Journal of Cleaner Production 17 (2009) 1–12

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study

E. Friedrich [a,*], S. Pillay [b], C.A. Buckley [b]

[a] Centre for Research in Environmental, Coastal and Hydrological Engineering (CRECHE), School of Civil Engineering, Surveying and Construction, University of KwaZulu-Natal, Durban, 4041, South Africa
[b] Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal, Durban 4041, South Africa

ARTICLE INFO

Article history:
Received 3 August 2007
Received in revised form 3 March 2008
Accepted 3 March 2008
Available online 21 April 2008

Keywords:
Life cycle assessment
Scenario analysis
Potable water supply
Sanitation
Urban water systems
Water recycling

ABSTRACT

This study investigates the environmental burdens due to the provision of potable water and sanitation in the eThekwini Municipality (Durban), South Africa. This was achieved by employing LCA studies for the individual parts of the urban water system (impoundment, water treatment, distribution, collection, sewage treatment and water recycling). Based on the results of the individual LCAs a base case was constructed.

For the provision of potable water and sanitation to new customers, which have not been previously served, two different scenarios (200 000 new customers in an urban environment with waterborne sewage and in a peri-urban environment with on-site sanitation) and three different options (maximising use of existing assets, recycling water and building new infrastructure) were considered and analysed. With regard to the impact scores calculated for both scenarios (urban and peri-urban), the recycling of water is followed by maximising the use of existing assets as the most environmentally friendly options. The construction of new infrastructure carries a higher environmental burden and the use of bottled water for drinking (an additional scenario) carries the highest environmental burden.

1. Background

Water scarcity is a South African reality. The country has an annual rainfall, which is below the world average (500 mm as opposed to the world average of 860 mm). In addition rainfall is seasonal and unevenly distributed throughout the country. In this context the South African government plans to provide safe potable water and sanitation to all its people [1]. The provision of water and sanitation to the previously unserved is a priority development goal in South Africa and one of the important Millennium Development Goals as set by the United Nations Millennium Summit in 2000. In terms of targets the UN aims to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. In South Africa the government is committed for reducing the backlog in services by 2008 in the case of water and 2010 in the case of sanitation [1].

The eThekwini Municipality is situated in the Province of KwaZulu-Natal on the eastern coast of South Africa. It has a population of approximately 3.1 million and covers an area of about 2300 km^2. From the 1990s up to the early 2000s the demographics of the area were characterised by rapid population increase due to urban migration. Recently, population size is stable and a slight decrease (0.07%) due to the AIDS epidemic is projected [2]. The census of 2001 shows an average household size of 3.9 people [3] for this municipality. The core city of the municipality is Durban; however, other urban nodes (previously white suburbs together with previously black and Indian townships) are also included. It contains a densely populated urban core and a few surrounding suburbs with state-of-the-art conventional potable water and sanitation services and sparsely populated peri-urban areas as well as informal areas with poor communities that lack adequate potable water and sanitation. There is an estimated backlog of 63 000 households which have to be provided with potable water and sanitation services. The municipality pioneered the concept of free basic water (6 kL/month/household) for all its residents and this concept has been adopted for the whole country and is included in government policies. *Everybody in South Africa has the right to a basic amount of water and a basic sanitation service that is affordable. With this comes a responsibility – not to abuse the right to free basic services and to pay for services where these are provided over and above a basic service* [1].

For the provision of potable water a variety of delivery options/levels ranging from standpipes, ground tanks, roof tanks and full-pressure supply are available within the municipality and they have different tariff structures associated with them. Initially, for informal settlements lacking any infrastructure, the free basic water supply was trucked in and distributed to individual households,

* Corresponding author. Tel.: +27 31 2607709; fax: +27 31 2601411.
E-mail address: friedriche@ukzn.ac.za (E. Friedrich).

0959-6526/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2008.03.004

and as informal settlements become more established standpipes are being used. With regard to sanitation, the government funds the supply of basic sanitation (ventilated improved pit latrines for dense settlements and urine diversion toilets for settlements where the distance between dwellings is greater than 50 m) to poor unserved households. In the peri-urban, rural areas and the informal areas within eThekwini Municipality the chosen method of sanitation is the (on-site) urine diversion toilet.

