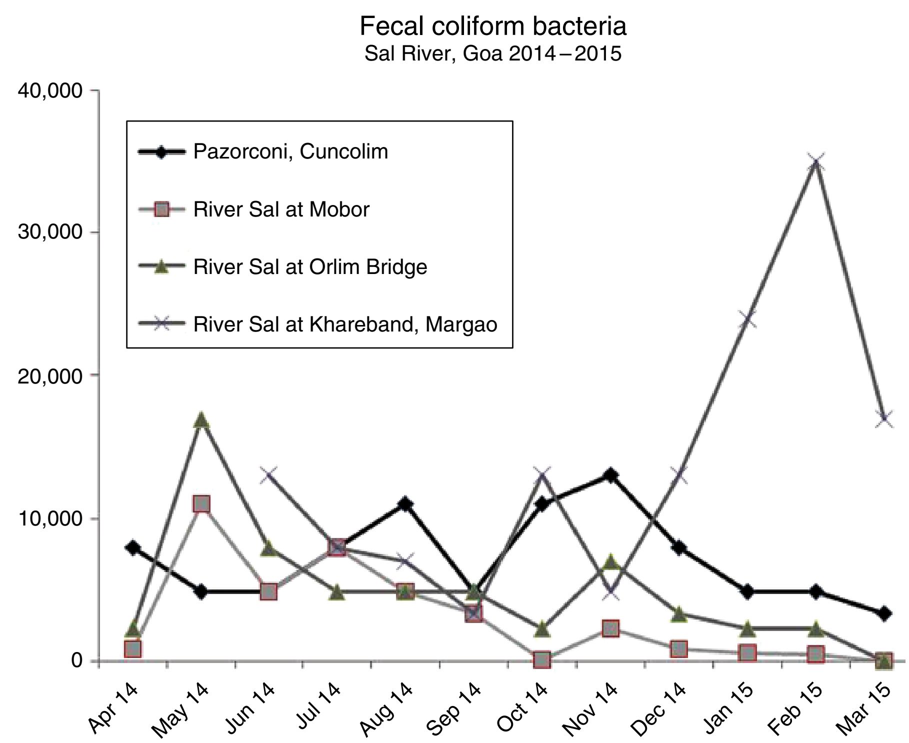

Figure 18.4 Fecal coliform bacteria concentration (MPN/100 ml) at four sampling points along the Sal River in Goa between April 2014 and March 2015. For reference, the monsoonal rains in this part of India typically occur from mid-June through early September. Source: Data reported by the Goa State Pollution Control Board.

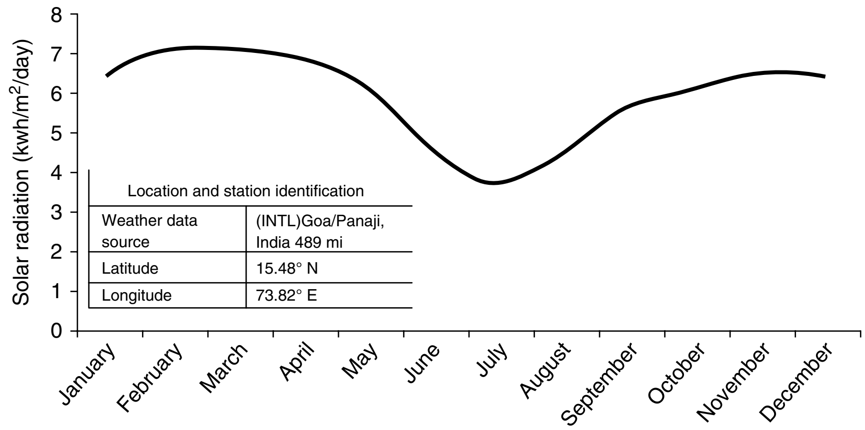

Figure 18.5 Daily amount of solar radiation (kWh/m²/day) at the field site along the Sal River, Goa (India). Source: Data from *PVWATTS* [2016].

solar radiation per day and per square meter received in Goa, India, ranges from 4.1 kWh in July to 7.2 kWh in March (annual average: 5.9 kWh). This amount of solar radiation is more than sufficient to meet the electric power demand via PV cells. Further, the length of daytime and nighttime in this region is approximately equal. However, the optimal time of operation of solar panels is between 9 AM and 3 PM during much of the year. During the remaining 6 h of daytime, the efficiency of the solar radiation decreases in relation to the azimuth of the sun. Further, during the dry season, cloudiness is not an issue in the region.

Regarding the pump selection, submersible pumps are preferred over other pump types (e.g., suction pumps) for several reasons, such as submersible pumps are self-primed and can produce water from greater depths than suction pumps. A disadvantage of this type of pump type is their higher cost. The electrical power need of an AC 220 V, 1 HP submersible pump is about 746 watts. Although a capacitor can reduce the surge power of the pump by 5–7%, the actual power need of the pump during start-up is about twice as high as the pump's continued operating power.

Solar-powered systems designed to operate continuously, that is, pump water even after sunset, require additional components, particularly batteries. These batteries are charged during the daytime while during the nighttime they discharge energy via an AC/DC inverter. For these battery-backed systems, a maximum power point tracking charger is preferred because it captures the maximum DC output from solar panels and converts it to the lower voltage needed to charge batteries.

A battery bank is an assembly of multiple, interconnected batteries that work as one large battery at a required voltage and amp-hour capacity. It is usually the costliest part of a solar power package. For delivering a high amount of current in a very short time, such as during pump start-up, lead-acid batteries have an advantage over deep-cycle batteries. An advantage of deep-cycle batteries is that they produce current for longer periods of time and can be discharged up to 80% without damage. Deep-cycle battery banks are available at reasonable cost.

Depending on the local irrigation schemes and distance to the agricultural fields, additional RBF system components may include a water distribution network consisting of water meters and flexible pipes for feeding the irrigation water to the plants. Water storage tanks might be installed at sites where excess RBF well capacity exists and where nighttime irrigation is desirable.

Scenario I: RBF system is 100% powered by solar energy during the day and connected to the electrical grid during nighttime. An RBF system that is powered by solar energy during daytime and which can be operated by power from the electrical grid during the remaining time was installed at the Sal River test site. This system consists of three PV panels with the technical specifications shown in Table 18.2. Their combined maximum power output is 0.9 kW. This system was designed to power the RBF well for approximately 10 h/day (7:30 through 17:30). Outside these daylight times, the power output of the three PVs is insufficient to power the pump and, in the absence of batteries, the system can be switched to power supply from the electrical grid. The cost of the entire system, including pump and installation, was about USD 3500. Overall, *Scenario I* is expected to reduce the amount of conventional, grid-supported electricity by almost 50% if round-the-clock water supply is required. The savings increase to 100% if water is needed only during the solar-powered system's peak operating time.

Scenario II: RBF system is 100% powered by solar energy. Based on the same technical specifications of the solar-powered system in operation at the Sal River

RBF field site (Table 18.2), a system entirely powered by solar energy would consist of 3 PV panels that power a 1 HP pump during 10 h of day time (7:30 through 17:30) and an additional 5 PV panels that produce the energy to power the pump via a battery bank during the remaining 14 h of dawn/dusk and nighttime. The combined capacity of these 8 solar panels would be 2.4 kW (8 × 300 W). However, many PV panel manufacturers recommend increasing the minimum peak power value by 25% to account for environmental factors, such as high heat, age, or dust accumulation. System energy losses by the inverter account for an additional 5–10% loss of efficiency [*USDA*, 2010]. Altogether, these inefficiencies and losses increase the number of panels to 10, delivering 3 kW combined. Assuming the battery bank consists of a number of 12 V batteries holding 100 ampere hours (Ah) each, the load of a single battery (12 V × 100 Ah = 1.2 kWh) would theoretically power a 1 HP pump for 1.6 h (1.2 kWh/746 W = 1.6 h). However, only 80% of the electrical energy stored in the battery can be discharged without damaging the battery. Hence, a single battery can power the pump for about 1.28 h. The battery storage capacity must be equal to or greater than 14 h of nighttime pump operation or at least 10.5 kWh (14 h × 746 W). To store this energy would require at least 11 batteries. To fully recharge these batteries would require 7 PV panels in addition to the 3 panels required for operating the RBF system during daytime. In case the RBF well is not operated round the clock, any excess electrical power can be diverted to power households in areas without electrical grid access. An advantage of an RBF irrigation system that is 100% powered by solar energy is that during nighttime, irrigation water loss due to evapotranspiration is minimized, thus increasing the water use efficiency compared to daytime irrigation patterns. However, a major drawback of such a system is the considerably higher initial cost associated with purchasing the battery bank.

The two scenarios presented herein suggest that there is a wide range of options available to the RBF system designer. According to an assessment by *IRENA* [2015], if *Scenario II* would be adopted to replace 5 million diesel pump sets with solar systems in India, savings of nearly 18.7 gigawatts (GW) worth of installed capacity, 23.3 TWh of electricity, 10 billion literes of diesel, and 26 million tons of carbon dioxide emissions electricity could be realized. Further, the conversion from conventional to alternative energy sources will likely accelerate as the falling prices of solar panels means that the payback for a solar water pump system is about 1–4 years [*Tweed*, 2014]. While this payback time is reasonable, it will likely be the magnitude of the up-front investment that determines which of these scenarios is feasible. The conversion from conventional to alternative energy may therefore require (micro)financing solutions that can be shouldered by small farming communities in developing nations. Either way, given the unfamiliarity of many farmers and irrigation experts with solar-powered RBF systems, more studies are needed to demonstrate the actual performance of alternative-energy-powered RBF systems.

18.5. RBF AT THE WATER-ENERGY-FOOD NEXUS

Beside the currently not realized potential to alleviate fossil fuel demand, solar-powered RBF makes it possible to clean and reuse polluted surface water and supply that water to agricultural applications that require high-quality irrigation water. The potential of RBF to possibly enable farmers to increase crop yields and thus income by switching to alternative, higher-value crops is illustrated in this section using projections and exemplary income numbers from India.

Water-intensive crops, such as sugarcane, are planted in large parts of South Asia. India has the largest area under sugarcane cultivation in the world. Approximately 4.0 million hectares held sugarcane in 2003–2004, making India the world's second largest producer after Brazil [*Mondal*, 2015]. Growing sugarcane using conventional furrow irrigation requires 1500–2000 mm of water [*Ikisan*, 2016]. While it is water intensive, sugarcane is easy to grow and is less sensitive to water pollution than leafy vegetables, such as cabbage or cauliflower. However, the income farmers can generate from growing sugarcane is much less compared to that from vegetables irrigated with clean water. For instance, as of April 2014, the price of cauliflower and cabbage was Rs 50/kg, onion was selling for Rs 60–65/kg, and tomatoes were Rs 55/kg (currently US$1 is approximately equal to Rs 66). In comparison, the sugarcane marked price was almost 25 times less, that is, 100 kg sugarcane sold for Rs 220 [*The Times of India*, 2015]. The average tomato productivity is 35 tons/ha, which translates to US$14,000 to US$30,000 crop values at the current retail market price [*The Hindu*, 2014]. In the case of sugarcane, the all-India average yield is 80 tons/ha or approximately US$2623. Hence, giving farmers access to clean, solar-pumped RBF water and enticing them to switch from sugarcane to crops like tomatoes could potentially increase their income by more than 10 times.

The choice of crop to substitute depends on local conditions. Water consumption for food production also differs by type of crop, geographic area, season, and irrigation technology. In our RBF study area in Goa, major vegetable crops grown during the rainy (Kharif) season (June through September) are cucurbits, okra, chilli, and gourds. During the winter (Rabi) season (October through February), cabbage, cauliflower, and other members of Brassicaceae, brinjals, amaranth, some green vegetables

Table 18.3 Estimation of drip irrigation water needs for common non-tuber/root crops and vegetables grown in Goa

Crop/vegetable	Water consumption (mm/ha)
Cabbage[a]	267
Cauliflower[a]	255
Lady's finger (Okra)[a]	86
Brinjal[a]	420
Tomato[a]	107
Amaranthus[b]	197
Chillies[a]	417

[a] After *Narayanamoorthy* [2014].
[b] After *Okunade et al.* [2008].

like spinach, methi, and onion, and garlic are grown in the plains. During the summer season (March to May), tomato, lady's finger (okra), some types of gourds, cluster beans, chilli, and amaranth are traditionally grown [*Thangam et al.*, 2009; *Desai*, 2011]. Table 18.3 summarizes drip irrigation water needs for common non-tuber or root crops and vegetables grown in Goa. Drip irrigation water needs for vegetables range from 86 mm/ha for lady's finger to 740 mm/ha for gourds. Vegetables that may benefit the most from irrigation with treated water include leafy produce, such as cabbage, amaranth, or cauliflower. Cabbage and cauliflower require between 255 and 267 mm/ha drip irrigation water or about 5 L/day/m^2 for four plants. In the case of cauliflower, drip irrigation saves 68% of water relative to conventional irrigation methods, while increasing the yield by 70% [*NCPAH*, 2016].

In Goa, the cabbage and cauliflower crop cycle is between 60 and 70 days for early maturing varieties and 90–120 days for later ones [*IAN*, 2016]. The maximum rate of evapotranspiration (ET) in Panajim, Goa, is 4.72 mm/day during December [*Giridhar and Satyanarayana*, 2008]. Given these irrigation water needs and ET losses, the daily water need per hectare ranges between 70 and 90 m^3 for growing cabbage or cauliflower. With the RBF well at the Sal River site in Goa producing approximately 3.7 m^3/h, the continuous operation of the pump would yield sufficient water to irrigate between 1 and 2 ha of land or deliver water to approximately three to five farmers growing cabbage or cauliflower. The size of the irrigated area will vary by crop, that is, growing tomatoes with RBF water will expand the area more than twice while more water-intensive crops, like chillies or brinjal (Table 18.2), will decrease the area by approximately 50%. Examination of the water needs for growing vegetables on small-scale farms demonstrates that one RBF system can irrigate between 1 and 4 ha of land, depending on the crops, and can support up to 10 farmers. The cost of installing an electrical-grid-powered RBF well (1 HP capacity) and drip irrigation system in Goa, India, is approximately US$20,000. Considering that farmers can sell their RBF-irrigated vegetables for 10 times the cost of sugarcane, sharing the cost of an RBF system among 10 farmers reduces the financial burden and brings RBF technology within the reach of farming communities.

Finally, though solar-powered systems are often dismissed because of high up-front costs, they have long lifetimes, and, in the medium term, cost less than liquid-fuel-based pumping systems, particularly in areas where stable access to fuel is limited [*Kolhe et al.*, 2002; *Odeh et al.*, 2006; *Burney et al.*, 2010]. Hence, farmers generating higher incomes by growing high-value crops might eventually be able to invest in solar-powered RBF systems. Besides, such systems will generate additional (energy) cost savings for the farmers in the long term and make them more or less independent of the grid; in addition, less fossil fuel is consumed, resulting in lower carbon emissions from small-scale farming operations. Additional demonstration projects are required to convince farmers that investing in solar-powered RBF technology in combination with switching to high-value crops and drip irrigation will benefit them.

18.6. SUMMARY

The examples from the rural parts of Goa, India, and Jordan illustrate the nexus of RBF systems to water, energy, and food production. Most importantly, the two studies demonstrate how an RBF treatment system enables farmers to irrigate with treated river water that otherwise would be too polluted to be used on crops and plants. The Goa study also shows that a solar-energy-powered RBF system can compete with conventional water supply systems that are hooked up to the electric grid. Together, these findings support RBF as a suitable water treatment technology for small-scale farmers, particularly when combined with drip irrigation and powered by solar energy. These advantages of RBF technology are most pronounced in geographic regions with prolonged dry periods and depleting groundwater resources.