In the eThekwini Municipality potable water is sourced from two impoundments (Inanda Dam and Nagle Dam) and treated in two water treatment plants (Wiggins and Durban Heights Waterworks) after which it is reticulated to the consumers. The outer peri-urban regions of the municipality have on-site sanitation disposal. In the central area and in the suburbs of the municipality, a sewer system collects the used water, which is treated in a number of sewage treatment plants prior to final discharge into the Indian Ocean. A water recycling plant, commissioned in 2001, takes treated sewage to produce industrial grade water, which is used in a paper mill and in an oil refinery. This reduces the demand for potable water in the municipality, freeing this water to be supplied to previously unserviced households. In this paper, LCA studies were employed to explore the environmental burdens of supplying potable water and sanitation in the eThekwini Municipality and a series of scenarios were modelled in order to find the best environmental options for increasing supply. An important question was related to the recycling operation and its associated environmental burdens.

2. Brief description of the water systems investigated and the methodology employed

The components of the system investigated were: an impoundment (Inanda Dam), a potable water treatment works (Wiggins Waterworks), one particular distribution and collection network servicing a delimited area, a major wastewater treatment works (Southern Wastewater Treatment Works) and a water recycling plant (Durban Water Recycling). Environmental LCA scores were calculated for each component of the system. For the impact category of global warming these scores were summarised and a base case is presented. This base case was representative of the existing water and sanitation supply system in the eThekwini Municipality before the Durban Water Recycling Plant was commissioned in 2001. In this paper no industrial demand for potable water is taken into account.

When considering scenario analysis only the impact assessment scores for global warming were used due to two reasons. Firstly, global warming emissions are closely correlated with the use of electricity and as the LCA of the system shows [4], this is the input that causes most of the environmental impacts. Electricity in the production and treatment of water is the dominant contributor to all environmental categories investigated (global warming, acidification, eutrophication, photochemical oxidant formation and toxicity). In this study it was assumed that all electricity used was generated from coal, however, in reality the South African electricity production mix during the time of the study was as follows: coal 88.6%, nuclear 6.7%, hydro 0.7%, pump storage 1.3%, and imports 2.7%. Secondly, global warming is being currently politically prioritised as the important global environmental impact, locally and internationally. Based on the results from the LCA of the system, the emissions of greenhouse gases are a reliable reflection of the overall environmental impact of water and wastewater treatment processes.

2.1. The impoundment of raw water from the Inanda Dam

The Inanda Dam is one of the two impoundments supplying raw water for the eThekwini Municipality. Entering water has a residence time of approximately two years. The maximum daily abstraction capacity of the dam is 300 ML/day and the dam currently produces about 200 ML/day. The raw water is gravitated from the dam to Wiggins Waterworks through a system of pipes and tunnels and no pumping is necessary. In terms of the environmental impacts of the dam, the emission of greenhouse gases has been investigated. These gases were emitted during the construction stage due to the production of materials (cement, sand and stone) and due to the construction. Greenhouse gases are also emitted during the operation of the dam due to the aerobic and anaerobic decomposition of the organic material flooded and the organic material brought in by the feeding river.

The dam was constructed in 1989 and the expected lifetime is around 70–100 years. For calculation purposes it was assumed to be 60 years (worst case scenario). There are no decommissioning plans for the dam and this lifestage has been left out for the time being.

The inputs for the construction phase of the dam have been extracted from the bill of materials. They included cement, sand and stone used for the concrete poured as well as soft excavation, hard excavation and fill. Using these data, the amount of water extracted and the lifetime of the dam a final score for the construction stage, expressed in kg CO_2 equivalents/kL, were calculated (8.8E−03 CO_2 equivalents/kL of water extracted). The calculations were done using the GaBi 3 software and local data for the production of cement, sand and stone were used as well as local data on energy consumption (i.e. diesel consumption) for the excavation and fill.

To calculate the emissions for the operation stage of the dam a model developed by Rosa et al. [5] and similar to that of Liikanen et al. [6] was used. This model calculates how much of the total organic carbon entering the dam ends up as methane and carbon dioxide emitted to the atmosphere. It was assumed that none of the organic carbon is transferred to the sediments of the dam and that the total organic carbon entering and exiting the dam will be constant during the entire lifetime of the dam. Using these inputs a score for the operation stage (0.051 kg CO_2 equivalents/kL of water abstracted) was calculated and added to the score form the construction stage to obtain a final score (0.059 CO_2 equivalents/kL of water) for the abstraction of 1 kL of raw water.

The greenhouse gases emitted due to the construction and operation of the dam are independent from the quantity of water abstracted. These emissions are due to the use of construction materials and the construction process itself and due to the decomposition of organic material entering the dam and do not depend on how much of the water in the dam is extracted. However, when calculating the environmental burdens per unit of water from the dam, these emissions will be higher if only a small amount of water is abstracted and smaller if the dam is used at full capacity.

2.2. The treatment of raw water at Wiggins Waterworks

Wiggins Waterworks is one of the two waterworks supplying potable water for the eThekwini Municipality. It was commissioned in 1985 and expanded in 1995 and has now a capacity of 350 ML/day. However, during the study period (2001–2004) an average of 160 ML/day was produced. This represents about one quarter of the potable water distributed in the eThekwini Municipality. This waterworks was chosen to be included in the base case because it had the highest inputs in terms of energy and materials per kilolitre of water produced and, therefore, it represents the worst case scenario for the eThekwini Municipality.

The raw water enters the waterworks through the intake tower and flows through an aeration tank. After the aeration tank, the water passes through a covered concrete channel into a pre-ozonation tank. The addition of chemicals follows the preozonation operation and dosing facilities exist for lime, polymeric coagulant, bentonite, sodium hypochlorite, chlorine and powdered activated carbon. The water then flows into four banks of pulsator clarifiers. The clarified water is directed into 24 rapid gravity filters after which it is passed through the intermediate ozonation tank. It is chlorinated before flowing into two storage reservoirs from where it is distributed. The sludge from the clarifiers is directed to the homogenisation tank after which it enters the sludge plant. The washwater from the filters is directed through a sand trap to the washwater recovery tanks from where the clear water is recycled to the head of the waterworks and the settled solids (sludge) are pumped to the homogenisation tank. Sludge is further treated either through the dissolved air floatation unit or through a gravity thickener. The thickened sludge is either released in batches to a municipal sewer (preferred practice) or is centrifuged, the water recovered and the solids transported to a landfill-site (seldom practiced). More details on individual processes are presented by Friedrich [7] and Friedrich [8].

For this waterworks an LCA study, guided by the ISO 14040 series of standards and using the CML (Center of Environmental Science – University of Leiden) methodology was performed and the results are presented by Friedrich [7] and updated by Friedrich et al. [4]. An environmental profile per kilolitre of water treated (the functional unit) was calculated. The operation stage of the waterworks carries the highest environmental burdens and most of these burdens are traced to the consumption of electricity. The process with the highest electricity consumption is ozonation and as a result of this study the thermal destruction units for this process have been redesigned. In terms of energy consumption 0.10 kWh/kL water treated is used and in terms of the global warming potential the operation stage has a score of 2.19E−01 kg CO_2 equivalents/kL water treated.

2.3. The distribution of potable water and the collection of wastewater

The distribution of potable water is the responsibility of the eThekwini Municipality and Umgeni Water, the operators of the two potable waterworks. From Wiggins and Durban Heights Waterworks the potable water is transported to municipal reservoirs through gravity and pumping. The same is valid for the further distribution of potable water to consumers. Therefore, to obtain a total figure for the energy consumption due to distribution, the energy consumption of all pumping stations (107 metro pumping stations and three Umgeni Water pumping stations) was summed and then divided by the amount of potable water purchased by the municipality. It resulted in a total energy of 0.10 kWh/kL to move the water in the eThekwini potable water distribution system. If one takes into account that there is a loss of 30% in the distribution system (eThekwini Municipality data from direct measurements) the energy figures are calculated as 0.13 kWh/kL of potable water delivered to customers in the entire municipality. The energy required depends mainly on the length of the distribution network (14 600 km for the entire municipality) and on the elevation of the network (some areas use free gravity but in some areas pumping is needed to move water uphill).

In order to obtain the material consumption associated with the infrastructure of the eThekwini potable water distribution net, a geographical area in the immediate vicinity of Southern Wastewater Treatment Works and the Durban Water Recycling Plant was defined. Data on this area were extracted from the eThekwini GIS (Geographical Information System). These data included cadastral information (number of households (1828) and their location), information on the piping system (diameter and length of pipes and pipe materials) for potable water distribution and wastewater collection, the trunk system, number of manholes, pumping stations and reservoirs. From the eThekwini billing system the amount of potable water (1614.7 kL/day) metred and billed at the consumer's connection for the area, was extracted. Therefore, taking into account the lifetime of the infrastructure, it was possible to calculate the materials associated with the delivery of 1 kL of potable water in the delimited area. Using these inputs and the energy figure for pumping, LCA scores were calculated for the distribution of potable water in that area. For the impact category of global warming it translates into 1.39E−01 kg CO_2 equivalents/kL water distributed.