The combination of RBF and alternative power sources can conserve water, increase agricultural productivity, and thus generate higher incomes per unit of farmland for small-scale farmers in developing countries. Furthermore, there is mounting evidence that access to RBF technology enhances the health of villagers who switch from consuming untreated surface water to cleaner RBF water. However, a big challenge remains: can renewable energy technologies, such as solar power, address some of the trade-offs between water, energy, and food, bringing substantial benefits in all three sectors? Despite the compelling case, a widespread adoption of solar-based RBF systems is hindered by a variety of factors, including relatively high capital costs, inertia in the adoption of new technologies, establishing markets for the technology, and ensuring adequate training for installers and operators. Risks are also associated with excessive water withdrawal, since operational costs of solar-powered pumping systems are negligible [*IRENA*, 2015].

As concisely summarized in *REEEP* [2015], the widespread adoption of solar pumping solutions requires financing schemes, such as credit mechanisms, as well as capacity-building programs to ensure that technical skills are available for system maintenance needs over time. There is of course the risk of over-pumping RBF wells, that is, withdrawing more water than can be replenished from the river, thereby tapping into local groundwater bodies. Although any pumping from subsurface water bodies represents an invaluable source of irrigation water, it is often difficult to regulate. These scientific and resource management questions, together with a rigorous examination of the economic feasibility of solar-powered RBF systems, warrant further investigations.

ACKNOWLEDGMENTS

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Section IV
Future of the Nexus Agenda

19

Water-Energy-Food (WEF) Nexus and Sustainable Development

Ashim Das Gupta

ABSTRACT

This chapter deals with the perspective of a nexus in the sustainable development agenda. Achievements of Millennium Development Goals and their shortcomings are mentioned first. The Sustainable Development Goals are then reviewed considering the need of a nexus among different disciplines and sectors while addressing development issues and concerns based on the interdependencies among goals and targets. A review of selected frameworks and case studies on the water-energy-food nexus is then provided and the challenges and opportunities for implementing such an approach are indicated. A recent initiative for integrating research, education, and capacity development across disciplines is then highlighted.

19.1. INTRODUCTION

Nexus in the context of development and management of natural resources implies consideration of interactions of all elements involved in the process and giving due regard to their contributions and trade-offs with the objective of maximizing the benefit derived from their utilization while maintaining environmental integrity. Water, energy, and food are essential elements to satisfy basic human needs, to meet the necessity of life-supporting functions and, in turn, to contribute to social development. The water-energy-food (WEF) nexus involves interaction between the three entities. There are many interconnections between water and food, water and energy, and water, energy, and food, which lead to such strong interdependencies that integrated solutions are required to address the pressure on the ecosystems that supply these vital resources.

The report of the *WEF* [2011] identified the WEF security nexus as one of the three greatest threats to global economy, outlined the economic implications of the nexus, and proposed actions that nations can take to address the problems related to the nexus. Global projections indicate that demand for freshwater, energy, and food will increase significantly over the next decades under the pressure of population growth and mobility, economic development, international trade, urbanization, diversifying diets, cultural and technological changes, and climate change. The World Economic Forum described the "water-food-energy" security problem as follows: A rapidly rising global population and growing prosperity are putting unsustainable pressures on resources. Demand for water, food, and energy is expected to rise by 30–50% in the next two decades, while economic disparities incentivize short-term responses in production and consumption that undermine long-term sustainability. Shortages could cause social and political instability, geopolitical conflict, and irreparable environmental damage. Any strategy that focuses on one part of the WEF nexus without considering its interconnections risks serious unintended consequences [*WEF*, 2011].

The global initiative undertaken by the United Nations, with the launching of the Millennium Development Goals (MDGs) in 2000, has made remarkable achievement in

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addressing the issues of poverty, hunger, disease, unmet schooling, gender inequality, and environmental degradation. Following the completion of the period of implementation of the MDGs in 2015, the United Nations, with the endorsement of world leaders, framed a set of Sustainable Development Goals (SDGs), which embrace a wider perspective of economic development, environmental integrity, and social equity gearing the development in a sustainable trajectory. This certainly requires a cross-sectoral integration for cost-effective and efficient implementation of SDGs and to ensure sustainable resource use. Water, energy, and food have been identified as priority areas for SDGs in the Rio+20 outcome document [*UN*, 2012a], as well as in many preparatory documents, meetings, and discussions [*UN*, 2012b]. Principles of sustainable development and the challenges for their implementation are mentioned in the next section. This is followed by an overview of MDGs with their successes and shortcomings. With a discussion on SDGs in the next section, the need of considering a nexus among different disciplines and sectors is stressed while addressing development issues based on the interdependencies among goals and targets. A review of selected frameworks and case studies on WEF nexus is then provided and the challenges and opportunities for implementing a nexus approach are indicated. Finally, a recent initiative for integrating research, education, and capacity development across disciplines is highlighted.

19.2. SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

19.2.1. Emergence of the Sustainability Concept

The two concepts, "sustainability" and "sustainable development," are not necessarily the same. "Sustainability" refers to the long-term ability to continue to engage in a particular activity, process, or use of natural resources. In contrast, "sustainable development" reflects a broader societal goal of how economic and social development should proceed, namely, with adequate consideration of the environment and natural resources to assure the continuing availability of natural capital and other ecological amenities [*Benson and Craig*, 2014]. For human populations, sustainability means transforming our ways of living to maximize the chances that environmental and social conditions will indefinitely support human security, well-being, and health.

It is nearly three decades since the terms "sustainability" and "sustainable development" rose into prominence following the 1987 publication "Our Common Future," a report of the World Commission on Environment and Development (WCED). Since then, numerous initiatives have been taken at local, national, and global levels to address different aspects of environmental challenges in line with the underlying concepts of sustainability and sustainable development. Global summits in Rio de Janeiro in 1992 and Johannesburg in 2002 led to multiple governmental commitments on sustainable development, and helped to extend the concept's reach into the worlds of business, local government, and civil society. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [*WCED*, 1987]. This definition of Brundtland Commission contains two key concepts: the concept of "needs," in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. These concepts underline the strong linkage between poverty alleviation, environmental improvement, and social equitability through sustainable economic growth [*Mebratu*, 1998].

Sustainable development is a complex and multidimensional issue, which has to combine efficiency, equity, and intergenerational equity on economic, social, and environmental aspects. The definition provided by the Brundtland Commission does not provide any more detailed explanations of what sustainable development may require in practice and what actions should be taken. It has been formulated more as a universally agreed moral principle, and in many cases it is more imagined than practically applicable. On the other hand, one may conclude that the sustainable development concept and its definition presented in the Brundtland Commission's Report merge two urgent *goals*: (i) *to ensure appropriate, secure, wealthy life for all people*: this is the goal of *development*; and (ii) *to live and labor in accordance with biophysical limits of the environment*: this is the goal of *sustainability*. This implies that sustainable development calls for a certain level of compromise among environmental, economic, and social goals of community, allowing for well-being for the present and future generations.

19.2.2. Sustainability as the Policy Concept

Sustainability is an evolving policy concept and its focus has evolved over time. The contemporary interpretation of the "three pillars" concept of integrating environmental, economic, and social objectives has been adopted by many governments in their policies, in their national sustainable development strategies, and in emphasizing sustainability components in development plans. But only some of them have been effective, as pointed out by *Bass* [2007]. In contrast, the author mentioned that many traditional, local approaches could hold the key to achieving sustainable development on the ground, but most are unexplored. Their impact in shaping "our common future" on a more sustainable basis seems to be minimal when measured against the enormity of the global environmental challenges. However, these local-level achievements should be taken as inputs for upscaling and bringing in changes needed at a broader scale in the operational process of development. For mainstreaming principles of sustainable development in practice one needs to understand the scope of the physical, social, economic, and environmental systems considered; the degree of environmental protection that is envisioned to attain sustainable development; the emphasis placed on equity as a prerequisite for sustainable development; and the measure and nature of participation required for attaining sustainable development.

The implementation of any policy, however, depends on the *institutional* aspect: the importance and significance of institutions in the policy, and the competence of these institutions. For this reason, the implementation of the policy of sustainable development requires an evaluation of the organization (institutional) sustainability dimension, since effective and properly functioning institutions are essential for sustainable development in the realization of the social, economic, and environmental aims set by the society.

19.3. MILLENNIUM DEVELOPMENT GOALS (MDGs)

19.3.1. An Overview

The first prime move by the global community to formulate joint initiatives for "our common future" was through the framing of MDGs. The MDGs were officially established following the Millennium Summit of the United Nations in 2000, in which world leaders from 189 countries adopted the United Nations Millennium Declaration [*UN*, 2000]. This adoption clearly signified world leaders' determination to work toward development and poverty eradication, peace and security, environmental conservation, democracy, and human rights. They pledged to "spare no effort to free our fellow men, women and children from the abject and dehumanizing conditions of extreme poverty." They further emphasized that the global reach of these commitments would go beyond their own national borders to people worldwide, notwithstanding the primary responsibility that governments have for their own citizens [*Fukuda-Parr*, 2012].

The MDGs are arguably the most politically important pact ever made for international development and are comprised of eight development goals addressing targets to increase incomes; reduce hunger; achieve universal primary education; eliminate gender inequality; reduce maternal and child mortality; reverse the spread of HIV/AIDS, tuberculosis, and malaria; reverse the loss of natural resources and biodiversity; improve access to water, sanitation, and good housing; and establish effective global partnerships. MDGs 1–7 shared a focus, across very different sectors, on action in and by developing countries, whereas MDG 8 focused more on actions by wealthy countries. These goals are indicated in Table 19.1. The eight MDGs are high-level ambitions, supported by 21 specific targets and more than 60 indicators.

Table 19.1 The eight millennium development goals (MDGs)

MDG1	Eradicating extreme poverty and hunger
MDG2	Achieving universal primary education
MDG3	Promoting gender equality and empowering women
MDG4	Reducing child mortality rates
MDG5	Improving maternal health
MDG6	Combating HIV/AIDS, malaria, and other diseases
MDG7	Ensuring environmental sustainability
MDG8	Developing a global partnership for development

The MDGs have been described as "the most broadly supported, comprehensive and specific poverty reduction targets the world has ever established" [*UNDP*, 2005] and are widely credited with having mobilized and maintained support for global poverty reduction. Several analyses provide a useful insight into how the MDGs represent an integration of different international development strategies and initiatives emerging over recent decades. These goals have substantially shaped development dialogue and investment; some development agencies judged all their activities according to their contribution to achieving the MDGs [*Waage et al.*, 2010].

19.3.2. Successes and Shortcomings

With concerted global, regional, national, and local efforts, remarkable progress was made toward achieving the MDGs during the last 15 years. According to the UN MDG Report 2015, the MDGs helped lift more than 1 billion people out of extreme poverty, make inroads against hunger, enable more girls to attend school than ever before, and protect our planet. They generated new and innovative partnerships, galvanized public opinion, and showed the immense value of setting ambitious goals. By putting people and their immediate needs at the forefront, the MDGs reshaped decision making in developed and developing countries alike. Table 19.2 presents an overview of indicators for global progress on key targets, including halving the proportion of people living in extreme poverty, and getting all children into primary school. Even though significant achievements have been made on many of the MDG targets worldwide, progress has been uneven across regions and countries, leaving significant gaps. Millions of people are being left behind,

Table 19.2 Achievement of MDGs in selected targets

Target	Status	
	Year (level)	Year (level)
Poverty: halve the proportion of people living in extreme poverty	1990 (46.7%)	2015 (14%)
Hunger: halve the proportion of hungry people	1990–1992 (23.3%)	2014–2016 (12.9%)
Education: ensure all children can complete primary school	2000 (83.0%)	2015 (91.0%)
Gender equality: end gender disparities in schools[a]	1990 (0.74)	2015 (1.03)
Child mortality: cut under-5 mortality rate (per 1000 live births) by two thirds	1990 (90)	2015 (43)
Maternal mortality: cut maternal mortality rate (per 100,000 live births) by three quarters	1990 (400)	2015 (220)
HIV and AIDS: halt and begin to reverse the spread of HIV and AIDS[b]	2000 (3.5)	2015 (2.1)
Water: halve the proportion of people without access to safe drinking water	1990 (24%)	2015 (9%)
Sanitation: halve the proportion of people without access to basic sanitation[c]	1990 (46%)	2015 (32%)

[a] Gender parity index (ratio of girls to boys).
[b] Incidence of new cases (million cases).
[c] Data taken from *UNICEF and WHO* [2015].

especially the poorest and those disadvantaged because of their sex, age, disability, ethnicity, or geographic location. Targeted efforts will be needed to reach the most vulnerable people [*UN*, 2015a].

The performance of individual MDGs suggests that they have made four important positive contributions: encouraging global political consensus, providing a focus for advocacy, improving the targeting and flow of aid, and improving the monitoring of development projects [*Waage et al.*, 2010]. The MDGs identified sectoral goals with targets and indicators to measure the progress and attainment of goals. However, very little consideration was given to the possible interaction of how efforts to attain a goal in one sector would affect efforts in another sector and vice versa. This very nature of interdependency of many goals and their implementation process has often affected the creation of the synergies that could arise across different targets, in particular between education, health, poverty, and gender. Even if acceleration in one goal is likely to improve progress in others, these synergies are not always evident, and often vary across countries [*Lomazzi et al.*, 2014].

The MDG process has largely been seen as donor driven, and issues of concern to civil society have been neglected from the agenda. The adopted framework was mostly not derived from a comprehensive analysis and prioritization of development needs of a country, and consequently the development thrust was sometimes too narrowly focused on a subset of specific targets that were easier to achieve, implement, and monitor without giving due regard to the variation of the cross sections of the population at different economic levels. This certainly leads to the issue of equity that is inherent in the system which should be addressed in the future. Despite the widespread support for the MDGs internationally, to ensure ownership of the MDG process (development and implementation) at different levels and by different stakeholders has been problematic [*Waage et al.*, 2010; *Lomazzi et al.*, 2014]. The challenge is how to sustain the value of the development and services attained through MDGs.

The overall framework of MDGs has not incorporated enough consideration to the potential impacts on environmental, social, and economic dimensions. Environmental aspects are addressed under Goal 7 but only some topics are covered, with no consideration being given to climate change and neglecting key issues for sustainable development [*Waage et al.*, 2010]. As each sector worked independently to meet the target, there was no measure on whether the total demand for key resources could be met by existing supplies without degrading the resource base and underlying ecosystems. Long-term sustainability requires acknowledging that many of the resources that support development, such as water, land, and materials, are finite and are also needed to support vital ecosystem services. Development can only be sustainable if it works within those constraints, over time, and across sectors and locations [*Lomazzi et al.*, 2014].

Finally, it is to be pointed out that the interconnecting issues or, in other words, the nexus aspects are not explicitly considered while addressing MDGs and their implementation through the realization of specific targets in different sectors as meeting each and every individual goal could depend on the level of achievement in one or more of the remaining goals. For example, health-related goals either directly or indirectly depend on poverty alleviation as well as on maintaining a clean environment. Health could also be an important precondition for the education-related goals. However, it can always be argued that clearly defined goals are necessary to focus attention on certain issues; nevertheless, paying attention to the interconnected nature of most of the goals, that is, taking a nexus approach, will help avoid duplication of efforts, get better target assistance, and use the available resources effectively and sustainably.

19.4. SUSTAINABLE DEVELOPMENT GOALS (SDGs)

The concept of the SDGs was initiated following the Rio+20 Conference, the United Nations Conference on Sustainable Development in 2012. The outcome document of this conference entitled "The future we want" set out a mandate to establish an open working group to develop a set of SDGs for consideration and appropriate actions by the General Assembly at its sixty-eighth session. The document gave the mandate that the SDGs should be coherent with and integrated into the UN development agenda beyond 2015. It was decided that the process leading up to the adoption of the SGDs by the UN General Assembly would be "an inclusive and transparent process open to all stakeholders." The SDGs should be "action-oriented, concise, easy to communicate, limited in number, aspirational, global in nature, and universally applicable." Poverty eradication, changing unsustainable and promoting sustainable patterns of production and consumption, protecting and managing the natural resource base, and ensuring economic and social development are the overarching objectives of and essential requirements for sustainable development [*UN*, 2014].

The Heads of State and Government and High Representatives who met at the UN Headquarters in New York in September 2015 have endorsed and adopted the 2030 Agenda for Sustainable Development. The agenda comprises of 17 SDGs with 169 associated targets which are integrated and indivisible, global in nature, and universally applicable, taking into account different national realities, capacities, and levels of development and respecting national policies and priorities. By endorsing the agenda for 2030, the world leaders have pledged to end poverty and hunger everywhere; to combat inequalities within and among countries; to build peaceful, just, and inclusive societies; to protect human rights and promote gender equality and the empowerment of women and girls; and to ensure the lasting protection of the planet and its natural resources. They have resolved to create conditions for sustainable, inclusive, and sustained economic growth, and shared prosperity and decent work for all, taking into account different levels of national development and capacities. The goals and targets are the result of over two years of intensive public consultation and engagement with civil society and other stakeholders around the world which paid particular attention to the voices of the poorest and the most vulnerable [*UN*, 2015b].

SDGs as a step forward in the continuation of the MDGs that ended in 2015 have set forth the aspirations and targets to be achieved by all countries and are framed as an integrative concept encompassing the so-called triple bottom line to human well-being with a combination of economic development, environmental sustainability, and social integrity. The "triple bottom line" dimensions of sustainability are fundamental to a country's progress and sustainable future. The focus of the MDGs was on reducing poverty and improving the well-being of individuals in developing countries, mainly geared to the human development objective; and different goals and targets were set to measure achievement in its multidimensional aspects (lack of income, education, water and sanitation, political participation, etc.). The SDGs also involve these aspects as well as goals and targets that refer to the preservation or establishment of public goods and services, and consumption and production patterns including response to climate change, and institutions and finance. This holistic consideration embraces the social, environmental, and financial conditions that are geared toward shaping development sustainably. The 17 SDGs with their scope are listed in Table 19.3.

The SDGs and targets are inclusive and highly ambitious. It is expected that the institutions, services, and legislative framework of regional and national government will play a dominant role to ensure implementation and realization of the majority of the goals and targets. It is important to recognize the link between sustainable development and other relevant ongoing processes in the economic, social, and environmental fields. The authority concerned needs to decide how these aspirational and global targets of SDGs are to be incorporated in their national planning processes, policies, and strategies. The institutional mechanism for implementation is also an important factor: who should lead the process and how actions from different institutions at different administrative levels are coordinated? Efforts are needed at international and national scales for mobilizing financial and nonfinancial resources for the implementation of SDGs, which is also a challenge to be addressed. Fulfillment of development goals requires holistic and integrated approaches to engaging multiple actors, operating at multiple levels and across multiple scales. It demands

Table 19.3 Sustainable development goals [*UN*, 2015b]

Goal 1. No poverty	End poverty in all its forms everywhere
Goal 2. Zero hunger	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
Goal 3. Good health and well-being	Ensure healthy lives and promote well-being for all at all ages
Goal 4. Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5. Gender equality	Achieve gender equality and empower all women and girls
Goal 6. Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
Goal 7. Affordable and clean energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
Goal 8. Decent work and economic growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
Goal 9. Industry, innovation, and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
Goal 10. Reduced inequalities	Reduce inequality within and among countries
Goal 11. Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient, and sustainable
Goal 12. Responsible consumption and production	Ensure sustainable consumption and production patterns
Goal 13. Climate action	Take urgent action to combat climate change and its impacts
Goal 14. Life below water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
Goal 15. Life on land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss
Goal 16. Peace, justice, and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels
Goal 17. Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development

competent human resource in different sectors and disciplines and a structured system of participation and needs to have a strengthened accountability and legitimacy process. Finally, an adequate monitoring of data and the evaluation process is to be established to assess the progress on the achievement of the development goals and targets.

19.5. NEXUS PERSPECTIVE ON SDGs

A nexus approach tries to build in synergies among sectors, reduces trade-offs, and enhances the efficiency of the entire system rather than increasing the productivity of specific sector(s), often at the expense of other sectors. The guiding principles of the nexus approach are to promote sustainable and efficient resource use, doing more with less, to ensure access to resources for the most vulnerable, especially the poor, and to maintain healthy and productive ecosystems [*Hoff*, 2011]. A review of SDGs clearly indicates that in order to achieve the proposed goals and targets, there would be inherent conflicts while using the natural resources unless and until synergies and trade-offs among different goals and targets are accounted for based on certain criteria. For example, to meet the targets for food security (Goal 2), clean water and sanitation (Goal 6), and affordable and clean energy (Goal 7), consideration of interdependency (or nexus consideration) is a must, otherwise achieving these without compromising natural resource base and planetary systems on which life depends will be a formidable challenge. In a brief discussion, *Weitz et al.* [2014] demonstrated how the WEF nexus can provide a framework for systematically assessing the cross-sectoral interactions in the SDGs. Targets of two proposed SDGs, Goal 12 "Ensure sustainable consumption and production patterns" and Goal 10 "Reduce inequality within and among countries," reflect the need for considering critical connections among the goals and whether their universality is relevant to all countries deemed to contribute to achieving them. The means of implementation of SDGs are highlighted through Goal 17 "Strengthen the means of implementation and revitalize the global partnership for sustainable development," which comprises 19 targets in the areas of finance, technology, capacity building, trade and systemic issues like policy and institutional coherence, multi-stakeholder partnerships, and data, monitoring, and accountability.

By using the network analysis technique, *Blanc* [2015] showed how the SDGs seen through the nexus lens are

Table 19.4 An integrated representation of links between the SDGs through targets

Rank	Sustainable development goal (SDG)	No. of other goals to which the goal is connected
1	12: Ensure sustainable consumption and production patterns	14
2	10: Reduce inequality within and among countries	12
3	1: End poverty in all its forms everywhere	10
4	8: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all	10
5	2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	8
6	3: Ensure healthy lives and promote well-being for all at all ages	8
7	5: Achieve gender equality and empower all women and girls	8
8	4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	7
9	6: Ensure availability and sustainable management of water and sanitation for all	7
10	11: Make cities and human settlements inclusive, safe, resilient, and sustainable	6
11	13: Take urgent action to combat climate change and its impacts	6
12	15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss	6
13	16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels	6
14	7: Ensure access to affordable, reliable, sustainable, and modern energy for all	3
15	9: Build resilient infrastructure, promote inclusive and sustainable industrialization and forest innovation	3
16	14: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	2

Source: After *Blanc* [2015]. Reprinted with the permission of the United Nations.

unequally connected, with some goals connected to many other goals through multiple targets, while other goals are weakly connected to the rest of the system. This analysis excluded Goal 17 dedicated to cross-cutting means of implementation as well as all related targets that appear under other goals. The aggregated presentation of the links among the goals as deduced by the author from network analysis is given in Table 19.4. It ranks 16 goals according to the number of other goals to which they are linked. Responsible Consumption and Production (Goal 12), Reduced Inequalities (Goal 10), No Poverty (Goal 1), and Decent Work and Economic Growth (Goal 8) top the list and all have links with 10 or more other goals. Three goals, namely, Affordable and Clean Energy (Goal 7) with three links, Industry, Innovation, and Infrastructure (Goal 9) with three links, and Life below Water (Goal 14) with two links, are at the bottom of the list. The remaining nine SDGs, Goals 2, 3, 4, 5, 6, 11, 13, 15, and 16, are all connected to six to eight other goals, either directly or indirectly. In a similar study commissioned by the German Council for Sustainable Development, *Cutter et al.* [2015] of the Stakeholder Forum highlighted some key observations about the balance of the social, economic, and environmental dimensions in the SDGs and examined integration in the proposed SDGs. The interpretation on interlinkages between goals reported in this study is slightly different from the interpretation reported by *Blanc* [2015]. It is to be noted that these interpretations are based on the general perception of considering linkages among goals and targets in individual cases; nevertheless, they reflect a comparable form with regard to interdependency of goals and targets. For many of the thematic areas covered by the SDGs, targets relating to those areas are found to have implication not only for the goal under which they are indicated, but also across a range of other goals. However, the final document on "Transforming Our World: the 2030 Agenda for Sustainable Development" produced by the *UN* [2015b] fell short of mentioning explicitly the need of considering interaction among different goals and targets while addressing specific country-level issues and concerns to sustain the development in an effective and efficient manner.

19.5.1. Interactions in SDGs

The example of the WEF nexus is provided to illustrate interactions between SDGs and possible targets. The SDGs directly related to the themes of water, energy, and food are Goal 6 “Ensure availability and sustainable management of water and sanitation for all,” Goal 7 “Ensure access to affordable, reliable, sustainable and modern energy for all,” and Goal 2 “End hunger, achieve food security and improved nutrition and promote sustainable agriculture.” The interlinkages of these relevant goals and their respective targets with other SDGs/targets are indicated in Table 19.5. This is derived based on a conceptual interpretation of the WEF nexus and their dependency on other goals. For the targets of Goal 2, interlinkages with 10 goals/targets are identified, with 3 targets linked to Goals 1, 5, and 6; 2 targets linked to Goals 8, 10, 12, and 15; and 1 target linked to Goals 3, 7, and 13. For the targets of Goal 6, interlinkages with 10 goals/targets are identified, with 3 targets linked to Goals 3, 9, and 12; 2 targets linked to Goals 7 and 10; and 1 target linked to Goals 2, 5, 11, 13, and 15. For the targets of Goal 7, interlinkages with 5 goals/targets are identified, with 3 targets linked to Goals 9, 10, and 12; and 2 targets linked to Goals 2 and 6. Apart from having linkages among the three areas of water, energy, and food, fulfillment of specific targets under each will meet the requirement of Goal 1 “No Poverty,” Goal 3 “Good Health and Well-being,” and Goal 5 “Gender Equality.” Moreover, many of the targets under water, energy, and food complement several targets under Goal 12 “Responsible Consumption and Production,” indicating the need for mainstreaming the targets for sustainable

Table 19.5 Interlinkage of relevant goals and targets of WEF nexus in SDG framework of *UN* [2015b]

GOAL 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	Interlinked goals/targets
2.1. By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations including infants, to safe, nutritious, and sufficient food all year round	Goal 1 No Poverty 1.5 Goal 5 Gender Equality 5.a Goal 6 Clean Water and Sanitation 6.1 Goal 10 Reduced Inequalities Goal 12 Responsible Consumption and Production 12.3
2.2. By 2030, end all forms of malnutrition, including achieving by 2025 the internationally agreed targets on stunting and wasting in children under five years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women, and older persons	Goal 3 Good Health and Well-being Goal 5 Gender Equality Goal 6 Clean Water and Sanitation 6.2
2.3. By 2030, double the agricultural productivity and the incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets, and opportunities for value addition and nonfarm employment	Goal 1 No Poverty 1.4 Goal 5 Gender Equality 5.a Goal 6 Clean Water and Sanitation 6.5 Goal 7 Affordable and Clean Energy 7.1 Goal 8 Decent Work and Economic Growth Goal 10 Reduced Inequalities
2.4. By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters, and that progressively improve land and soil quality	Goal 1 No Poverty 1.5 Goal 8 Decent Work and Economic Growth Goal 12 Responsible Consumption and Production 12.1 Goal 13 Climate Action Goal 15 Life on Land
2.5. By 2020, maintain genetic diversity of seeds, cultivated plants, farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at national, regional, and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge as internationally agreed	Goal 15 Life on Land 15.6
GOAL 6: Ensure availability and sustainable management of water and sanitation for all	**Interlinked goals/targets**
6.1. By 2030, achieve universal and equitable access to safe and affordable drinking water for all	Goal 3 Good Health and Well-being Goal 7 Affordable and Clean Energy Goal 10 Reduced Inequalities Goal 11 Sustainable Cities and Communities Goal 12 Responsible Consumption and Production 12.1, 12.2

Table 19.5 (Continued)

GOAL 6: Ensure availability and sustainable management of water and sanitation for all	Interlinked goals/targets
6.2. By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	Goal 3 Good Health and Well-being Goal 5 Gender Equality Goal 7 Affordable and Clean Energy Goal 9 Industry, Innovation and Infrastructure Goal 10 Reduced Inequalities
6.3. By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and increasing recycling and safe reuse globally	Goal 3 Good Health and Well-being Goal 12 Responsible Consumption and Production 12.4, 12.5 Goal 13 Climate Action
6.4. By 2030, substantially increase water use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	Goal 2 Zero Hunger Goal 9 Industry, Innovation, and Infrastructure 9.1, 9.4 Goal 12 Responsible Consumption and Production 12.2
6.5. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	Goal 9 Industry, Innovation, and Infrastructure 9.1
6.6. By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes	Goal 15 Life on Land 15.1

GOAL 7: Ensure access to affordable, reliable, sustainable, and modern energy for all	Interlinked goals/targets
7.1. By 2030, ensure universal access to affordable, reliable, and modern energy services	Goal 2 Zero Hunger Goal 6 Clean Water and Sanitation Goal 9 Industry, Innovation, and Infrastructure Goal 10 Reduced Inequalities Goal 12 Responsible Consumption and Production
7.2. By 2030, increase substantially the share of renewable energy in the global energy mix	Goal 9 Industry, Innovation, and Infrastructure Goal 10 Reduced Inequalities Goal 12 Responsible Consumption and Production
7.3. By 2030, double the global rate of improvement in energy efficiency	Goal 2 Zero Hunger Goal 6 Clean Water and Sanitation Goal 9 Industry, Innovation, and Infrastructure Goal 10 Reduced Inequalities Goal 12 Responsible Consumption and Production

Interlinked goals are indicated in short form as given in Table 19.3; specific targets of some goals are indicated by number (for details refer to *UN* [2015b]).

management and efficient use of natural resources, environmentally sound management of chemicals and all wastes, reducing waste generation, and minimizing food wastes in sectoral development policy, strategy, and action plan. This will certainly require professionals in many sectors to come out of their institutional "silos" and interact with professionals from other disciplines as they need to incorporate targets related to sustainable consumption and production in activities under their goals.