Similar to the distribution, LCA scores have been calculated for the collection of wastewater. The energy figure used for pumping was calculated by totalling all electricity consumption by all wastewater pumping stations in the municipality and dividing it by the amount of wastewater accepted for treatment at all treatment works in the eThekwini Municipality minus the stormwater. A figure of 0.14 kWh/kL of wastewater moved in the system resulted. Similar to the distribution of potable water calculations were employed in order to obtain figures for the infrastructure involved in the collection of wastewater from the delimited area. Based on the energy and materials inputs, LCA scores have been calculated for the collection of wastewater. For the impact category of global warming it translates into 1.50E−01 kg CO_2 equivalents/kL wastewater collected.

2.4. Treatment of wastewater

The Southern Wastewater Treatment Works was constructed in 1969 and currently it processes 168 ML/day. This represents about 36% of the wastewater treated in the eThekwini Municipality.

The processes involved at the Southern Wastewater Treatment Works are organised into two major components: the primary treatment (head of works, screw pumps and primary settlers) and secondary treatment (nutrient removal activated sludge units and clarifiers). At the head of the works coarse screens are used to remove gross pollutants from the wastewater, then screw pumps lift the wastewater into the primary settlers. The wastewater after primary treatment is discharged to the Indian Ocean through a 4.2-km marine pipeline. Only water, which is to be treated in the water recycling plant for reuse by industry, is further processed through the secondary treatment plant. The settled sewage is then pumped into the secondary treatment plant consisting of the aeration basins and the clarifiers. Two types of aeration systems are used: mechanical aerators or a diffused air system. A circular type clarifier is used in the secondary treatment plant.

Similar to the treatment of raw water, an LCA study for the wastewater works was performed and the detailed results are presented by Pillay [9] and Friedrich et al. [4]. An environmental profile per kilolitre of wastewater treated (the functional unit) was calculated taking into account all the inputs from the construction (materials), operation (chemicals and energy) and decommissioning stage. The operation stage of the wastewater works carries the highest environmental burdens (for global warming, primary treatment accounts for 1.12E−01 and secondary treatment for 2.97E−01 kg CO_2 equivalents/kL wastewater treated) and most of these burdens are traced to the consumption of electricity. The process with the highest electricity consumption is the activated sludge process (98%). An improvement analysis for this waterworks was performed and is presented by Pillay [9].

2.5. Recycling of treated wastewater

The Durban Recycling Plant is the first of its kind in South Africa. It has a capacity of 40 ML/day and was operated at full capacity during the period of investigation (2001–2004). It is located adjacent to the Southern Wastewater Treatment Works and is referred to as the tertiary treatment of wastewater. The incoming effluent resulting from the secondary treatment is dosed with chemicals (hydrated lime, polyaluminium chloride and ferric sulphate), and then passed through the rapid mixers and the lamellae settlers. From the lamellae settlers the incoming water is directed to the dual media filters. These are deep bed filters with an anthracite layer covered by a sand layer. The addition of coagulants (polyaluminium chloride and/or a polymeric coagulant) enhances the performance of these filters. The treated water is passed through the ozonators (disinfection) and into the granular activated carbon contactors. From there it is directed to the chlorination tanks.

For the LCA study of the recycling plant the same methodological approach was used as in the case of the potable water and wastewater plants. Environmental scores were calculated for the recycling of 1 kL of wastewater and are presented by Pillay et al. [10] and updated by Pillay [9]. Again the operation stage carries the highest environmental burdens (90%) and the majority is traced to electricity consumption. For the impact category of global warming a score of 0.94E−01 kg CO_2 equivalents/kL water recycled was calculated due to the operation of this plant. The process with the highest electricity consumption is ozonation.