A further scrutiny of the interactions between goals and targets will reflect that some interactions are interdependent, some impose constraints or conditions on one another, and some reinforce each other. Accessibility to water, energy, and land would lead to viability of food security, indicating their interdependency. On the other hand, the target to achieve the sustainable management and efficient use of natural resources sets a condition for how access to water and energy can be provided. By addressing the target of reducing food waste and food losses, under Goal 12: target 12.3, one can ensure that more food will be available for the population, thereby reinforcing the need to achieve the target of food security. Areas of reciprocity within the framework can also be identified, indicating targets in different goals that are mutually reinforcing without being duplicative. For example, by referring to Table 19.5, target 2.5 and target 15.6, target 6.5 and target 9.1, and target 6.6 and target 15.1 are found in areas of reciprocity. These are listed separately in Table 19.6. Reciprocity creates a two-way relationship between thematic areas and therefore is a more evolved form of interlinkages, which are important for achieving integration as well as for delivering co-benefits. Furthermore, it indicates the need for a coherent policy across goals to ensure efficient use of resources and a desirable outcome.

19.5.2. Adopting SDGs in Development Processes

The interlinkages and interdependencies between SDGs as reflected in Table 19.4 and as elaborated in Section 19.5.1 for the WEF nexus clearly indicate that in order to implement SDGs in practice priority areas must be identified along with relevant goals and targets to address specific issues and concerns where efforts are to be delegated in coherence to progress in a sustainable manner. What this implies is that the normal practice of working toward a specific goal (as practiced with implementation of MDGs) would make it difficult to address interactions across goals and the effective use of common resources they involve. Traditionally, development activities are undertaken on sectorial basis and "normal" professional thinking is narrowly focused within sectors, reinforced by institutional "silos" that arbitrarily separate their domains of activities and actions. A certain reform in the operational process is to be instituted and the most practical implementation option in this situation would be to identify country-level issues and concerns from the socioeconomic and environmental point of view and then define activities for a set of identified targets that might cut across a number of goals. This target-focused process is likely to stimulate discussions on the scope of development issues, not sectoral challenges, and bring in cross-sectorial integration. Accordingly, a nexus approach with a cross-sectoral interacting framework is to be adopted to ensure efficient allocation of resources between competing needs to support sustainable development pathways.

With the endorsement of the 2030 Agenda for Sustainable Development, the national governments are committed to mainstream the new agenda at the national and local levels, and to integrate it into national, subnational, and local plans for development. The SDGs and associated targets are integrated and indivisible, global in nature, and universally applicable. However, each government can set its own national targets guided by the global level of ambition but taking into account national circumstances, and each government can also decide how these targets should be incorporated in the national planning processes, policies, and strategies. During this process, public awareness building is of prime importance and it is imperative that the stakeholders at national, subnational, and local levels are engaged at all stages for the successful implementation of SDGs.

Table 19.6 Reciprocity among targets of selected goals

Target under Goal 2	Reciprocity target under Goal 15
2.5. By 2020, maintain genetic diversity of seeds, cultivated plants, farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional, and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed	15.6. Promote fair and equitable sharing of the benefits arising from the utilization of genetic resources, and promote appropriate access to genetic resources
Target under Goal 6	**Reciprocity target under Goals 9 and 15**
6.5. By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	9.1. Develop quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all
6.6. By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes	15.1. By 2020, ensure conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements

National governments need to develop and implement strategies, plans, and policies that target systemic transformation and develop coherence among sectors/departments contributing to the attainment of common goals and targets. This certainly requires an acknowledgment and better understanding of the dynamic interdependence and interconnectedness of numerous complex systems and subsystems, such as water, energy, and ecosystems, and the impacts and changes they will undergo from various external drivers, including climate change. Traditional sector-based approaches and tools are not fit for this purpose as the challenges are more complex and systemic in nature, which highlights the integrated systems approach as being critical to sustainable development planning and strategy formulation.

Formalized institutional mechanisms in the form of interagency coordinating bodies are to be in place for purposes of forging integration and partnership, for creating horizontal policy coherence with the objective of building awareness and common understanding of issues and concerns, and for dedicating necessary resources toward the achievement of common goals and targets. In addition, creating policy coherence, integration, and partnerships in the vertical direction among governments, civil society, the private sector, and other actors is essential and complementary to creating horizontal policy coherence. With mandates and involvement of the highest-level offices in the government (i.e., Prime Ministers and Presidents offices, Cabinet Offices), these coordinating institutions can serve to connect and break down silos across sector-based organizations/departments of the ministries under the government.

A multistage process is recommended to adapt SDGs to national contexts. It begins with reviewing existing strategies and development plans at national, subnational, and local levels and then by comparing these with the global SDGs and targets to identify gaps, which provides the basis for recommending areas for change. Initial recommendations are then made for addressing gaps to the leadership of the national government, thereby setting nationally defined SDGs and targets. Following this, a more in-depth systems analysis (using integrated modeling) is undertaken considering the causal relationships and interactions among the subsystems to incorporate recommendations and comprehensions from the previous steps into strategies and plans, matching ambition and commitments with resources and capacities. By this process, trade-offs and synergies are identified and agreed targets are translated into national policy frameworks.

Innovative systems modeling tools are currently being developed to support the national planning process. These tools are used in a participatory manner to foster a shared understanding of complex issues. Government planning agencies can use these integrated modeling tools to gain a systems-wide perspective on sustainable development issues to inform the setting of achievable and ambitious targets for plans and policies. The Millennium Institute's Threshold 21 (T21) model has been applied by governments in the national planning process to generate scenarios describing the future consequences of the proposed strategies. A companion model has recently been developed by the Millennium Institute, iSDG, which simulates the fundamental trends for SDGs until 2030 under a business-as-usual scenario, and supports the analysis of relevant alternative scenarios (http://www.millennium-institute.org/integrated_planning/tools/). Another promising integrated modeling system, the CLEW model for Climate, Land Use, Energy, and Water simulations, integrates different modeling approaches for different resources, analyzes the interactions, and demonstrates trade-offs associated with interventions aimed at meeting development goals. Use of this model in the context of a specific case study can be found in the literature [*Howells et al.*, 2013]. In a recently published article [*Leslie et al.*, 2015], the authors discussed a social-ecological systems (SESs) framework, providing guidance on how to assess the social and ecological dimensions that contribute to sustainable resource use and management study. The SES framework enables the integration of data from diverse natural and social science disciplines, and thus provides a theoretically grounded means of testing hypotheses about the dynamics and implications of social-ecological interactions.

19.6. IMPLEMENTING THE NEXUS APPROACH: CHALLENGES AND OPPORTUNITIES

The WEF nexus is considered as a security nexus for the society and social well-being. Implementing a nexus approach requires recognizing, understanding, and evaluating the interconnectedness of related disciplines and sectors with the realization of efficient use of their resources in a sustainable manner. This evaluation has to be conducted in a structured manner depending on the situation, particularly when dealing with a resource scarcity situation that calls for appraising trade-offs on common as well as independent activities and resource uses among the nexus focus areas. The academic and policy literature on current and future challenges in water, food, and energy security explores three main themes. The first theme is the nature of the relationships among the three elements (through input-output analysis). The second is the consequences of their changes in various sectors, including geopolitical implications. The third includes implications for policy development and actions for addressing the three securities [*Bizikova et al.*, 2013].

A number of international organizations and research institutes put forward conceptual frameworks for the

WEF nexus that build on a systems perspective to understand the linkages between the sectors, to address cross-cutting issues and challenges in assessing consequences of development planning, and to assist in formulating policies, investment, and action plans. *Bizikova et al.* [2013] provided an overview of the development of the WEF nexus framework and, based on a review of selected frameworks [*Hoff*, 2011; *WEF*, 2011; *ICIMOD*, 2012], the authors elaborated on a comprehensive framework for WEF securities addressing ecosystem goods and services. The development of this framework was the initiative of the International Institute for Sustainable Development (IISD) to put forward a practical planning and decision support system for landscape investment and risk management. The framework is embedded in a practical participatory planning process that allows stakeholders and communities to identify the key ecosystem services that would optimize their WEF security. The implementation process recommended is a generic one and passes through four phases; and the tasks/activities under each phase, as adopted from *Bizikova et al.* [2013], are indicated in Figure 19.1.

Adapting the WEF nexus is a challenging task and needs to be addressed in a country's sociopolitical, environmental, and economic context. Traditionally, most governments have separate agencies to oversee water, energy, and agricultural food production, and they set policies and plans for each sector separately. For the nexus to be considered in practice, forging integration across disciplines in different phases of development, operation, and management is a major challenge. Sectoral fragmentation still impedes effective implementation of integrated governance of individual sectors as well as their nexus entities and, in turn, sustainable management practices at global, regional, and national levels. It has been mentioned earlier (in Section 19.5.2) that institutional mechanisms in the form of interagency coordinating bodies are to be mandated by the highest-level offices in the government to bring about changes in the existing governance system by formalizing strategies to develop an understanding of the WEF nexus across sectors, to enable intersectoral and interdisciplinary analysis and evaluation based on the nexus concept, and to provide guidance on policy decisions. All involved sectors/departments are obligated to contribute with their dedicated human, financial, and other resources to operationalize the nexus concept. Only in recent years, the WEF nexus has become an issue of concern and attention is being directed toward understanding the interconnections, their trade-offs and synergies, and implications for policies

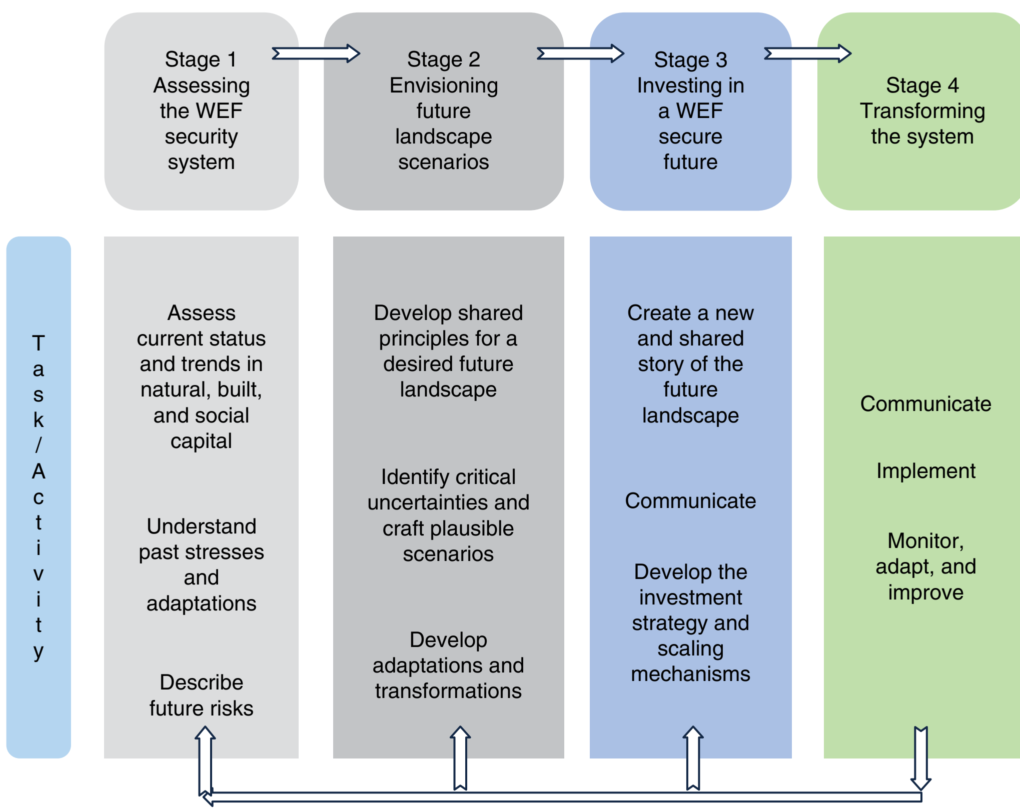

Figure 19.1 Participatory scenario planning process for WEF security nexus. Source: Adapted from *Bizikova et al.* [2013].

and management decisions. Several recently published articles deal with the development of a framework for the WEF nexus approach based on the conceptualization of different systems and address their interconnections and their consequences in order to elaborate on how to deal with their security in the respective case study areas [*Bach et al.*, 2012; *FAO*, 2014; *Rasul*, 2014; *Gain et al.*, 2015; *Keskinen et al.*, 2015; *Kibaroglu and Gürsoy*, 2015; *Mayor et al.*, 2015; *Meza et al.*, 2015; *Mirzabaev et al.*, 2015). A brief on selected published literature is provided in the following section giving the scope of the works along with their salient findings.

Rasul [2014] emphasized the role of Hindu Kush Himalayan (HKH) ecosystem services in sustaining food, water, and energy security for the downstream communities. The author suggested that along with cross-sectoral integration to improve the resource use efficiency and productivity of the three sectors, regional integration between upstream and downstream areas is critical in food, water, and energy security. *Mayor et al.* [2015] presented a case study of the Duero River Basin in Spain to illustrate how the nexus approach can help understand the trade-offs and synergies, diagnose the level of political coordination, and identify existing and potential solutions to improve WEF resource management in the region. *Gain et al.* [2015] analyzed the nexus in the context of Bangladesh and by adapting a conceptual framework developed by *Nilsson and Persson* [2003], the authors demonstrated that policy integration is essential for implementing the WEF nexus approach. *Kibaroglu and Gürsoy* [2015] analyzed the evolution of transboundary water resources management in the Euphrates-Tigris basin with specific reference to interlinkages between water, food, and energy policies at national and transboundary levels, and explored how the policy shifts at the highest decision-making level have served to produce synergies for cooperation among the riparian countries or vice versa. *Meza et al.* [2015] illustrated the nature of the WEF nexus in four regions of Chile currently under pressure due to climate variability and relative water scarcity that suffer from strong competition among their users. A synthesis of analyses presented by means of a conceptual figure allowed better communication of the status of the WEF nexus, and highlighted its dynamic nature in response to external driving forces. *Keskinen et al.* [2015] analyzed the case of Tonle Sap Lake of the Mekong River basin in Cambodia in the context of the WEF nexus and reported that the nexus approach was particularly useful in facilitating collaboration and stakeholder engagement because such an approach clearly defined the main themes included in the process, and at the same time widened the discussion from mere water resource management to the broader aspects of water, energy, and food security. *Mirzabaev et al.* [2015] provided a review of trade-offs and synergies of bioenergy within the WEF security nexus, with an emphasis on developing countries. They explored the links of bioenergy with food security, poverty reduction, environmental sustainability, health, and gender equity.

This review of selected published articles on the WEF nexus clearly indicates that opportunities exist to implement the nexus approach at different scales, that is, at national, regional, and local levels, provided there is recognition of the need, understanding of the extent of interconnections and their consequences, and willingness to reform sectoral policies and strategies toward more integrated and cost-effective planning, decision-making, implementation, monitoring, and evaluation. A nexus approach helps us better understand the complex and dynamic interrelationships. Effective cross-sectoral consultation mechanisms are needed to ensure the development of concerted efforts to address this WEF security issue, and to make sure that decisions are taken as part of an integrated, long-term, and multisectoral strategy. The following areas of interventions are recommended in order to promote the adoption of a nexus approach in planning and decision making (adopted from *Bizikova et al.*, 2013).

1. Involvement of stakeholders: to build awareness of and capacity for the interconnected nature of the elements of the WEF nexus, share ways to minimize trade-offs, explore synergies, and suggest actions for changing behaviors with regard to the nexus and with regard to other actors whose well-being relies on services and products associated with elements of the nexus. This includes community-level empowerment using core resources to focus on more sustainable consumption [*WEF*, 2011].

2. Improvement of policy development, coordination, and harmonization: to account for trade-offs and build on the increased interconnectedness of WEF. Part of this process is promoting, identifying, and eliminating contradictory policies [*WEF*, 2011].

3. Governance, integrated and multi-stakeholder resource planning: to promote cross-sectoral and cross-departmental approaches to planning and working with stakeholders at different levels to improve public-sector-led governance, planning, and information flows [*Bonn2011 Nexus Conference*, 2011; *WEF*, 2011].

4. Promoting innovation: to identify technological choices and investments that explore WEF synergies and could be implemented to achieve desired changes on the ground.

5. Monitoring, evaluation, and feedback mechanism: to appraise functioning of individual systems as per agreed policies and strategies, identify operational changes needed, and provide feedback to steps 2, 3, and 4.

6. Influencing policies on trade, investment in environment/climate: by focusing on improving ecosystem management to increase resource productivity, thus contributing to poverty alleviation and green growth.

19.7. CAPACITY DEVELOPMENT: ADDRESSING NEXUS AND SUSTAINABLE DEVELOPMENT

Capacity development and building awareness about the interconnected nature of all elements in the nexus, trade-offs needed in resource use, improved policy development, coordination, and overall governance of the nexus are some of the important elements needed to operationalize the nexus and gain benefit on a sustainable basis at all levels. The SDGs address all four dimensions of sustainable development, namely, economic, social, environmental, and governance, and set objectives for governments at all levels as well as for business and civil society. According to the Organization for Economic Cooperation and Development (OECD), "Capacity is the ability of people, organizations and societies as a whole to manage their affairs successfully. Capacity development is the process whereby people, organizations, and society as a whole unleash, strengthen, create, adapt and maintain capacity over time" [*OECD*, 2006]. The United Nations Development Programme (UNDP) defines capacity development as follows: "Capacity is the ability of individuals, organizations and societies to perform functions, solve problems, and set and achieve goals. Capacity development entails the sustainable creation, utilization and retention of that capacity, in order to reduce poverty, enhance self-reliance, and improve people's lives. Capacity development builds on and harnesses rather that replaces indigenous capacity. It is about promoting learning, boosting empowerment, building social capital, creating enabling environments, integrating cultures, and orienting personal and societal behaviour" [*UNDP*, 2009].

Capacity development is committed to sustainable development to a long- rather than short-term perspective of continual learning and acquiring of skills and resources through individuals' participation and dedication toward enhancement of organizational and institutional strength in addressing development issues. This clearly indicates that capacity development involves something more than the strengthening of individual skills and abilities. Trained individuals need an appropriate environment, and a proper mix of opportunities and incentives to use their acquired knowledge. The implication is that the capacity development initiatives should be addressed in an integrated manner at three levels: the individual, the institution, and the enabling environment. *Luijendijk and Arriens* [2009] elaborated on these three levels for capacity development with resulting outputs and goals as indicated in Figure 19.2. For an organization, this effort needs to be formulated and structured in a manner that depends on the issues to be addressed, so that the governing entity has the required resources, strength, and initiative with the proper enabling environment to tackle

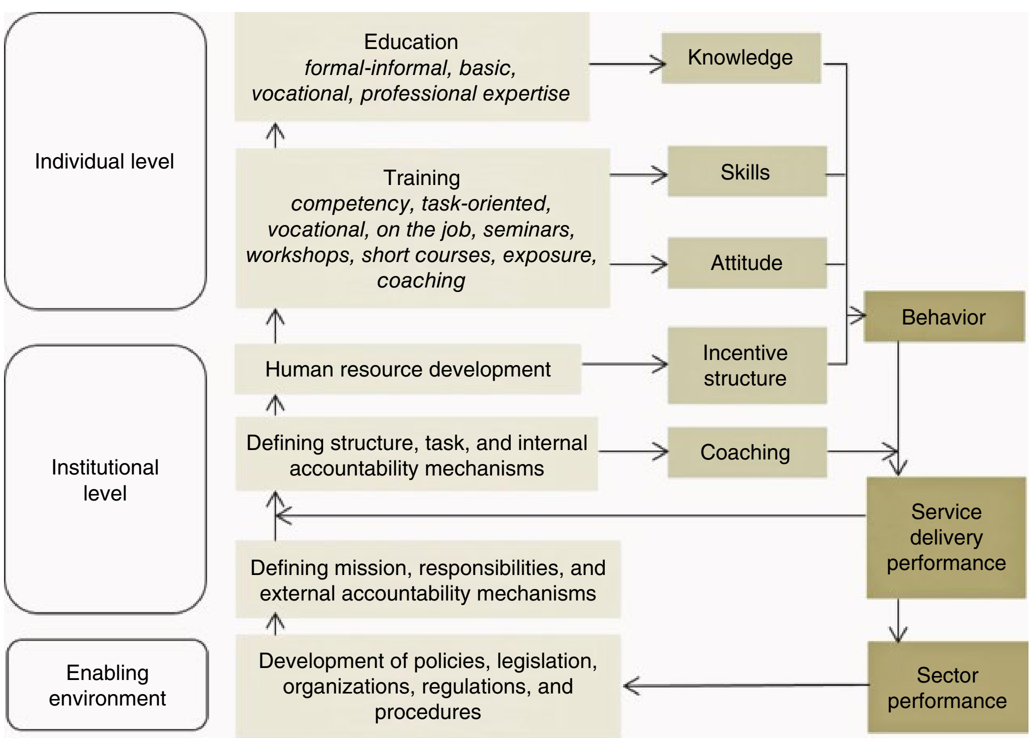

Figure 19.2 Capacity development: levels, activities, outputs, and goals. Source: Adapted from *Luijendijk and Arriens* [2009].

the problem. Capacity development has a broader scope than conventional human resources development, which typically neglects the influence of the organization's structure, incentives, and objectives, and of the institutional environment around the organization.

Formal education and training provides the basic foundation for knowledge building and capacity development. At the individual level, capacity development refers to the acquisition of knowledge, understanding, skills, and attitudes through formal education or other forms of learning. Although some of the necessary skills can typically be acquired on the job or through learning by doing, one needs to rely more on formal education and training for acquisition of knowledge, understanding, and attitudes. Training can be accomplished through apprenticeships and mentoring, seminars, workshops, classes, or through self-study. Ability to work in a team, capability to approach a complex challenge, and ambition and the drive to keep learning are some of the required skills and attributes the individuals must develop. The institutional capacity at different levels of the organizations and the enabling environment should be adequate to adapt modern approaches in science, technology, and management, which are essential to deal with the complex challenges in the development sector. As individuals enter into professions, they nurture their knowledge and acquired skills in a collective manner in addressing the management issues within the institutional and organizational framework. Capacity building at the organizational level is therefore needed, focusing on infrastructure and institution building, the availability of resources, and the development of organizational processes that would lead to an efficient and sustainable use of resources. At the systems scale, capacity development seeks to enhance the consistency of sector policies and promote better coordination between organizations of different sectors with the objective of a common goal of sustainable development. Organizations with the right capacity and procedures still need an enabling environment to implement legal and regulatory frameworks for development and management. Finally, knowledge and understanding at the society level is imperative through different means of awareness raising on the broader perspective of sustainable development.

19.7.1. Formal Education

Traditionally, formal educational programs in various disciplines of engineering and science at the undergraduate level are offered without an undue degree of specialization. It is only at the graduate level that the training in a specific disciplinary area becomes more focused. Over the years, many of the traditional graduate-level curricula have been reformed and/or new curricula have been introduced to deliver education and research programs with interdisciplinary focus gearing toward the concept of Integrated Water Resources Management (IWRM) mainly in the water sector and Integrated Natural Resource Management (INRM) with emphasis on the agricultural sector. The 2001 World Congress "Challenges of a Changing Earth 2001" in Amsterdam organized by the International Council for Science (ICSU), the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the World Climate Research Programme (WCRP) proclaimed the birth of a new academic field, namely sustainability science, with strong roots in the environmental aspects of the sustainability concept [*Kates et al.*, 2001]. With a growing interest in sustainability, a number of universities have engaged in educating future leaders, decision makers, scientists, and engineers in how their decisions can help societies become more sustainable. *Lozano and Lozano* [2014] mentioned about 26 bachelor's degree and 11 master's degree programs in engineering that focused on sustainability. These programs have been implemented in Australia, Europe, and the United States, and most of them focus on environmental engineering or on energy. In this article, the authors provided details on the process for developing the bachelor's degree curriculum in Engineering for Sustainable Development at Tecnológico de Monterrey, Mexico.

Sustainability science differs from standard science in that it seeks a complementary truth to traditional forms of knowledge generation. Sustainability science asserts that the search of sustainable solutions to global problems requires new methodologies that will bring together the three pillars of sustainability: environment, society, and economy. The Institute for Sustainability and Peace of the United Nations University (UNU-ISP) was established in 2009 to address the pressing global problems from a sustainability science perspective, taking a holistic view of the problems that cut across individual disciplines. In implementing the program, UNU-ISP encouraged research that seeks solutions based on different models that link environment, society, and economy. *Herath* [2014] stressed that a nexus approach is a platform that brings together different disciplines and sectors to support sustainable development. Researchers and practitioners in developing countries in particular should form partnerships in order to conduct and implement research which serves as the basis for advancing locally relevant sustainable development practices. Furthermore, the author provided an overview in terms of what is needed for integrating research, education, and capacity development across disciplines. A more holistic transdisciplinary approach is, therefore, required involving all stakeholders right from the start in developing projects and case studies, building on existing (local) knowledge and technologies, and linking research, capacity development, and implementation as outlined by *Herath* [2014]. Salient elements on education, research, and capacity development taken from this article are provided in the following section.

19.7.2. Nexus Approach to Education and Research

Developing educational programs across disciplines is a challenging task. Providing a broader understanding across disciplines is desirable, and will produce graduates who understand issues, but not experts to carry out research and implement programs. To strike a balance between a broad overview of education and the specialization required, the academic part of the UNU-IAS M. Sc. program consists of three components that provide the following: (i) a broad holistic viewpoint, through overview courses; (ii) a deep understanding of a particular field through specialized courses; and (iii) a set of courses to provide the skills needed to implement research, through competency courses. This is followed by a field-scale research on specific problems. A new mode of transdisciplinary, problem-and-solution-oriented education and research is to be adopted on top of the traditional academic research that seeks the involvement of a wider set of institutions and types of researchers to work together on specific problems within specific contexts. Research is not exclusively based in universities but is conducted on site together with the implementing agencies, user communities, and professional bodies. The objective of this arrangement is to bring in the local knowledge and perception into the process and the whole exercise is pursued in an interactive manner with active participation of all stakeholders. The field-scale research, in this sense, can be envisioned to seek solutions based on different models that link environment, society, and economy. A set of feasible solutions for a given problem is obtained through environmental analyses. A subset of those solutions is then identified which also satisfies economic constraints, and finally solutions that meet social acceptance are selected for implementation. The analysis of each structured case will enable policymakers, scientists, and community representatives to negotiate constraints and benefits while making a science-based selection. Details on degree programs for M.Sc. in Sustainability and Ph.D. in Sustainability Science can be obtained from the UNU web site (http://ias.unu.edu).

The University Network for Climate and Ecosystems Change Adaptation Research (UNCECAR) was established following the conference on the Role of Higher Education in Adapting to Climate Change held in June 2009 at the United Nations University (UNU) headquarters, Tokyo, Japan. It was conceived as a regional network to provide educational and research programs that are needed for effective adaptation to climate and ecosystem changes. It has developed six postgraduate courses and two training programs, which are regularly offered through a network of universities and practitioners to different stakeholders. The courses include building resilience to climate change, leadership for sustainability, renewable energy, and training on climate projection downscaling and application in the food and water sectors. The UNCECAR has proposed to establish an International Network for Advancing Transdisciplinary Education (INATE) to promote a transdisciplinary approach to knowledge generation and project implementation by inviting academia, professionals, local governments, the private sector, and communities to work together to share expertise and experiences. Reference can be made to the UNU web site (https://ias.unu.edu/en/, http://inate.info/inate) to learn more on the INATE concept and to know details of UNCECAR transdisciplinary pilot projects conducted in collaboration with a number of local/regional stakeholders. These projects served as platforms to integrate education, research, and capacity building to solve real-world problems through an iterative process that encourages collective problem definition, coordinated research, development of flexible and sustainable solutions, and strong commitment to these solutions.

19.8. CONCLUDING REMARKS

Water, energy, and food are vital to satisfy basic human needs and development. Access to these resources and amenities and their sustainable management are the basis for sustainable development. Sectoral policies regarding water, energy, and food are interdependent and policies for one sector often have consequences, identified as externalities, for the other two sectors. These interconnections and externalities should be taken into consideration in planning development strategies in individual sectors. In recent years, scientists and policy analysts have advocated the need for an integrated nexus approach to these sectors to ensure efficient use of these resources in a sustainable manner. Adapting the WEF nexus is a challenging task and this is to be addressed in a country's sociopolitical, environmental, and economic context. Recognition of the need, understanding of the extent of interconnections and their consequences, and willingness to reform sectoral policies and strategies toward more integrated and cost-effective planning, decision-making, and implementation with stakeholders' involvement will facilitate adoption of the nexus concept effectively.

The global initiative undertaken by the United Nations with the launching of MDGs in 2000 has made remarkable achievement in addressing the issues of poverty, hunger, disease, unmet schooling, gender inequality, and environmental degradation. Even though significant achievements have been made on many of the MDG targets worldwide, progress has been uneven across regions and countries, leaving significant gaps. Following the completion of the period of implementation of MDGs in 2015, the United Nations, with the endorsement of world leaders, framed a set of SDGs that embrace a wider perspective of economic development, environmental integrity, and social equity gearing the development in a sustainable trajectory. By endorsing the agenda for 2030, the world leaders have pledged to end poverty and hunger everywhere; to combat inequalities within and among countries; to build peaceful, just, and inclusive societies; to protect human rights and promote gender equality and the empowerment of women and girls; and to ensure the lasting protection of the planet and its natural resources. They have resolved to create conditions for sustainable, inclusive, and sustained economic growth, and shared prosperity and decent work for all, taking into account different levels of national development and capacities.

The Sustainable Development Agenda comprises 17 SDGs with 169 associated targets, which are integrated and indivisible, global in nature, and universally applicable, taking into account different national realities, capacities, and levels of development and respecting national policies and priorities. In order to achieve the proposed goals and targets, there will be inherent conflicts while using the natural resources unless and until synergies and trade-offs among different goals and targets are accounted for based on certain criteria. The normal practice of working toward specific goals (as practiced with the implementation of MDGs) will make it difficult to address interactions across goals and ensure the effective use of the common resources they involve. A certain reform in the operational process is, therefore, to be instituted and the most practical implementation option in this situation would be to identify country-level issues and concerns from the socioeconomic and environmental point of view and then define activities for a set of identified targets that might cut across a number of goals. This target-focused process is likely to stimulate discussions on the scope of development issues, not sectoral challenges, and bring in cross-sectorial integration. Accordingly, a nexus approach with a cross-sectoral interacting framework is to be adopted to ensure efficient allocation of resources between competing needs to support sustainable development pathways.