3. Results for the base case

Fig. 1 shows a flowsheet of the base case. The base case is representative of the existing water and sanitation supply system in Durban (eThekwini Municipality's core city) prior to 2001 when the recycling plant was commissioned. Hence there is no secondary treatment plant included. Under South African discharge regulations secondary treatment is not necessary for coastal discharge,

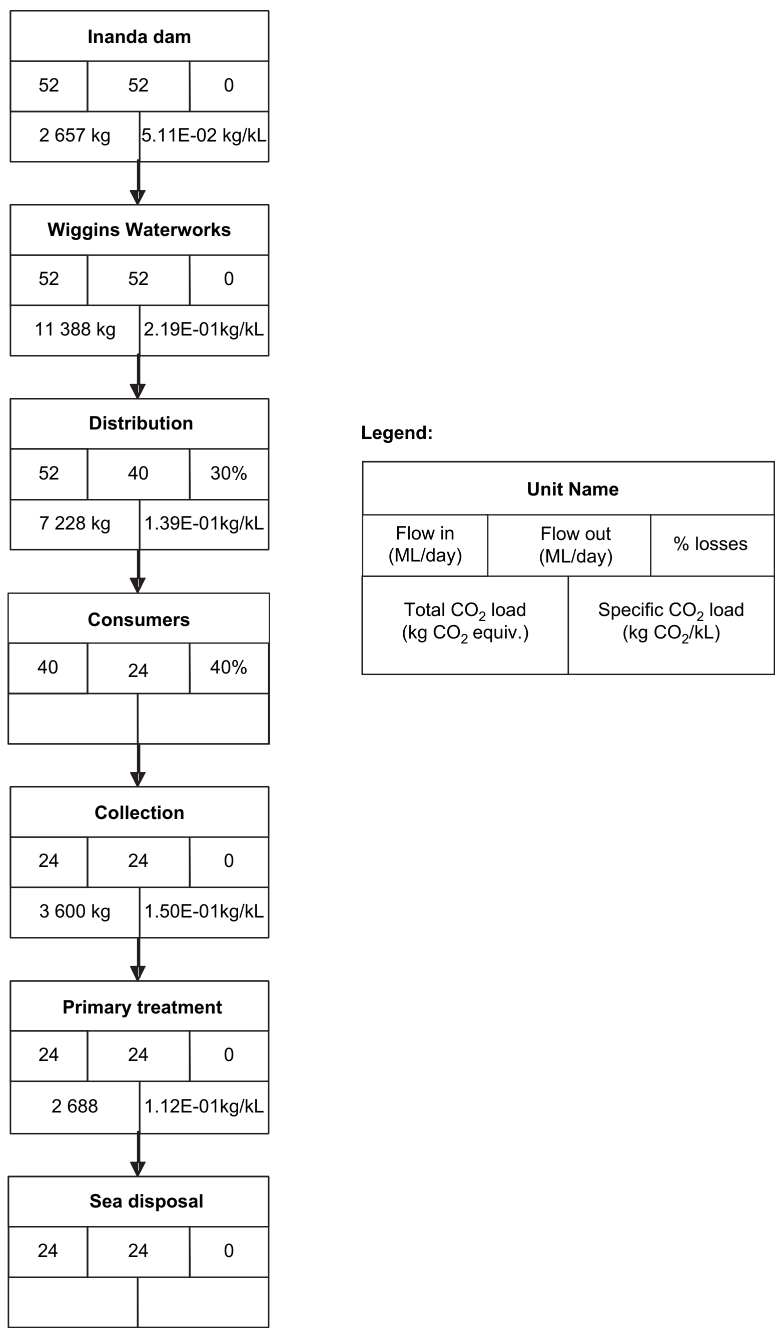

Fig. 1. The flowsheet for the base case (calculations for supplying 200 000 households).

however, it is necessary when the discharge is to a river as in the case of an inland scenario. In the bottom left of each box the total global warming impact (expressed as kg CO_2 equivalents) of each unit is shown and in the bottom right the global warming impact per kilolitre (expressed in kg carbon dioxide equivalents/kL water/wastewater).

There is a 40% loss at consumer's level because potable water is used by households in activities which make it impossible to be returned to the municipal water system (e.g. watering gardens). Unlike the 30% loss in the distribution of potable water (water which has to be abstracted, treated and transported), this loss at consumer level is assumed to carry no environmental burden. The water is returned to the environment (mainly through evaporation) just not inside the municipal water system.

Table 1 shows how a total burden for the entire system was calculated.