Capacity development and building awareness about the interconnected nature of all elements in the nexus, trade-offs needed in resource use, improved policy development, coordination, and overall governance of the nexus are some of the important elements needed to operationalize the nexus and gain benefit on a sustainable basis at all levels. Capacity development is committed to sustainable development of a long- rather than short-term perspective of continual learning and acquiring of skills and resources through individuals' participation and dedication toward enhancement of organizational and institutional strength in addressing development issues. A new mode of transdisciplinary, problem-and-solution-oriented education and research is to be adopted on top of the traditional academic research that seeks the involvement of a wider set of institutions and types of researchers to work together on specific problems within specific contexts. Research is not exclusively based in universities but is conducted on site together with the implementing agencies, user communities, and professional bodies.

It is advocated that the National Institutions of Higher Learning collectively take initiative in delivering a structured curriculum leading to a postgraduate degree in sustainability science across traditional disciplines of science and engineering. This endeavor is much needed in different country contexts as the need and extent of specialization in different disciplines varies from country to country depending on their level of development. Field-scale research, indicated as an important component of transdisciplinary education and research, is to be conducted in a "shared vision planning and analysis" mode incorporating tried-and-true planning principles, technical analysis, and public participation into a practical forum for making resource management decisions that address the identified issues and concerns.

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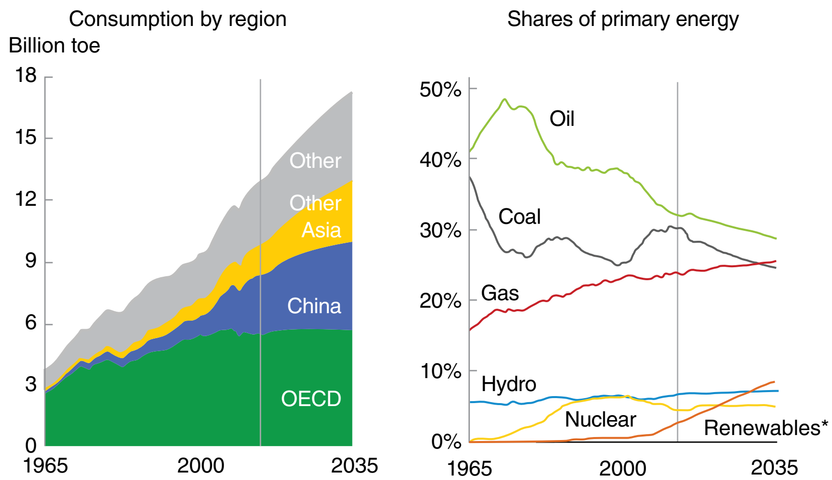

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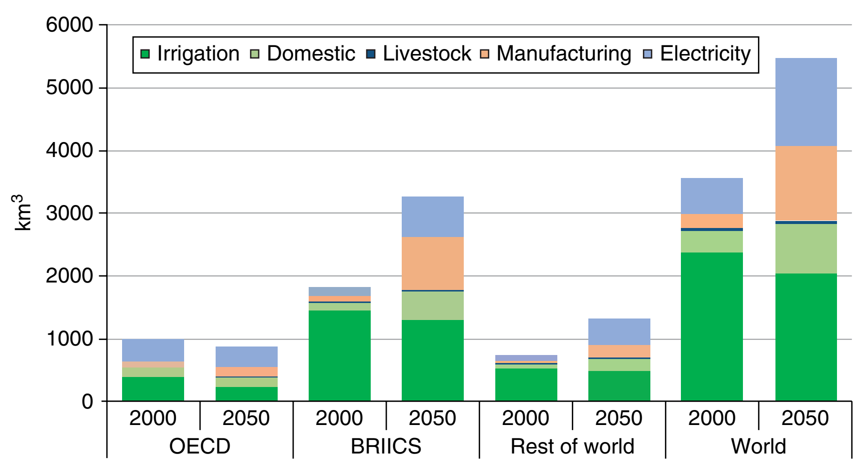

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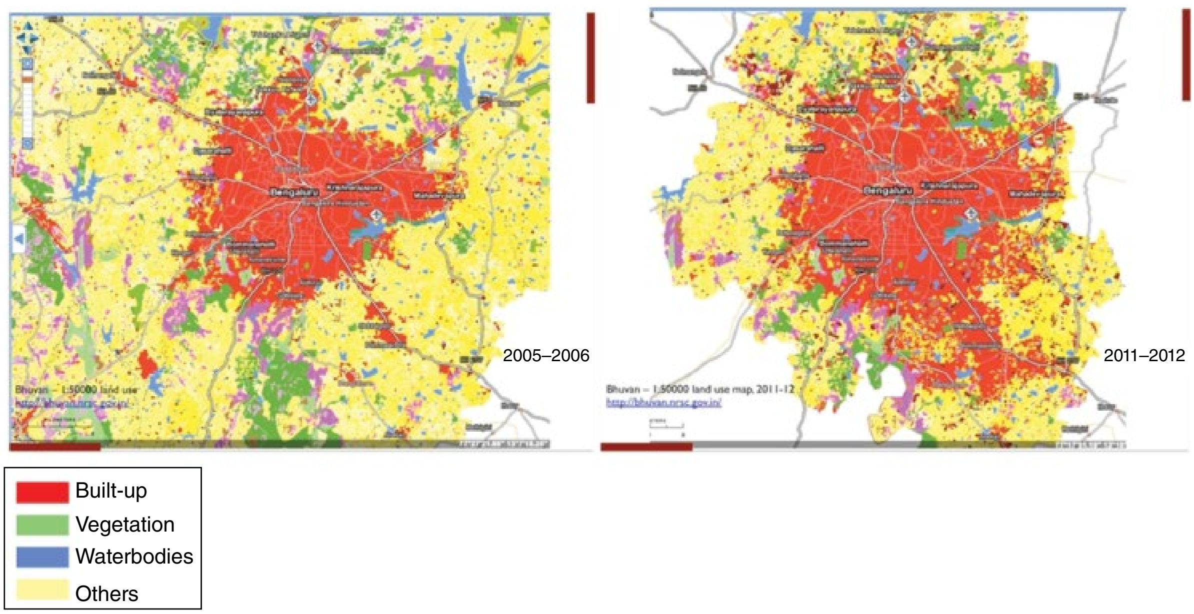

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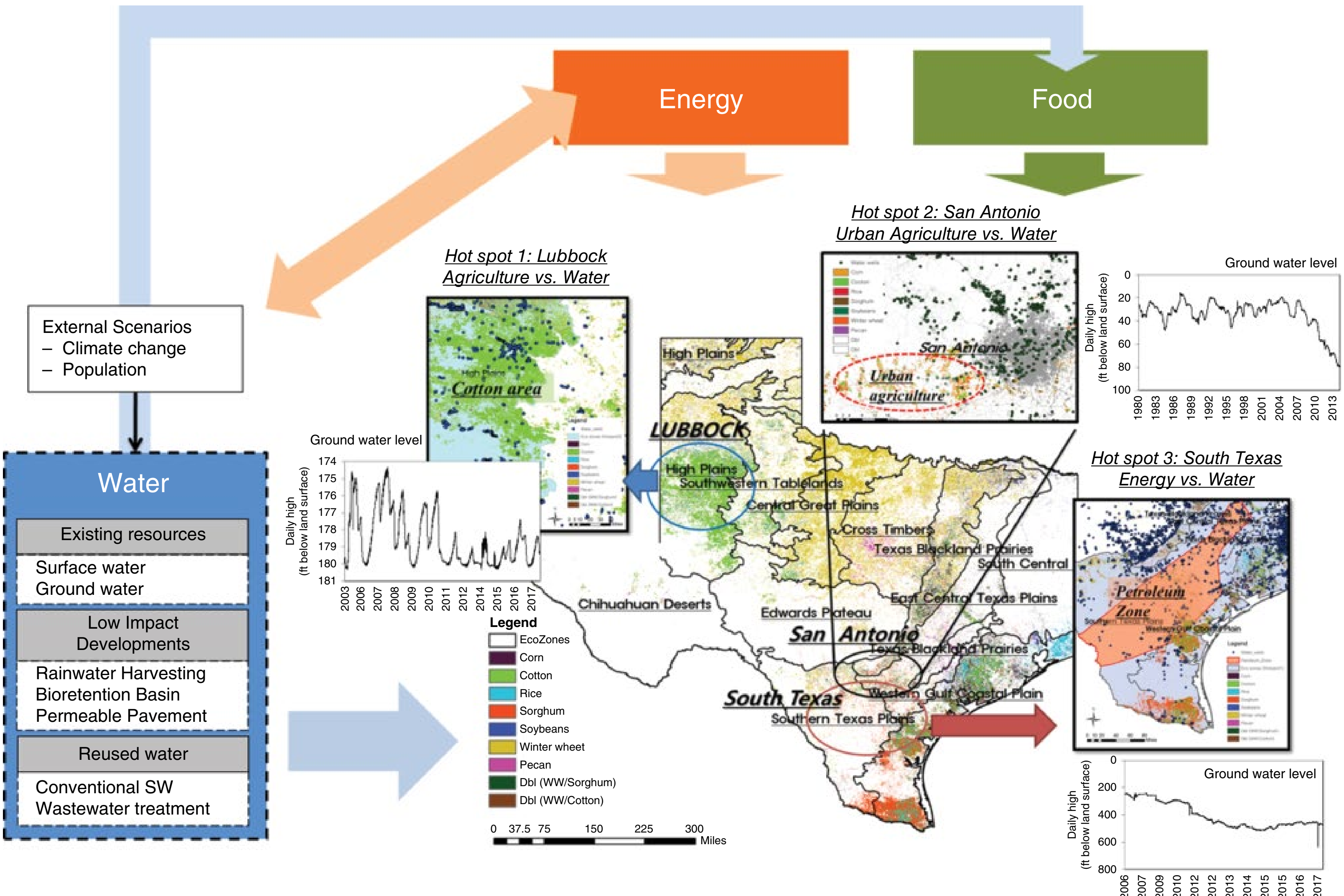

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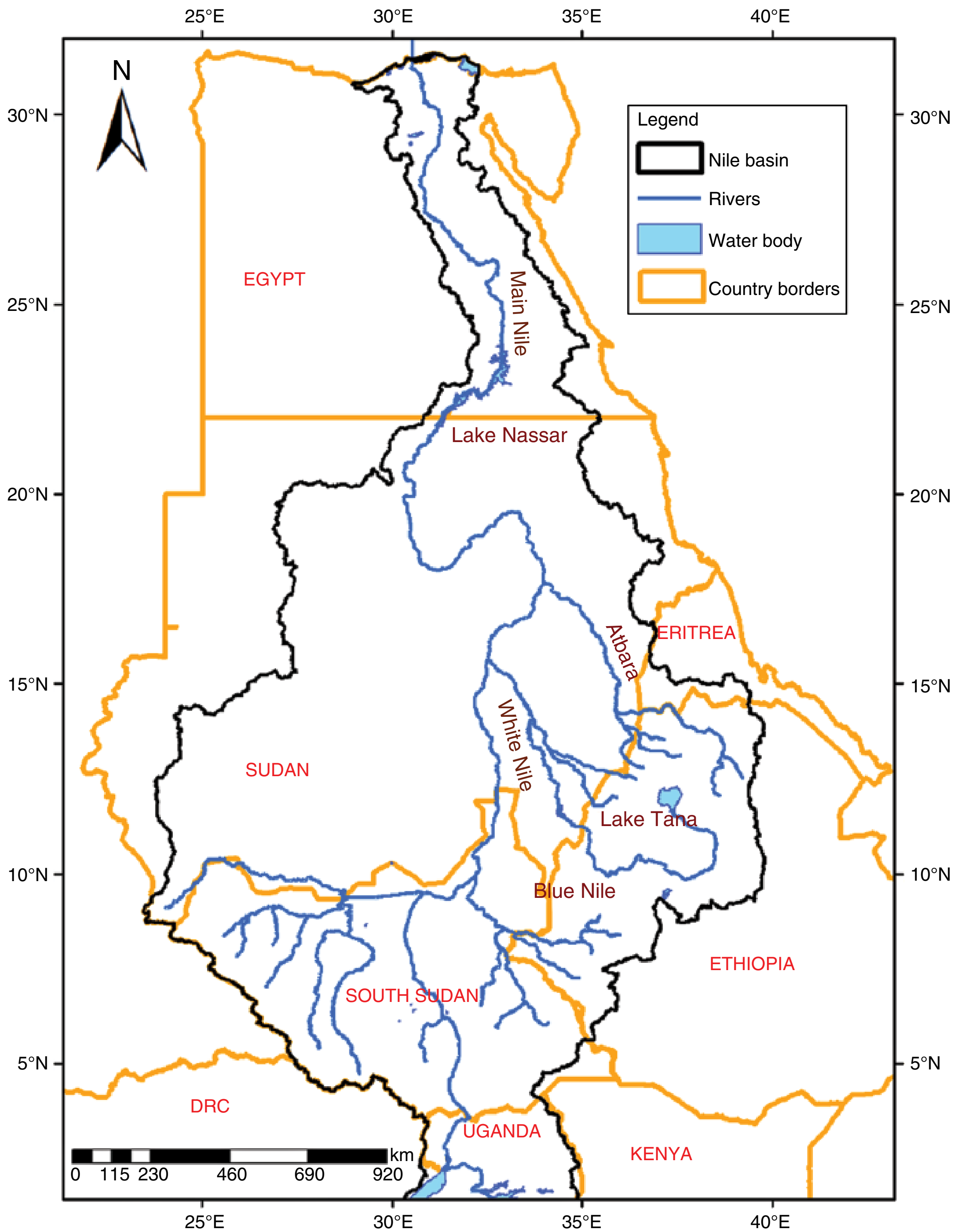

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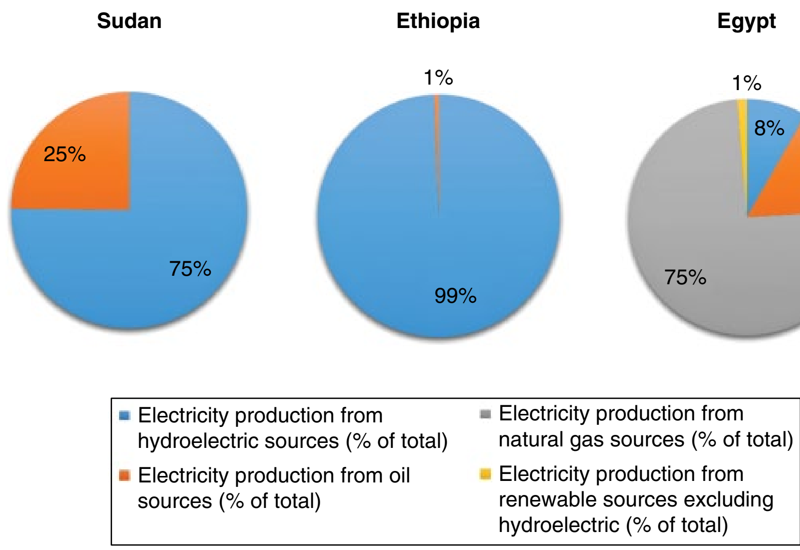

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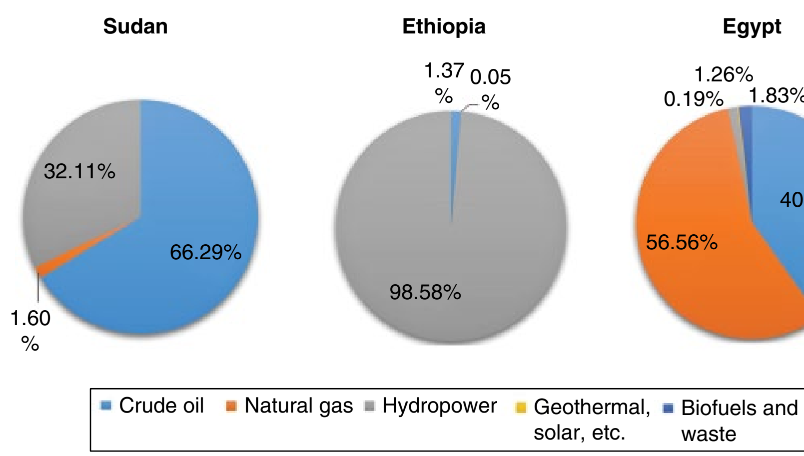

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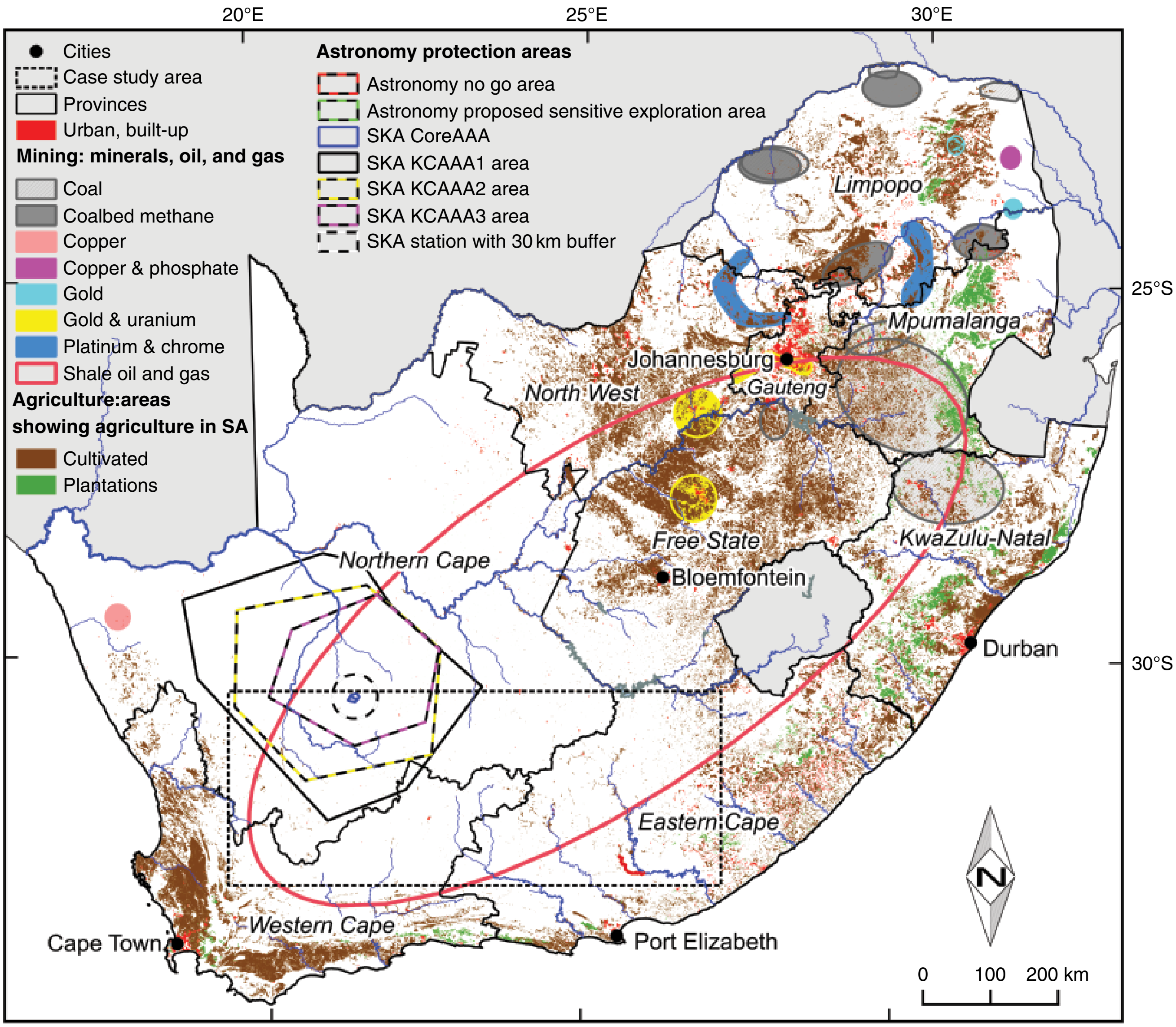

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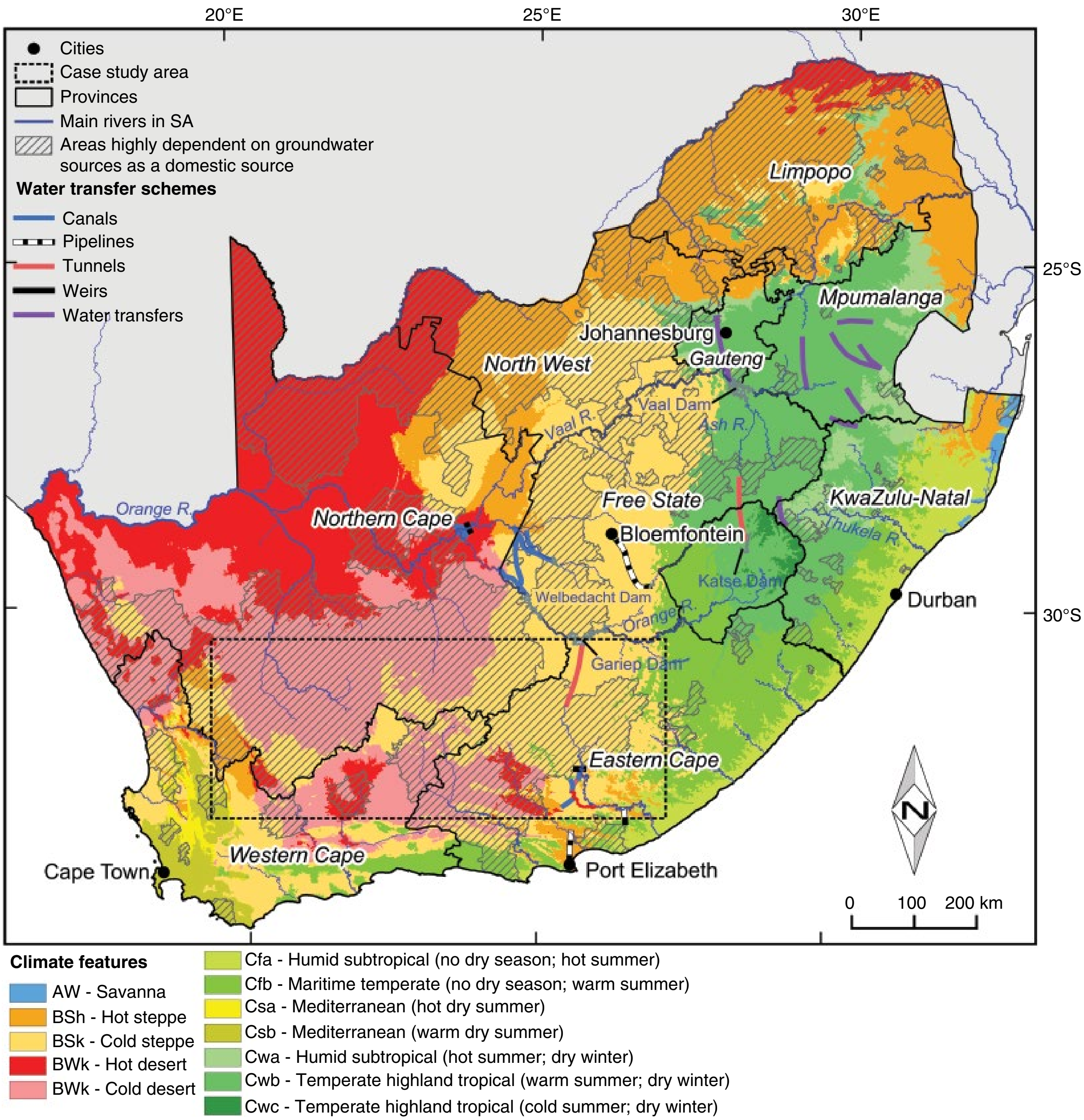

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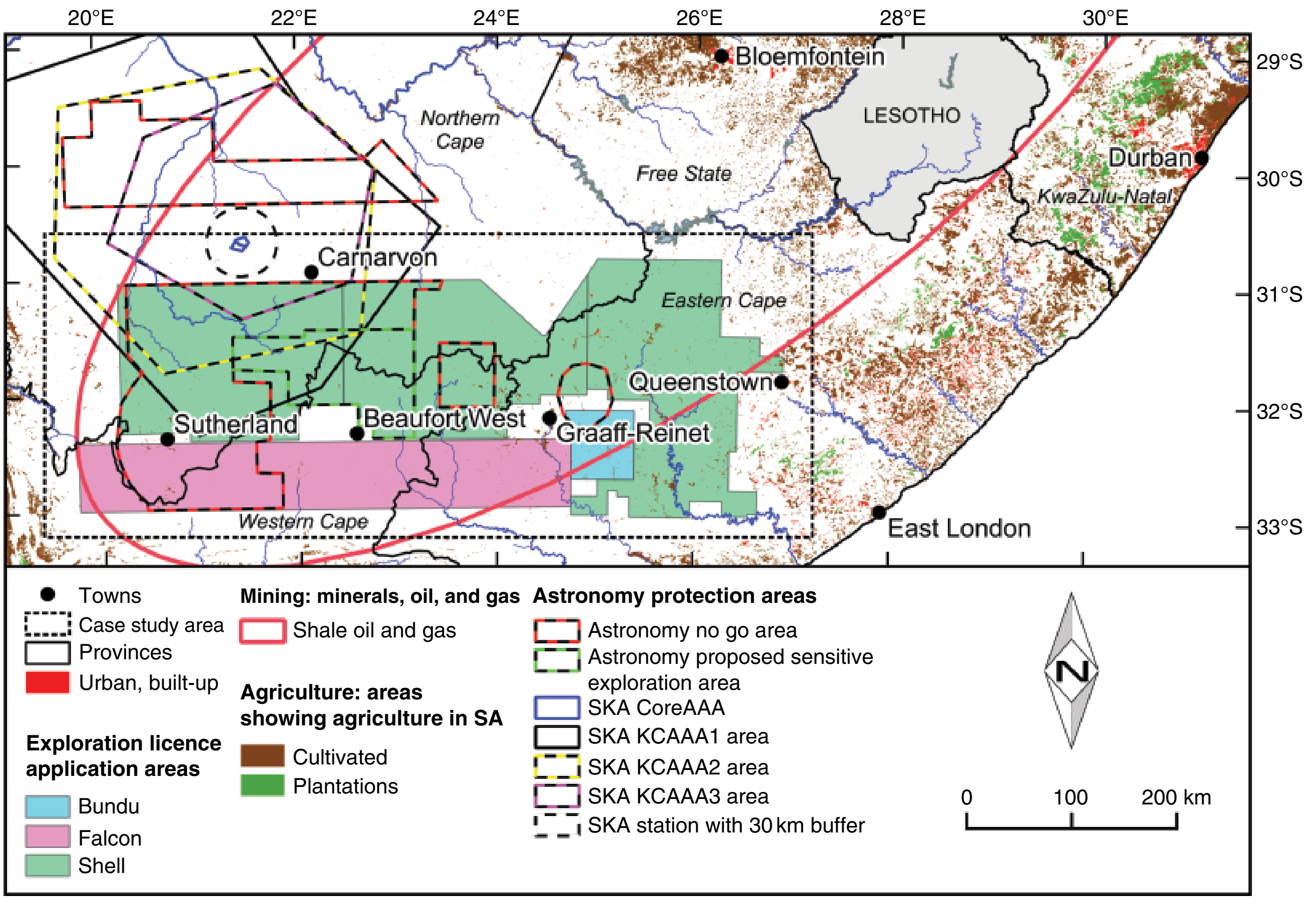

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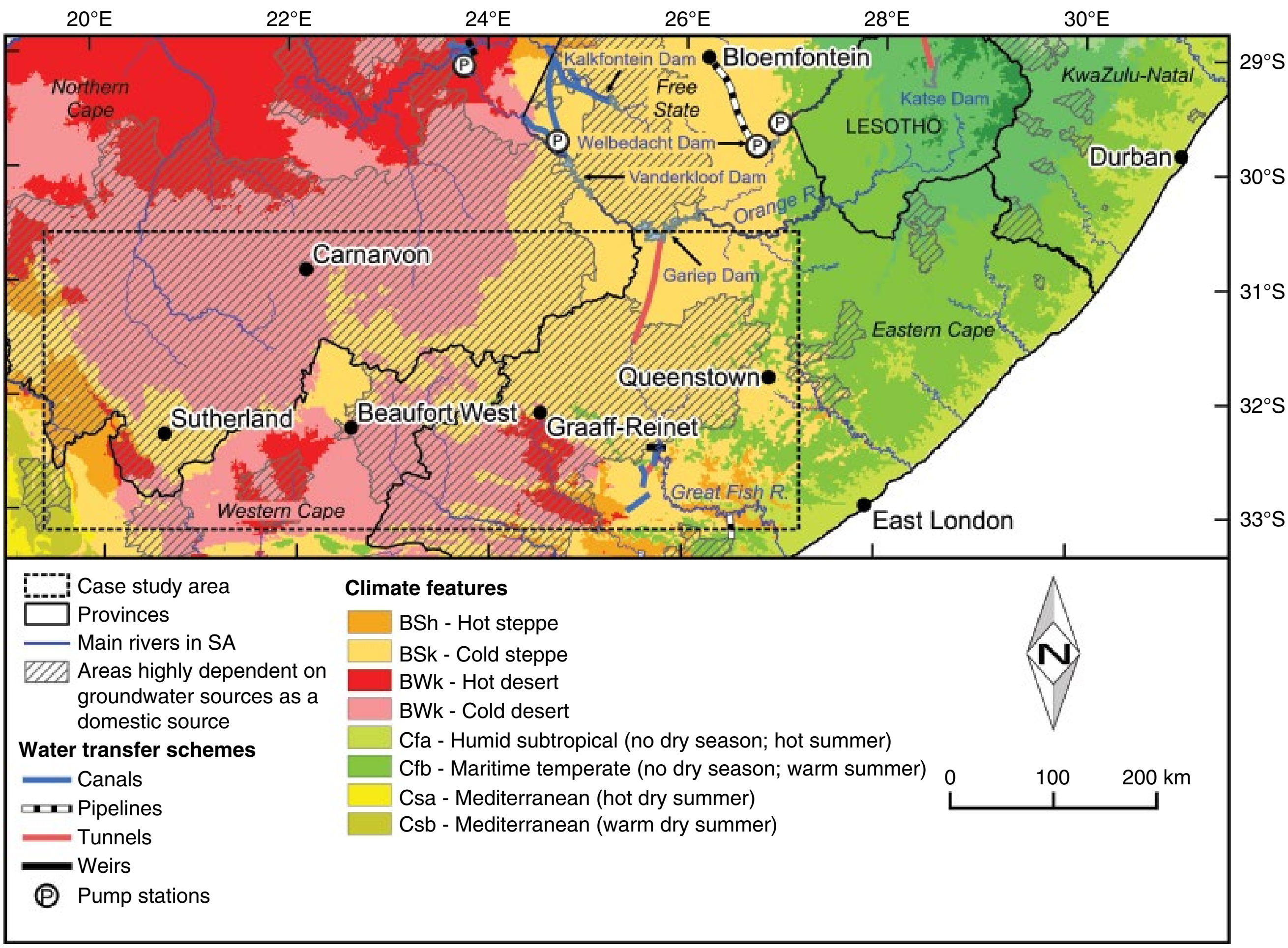