4. The different scenarios for increased supply of water and sanitation services

There are many ways of increasing the potable water supply for urban areas. Two scenarios, each with three options, are considered in this study, both taking into account an increase of 200 000 new households (with an average rate of 3.9 people/household) to the eThekwini Municipality's water provision and wastewater collection network. Because different sanitation options are used in the municipality and these options are reflected directly in the type of wastewater system provided, sanitation is also included in the two scenarios. Scenario A considers the case where the new consumers are located in an urban setting close to the urban core (e.g. the Cato Manor township, close to other established areas). Scenario B considers the case where the new customers are located in a peri-urban environment beyond the 'waterborne edge' as defined by the municipality. eThekwini Municipality defined the 'waterborne edge' as the boundary beyond which it is unfeasible to provide waterborne sewage within the next 20 years and on-site sanitation must be provided.

Thus in Scenario A the new customers are provided with sewered toilets, whilst in Scenario B on-site sanitation (in the form of urine diversion toilets) is provided. For each scenario three options were considered for the municipality to meet the increased demand. The *first* option looks at maximising the performance of the existing infrastructure to meet the increased demand. The *second* option investigates the construction of new infrastructure and the *third* option is to recycle water for use by industrial customers to free up existing potable water supplies. When considering each scenario and option, the impact assessment scores for the provision of 200 000 new households were used. In other words, not the difference in the inventories.

Table 2 presents a summary of the scenarios that are considered in this paper.

Table 1
Breakdown of the global warming impact of providing 200 000 consumers in the eThekwini Municipality with water and sanitation using the units from the base case

Unit	Volume produced (ML)	Impact (kg/kL)	Total impact (kg)
Inanda Dam	52	5.11E−02	2657
Wiggins Waterworks	52	2.19E−01	11 388
Distribution	52	1.39E−01	7228
Collection	24	1.50E−01	3600
Primary treatment	24	1.12E−01	2688
Total			27 561

Table 2
Options for providing potable water and sanitation for 200 000 new households

	Base case	Option 1: maximise use of existing assets	Option 2: recycle water	Option 3: build new infrastructure
Scenario A: 200 000 new customers in an urban environment – waterborne sewage				
	As presented	Increase the throughput of the current infrastructure to maximum capacity	Recycle sewage and wastewater (secondary and tertiary treatment) for use by industrial customers, freeing up potable water supplies	Construct new infrastructure to meet increased demand
New infrastructure required	None	Minimum	Water recycling plant (secondary and tertiary treatment) and the distribution and collection networks	Construct new dam, waterworks, and associated pumping and piping networks for distribution and collection
Process units	Dam, waterworks, distribution network for potable water, collection network for wastewater, primary treatment sewage works (for coastal discharge) and an additional secondary treatment works for inland discharge	Dam, waterworks, distribution network for potable water, collection network for wastewater, primary treatment sewage works (for coastal discharge) and an additional secondary treatment works for inland discharge	Dam, waterworks, distribution network for potable water, collection network for wastewater, primary, secondary and tertiary treatment (for coastal and inland discharge)	New dam, new waterworks, new distribution network for potable water, new collection network for wastewater, and new primary sewage works (for coastal discharge) and an additional new secondary treatment for inland discharge
Scenario B: 200 000 new customers in a peri-urban environment – on-site sanitation				
New infrastructure required	None	Minimum	Water recycling plant (secondary and tertiary treatment)	Construct new waterworks, dam and associated pumping and piping network
Process units	Dam, waterworks, distribution network for potable water, on-site sanitation	Dam, waterworks, distribution network for potable water, on-site sanitation	Dam, waterworks, distribution network for potable water, primary, secondary and tertiary treatment	New dam, new waterworks, new distribution network for potable water, on-site sanitation

5. Analysis of the different options and scenarios

Each option has the capacity to provide different amounts of water. There is a limit as to how much the present assets can be maximised, also the volume of sewage that is viable for recycling limits the amount of water that Option 2 can produce. Another important factor is that in a large city like Durban, there is a great deal of uncertainty regarding future demand, therefore to ensure that there are no shortages, planners usually over-design the available supply. Inevitably this leads to excess capacity and hence to inefficiencies. The maximum additional capacity for each option is presented in Fig. 2.

5.1. Option 1: maximise the use of existing assets

This option involves using all the present units at their maximum capacity – otherwise known as '*sweating the assets*'. When considering this option both Scenarios A (waterborne sanitation) and B (on-site sanitation) are discussed as they share a common supply chain and differ only in the sanitation method. The flowsheet for both scenarios is presented in Fig. 3.

The environmental burden per kilolitre produced will change for some of the units and these changes are as follows:

- Inanda Dam currently operates at a production level of 200 ML/day. This could be increased to a sustainable 300 ML/day if necessary. The effect of this change would be to reduce the impact per kilolitre of water from 5.11E−02 kg CO_2 equivalents to 3.40E−02 kg CO_2 equivalents. Thus the total impact of providing an additional 52 ML/day is 1768 kg CO_2 equivalents/day.
- Wiggins is another unit that is operating at less than the design limits. Wiggins currently (2005) produces 170 ML/day and has the capacity to produce 350 ML/day. This increase would result in a proportional increase in the environmental burden. The total environmental burden for the global warming category would be 11 388 kg CO_2 equivalents/day.
- New networks would have to be constructed for the new customers. It was assumed that the specific energy for pumping would remain the same.
- The primary treatment plant also has additional capacity available to treat the extra 24 ML/day that would be entering the plant. It was assumed that the specific energy for the treatment would remain the same.

The total global warming impact of providing 200 000 additional households with water and sanitation per day by maximising the use of the existing assets is presented in Table 3.

As anticipated, the burden attributable to Option 1 is lower than the base case (27 561 kg CO_2 equivalents) mainly due to the lower impact per kilolitre of water produced from Inanda Dam.

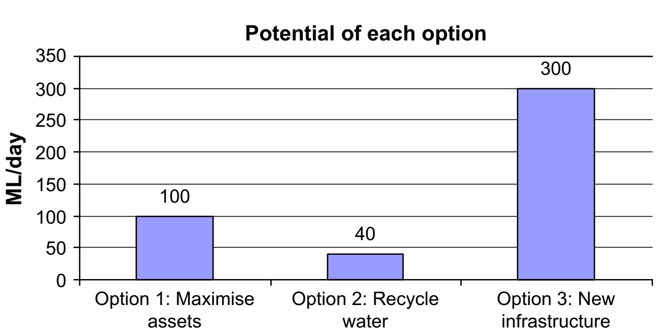

Fig. 2. The potential additional amount of potable water that each option can produce.

5.2. Option 2: recycle water

This is the current scenario in the eThekwini Municipality. The scenario was chosen for a number of reasons, of which the most important were: the sea outfall was rapidly reaching its maximum capacity, there was a rise in demand from industrial consumers and it made good financial sense. Whether this was the best option environmentally for increasing Durban's water supply was not stated. Fig. 4 illustrates this case.

There is a discrepancy in the outflow from the collection and the inflow to the primary treatment. This is due to the fact that one needs to recycle more than the wastewater of 200 000 households (24 ML/day) to produce 40 ML/day. This is made up by the domestic waste of other households in the eThekwini Municipality. When calculating the burdens attributable to the recycling plant, it is important that they are allocated properly. One must bear in mind that the functional unit is the provision of water and sanitation services to 200 000 new households. Thus by using the recycling plant to supply industrial users and therefore freeing up potable supplies, the households are responsible only for the environmental impact of the recycling plant and not the waterworks. Therefore the units leading up to the delivery of water to customers are given a zero environmental score. The new households still are responsible for the burdens of the primary treatment (those that have waterborne sewage).

In calculating the scores for this scenario the distribution losses of 30% have not been taken into consideration because in reality there are no losses. The industries using the recycled water are in close proximity to the recycling plant and have a dedicated pipe which is constantly checked and maintained. Therefore, the system losses do not apply in this case.

The total environmental impact of providing 200 000 additional households with water and sanitation by using recycled water is presented in Table 4.

By comparing the total global warming potentials in Tables 4 and 1, it is shown that Option 2 has a lower global warming impact than that of the base case. Therefore, it supports the case for introducing recycling schemes, since even though a lower quality of water is treated, the environmental burden is still lower than the base case. For the eThekwini Municipality this represents a win–win scenario, since it proves to be viable environmentally and financially.

From Fig. 4 and Table 4 it can be seen that the secondary treatment and, in particular, the activated sludge process, have one of the highest energy consumptions in the entire system. An improvement analysis for this process was performed. The impacts from the activated sludge units can be attributed to the large amount of electricity expended by the aerators in transferring air from the atmosphere into the liquid. The reason for this is due to the fact that many aeration processes fail to achieve an optimum level of energy consumption [11]. Two possible ways of reducing the electrical load were considered. The first is to use a diffused aeration system in conjunction with the current surface aerators. Provisions have already been made for periods of high-demand and oxygen diffusers are in place. Problems associated with this system are the high-cost of pumping (electrical and hence environmental) pressurised air and fouling of the diffuser network.