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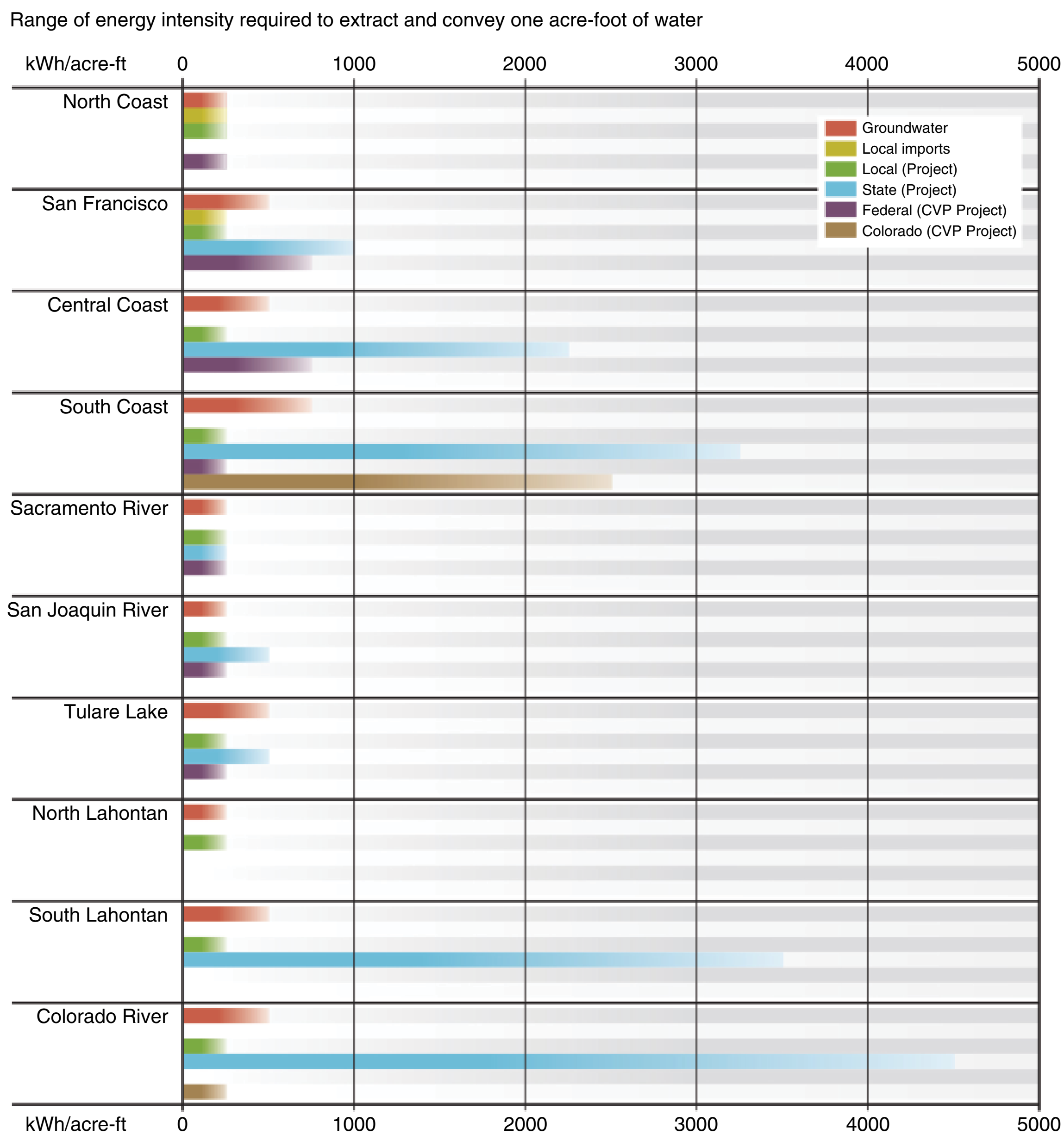

Energy intensity in this figure is the estimated range of energy required to move one acre-foot (af) of water from the supply source to a centralized delivery point. All water sources are presumed to have a minimum energy intensity greater than zero, but not all water sources in a region may be listed. The goal of this figure is to provide a general idea of the energy required to deliver water to a particular region to aid water managers who wish to include energy intensity as a factor in their management decisions. The regional energy intensity compiled in this figure is provided in the *California Water Plan, Update* 2013, *Volume* 2, *Regional Reports* and in the Water-Energy Nexus. For detailed descriptions of the methodology used to calculate energy intensity in this figure,see the *California Water Plan, Update* 2013, *Volume 5, Technical Guide, Energy-Intensity of Regional Water Supplies.*

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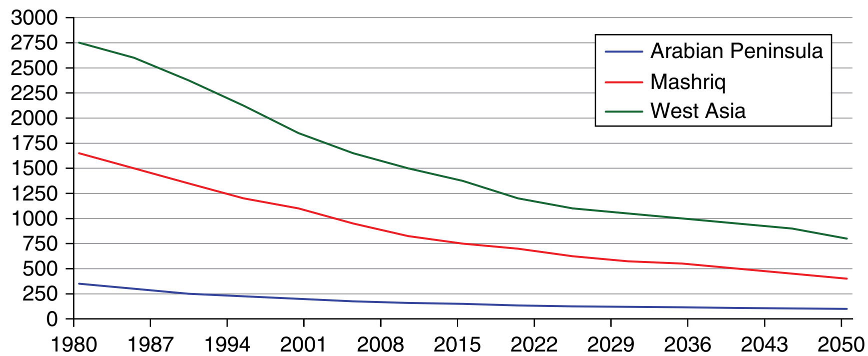

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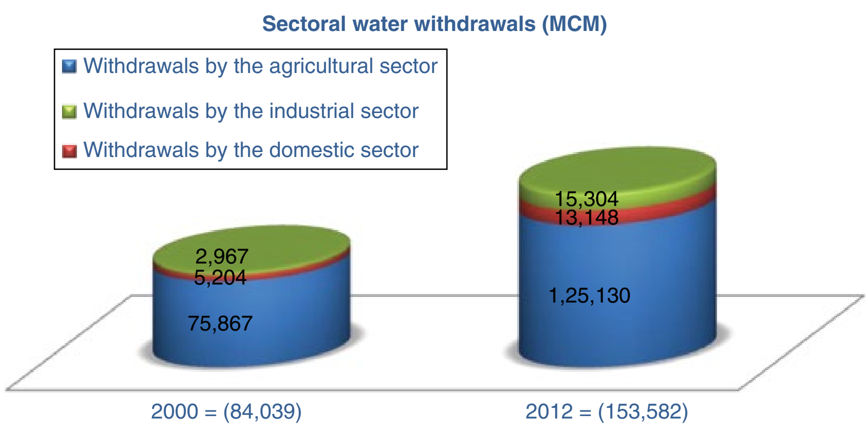

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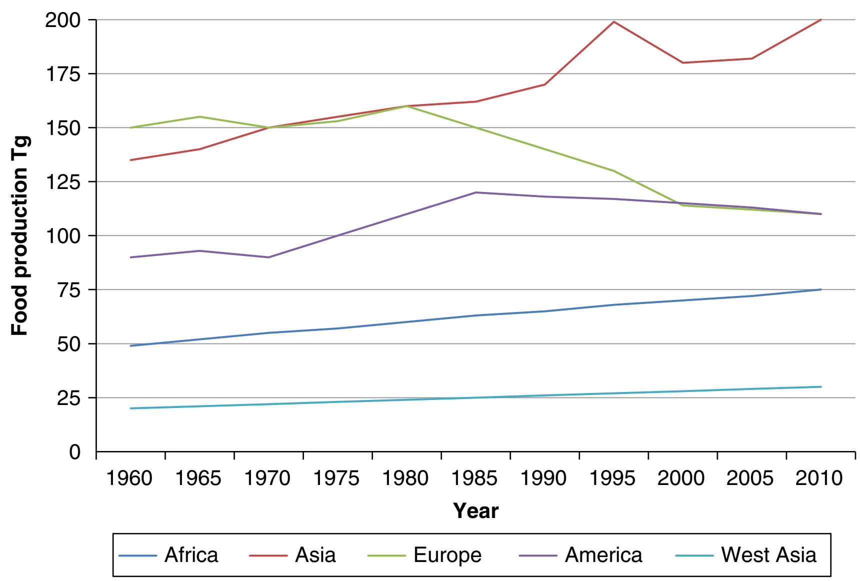

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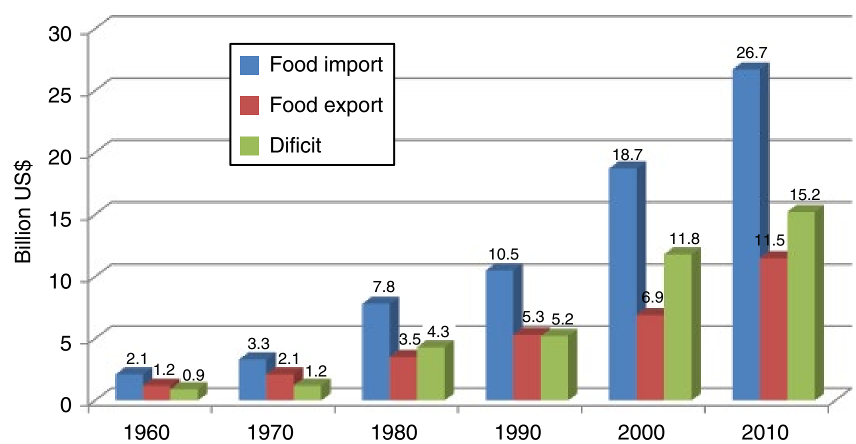

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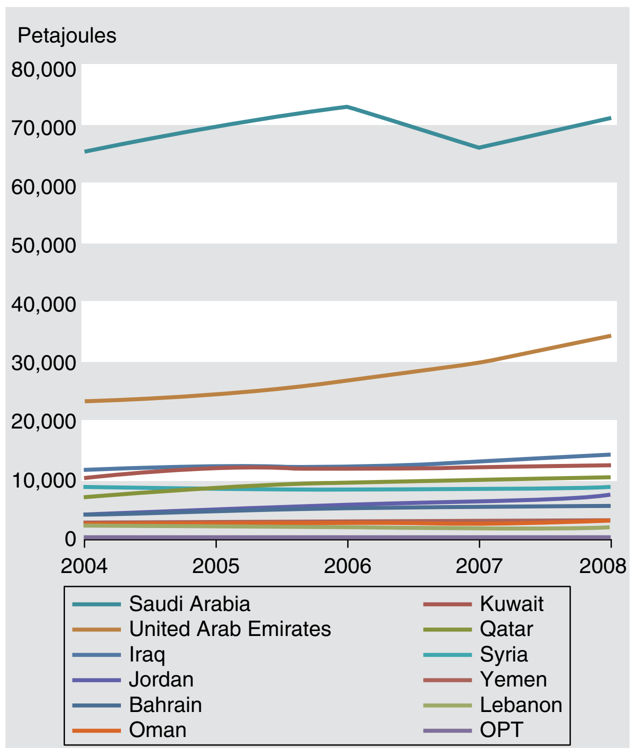

Figure 15.7 Energy consumption in West Asian countries (2004–2014).

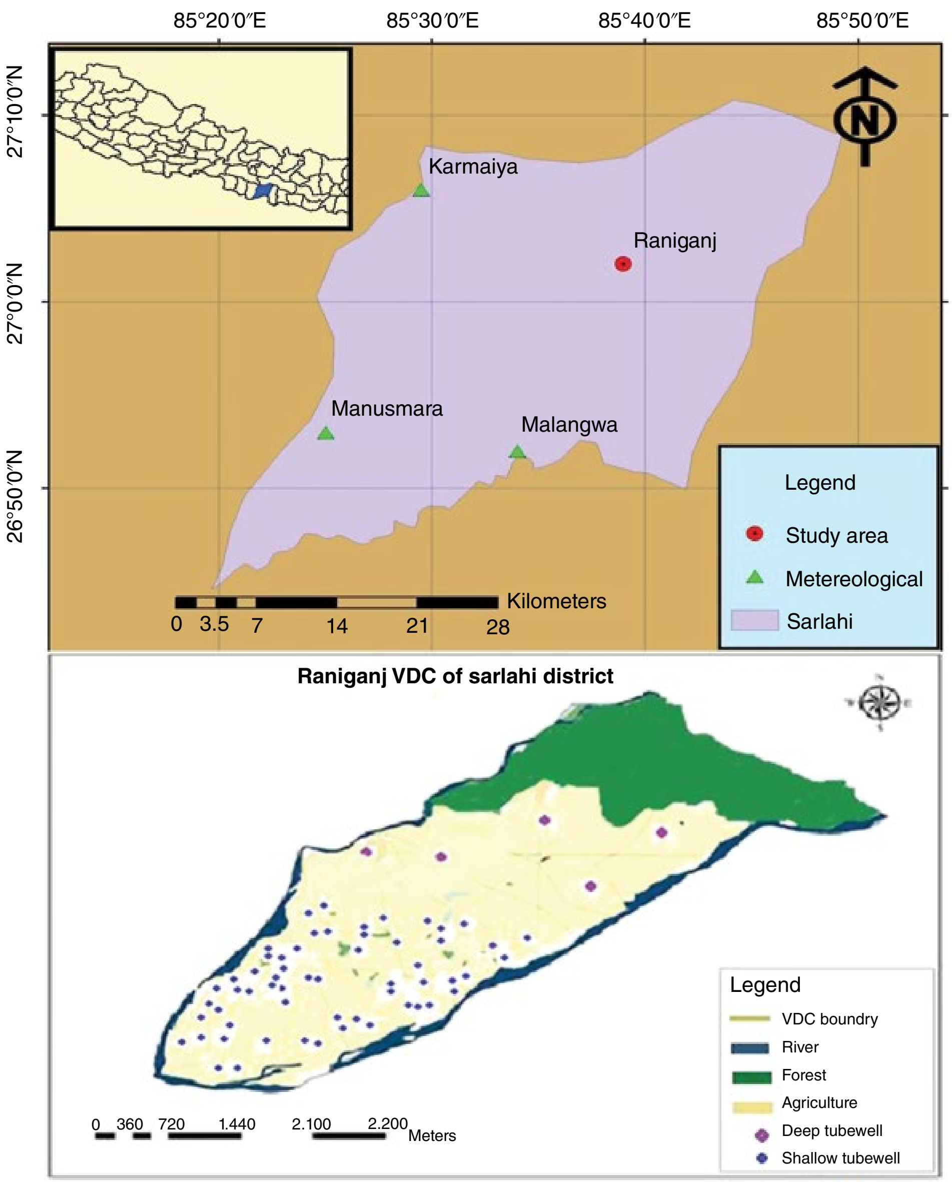

Figure 16.1 Location of Raniganj VDC in Sarlahi district, Nepal.