A second way of reducing the electrical load is to decrease the oxygen demand of the system. This can be achieved by optimising parameters such as sludge age, wastage rate, aeration levels, and recycle rate. A computer model was set up using the WEST (Worldwide Engine for Simulation, Training and Automation) software package to investigate these parameters. By using this model it was shown that a decrease in the dissolved oxygen set point from 2.0 mg/L to 1.5 mg/L resulted in a negligible change in the COD reduction. This reduction in the oxygen required by the

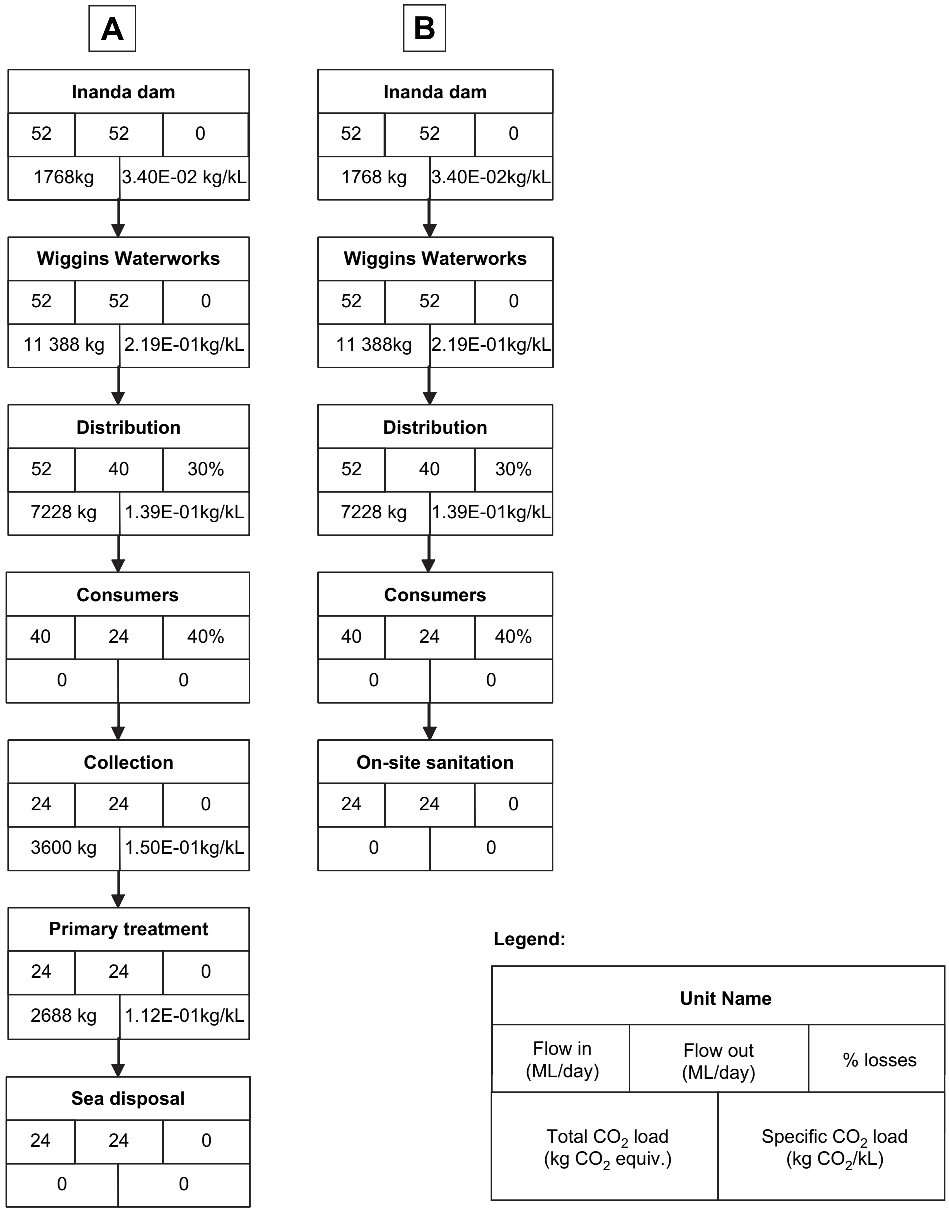

Fig. 3. Simplified flowsheet of Scenarios A and B for Option 1 (where the infrastructure is utilised to maximum capacity).

process translates to a large electrical saving by the aerators. It must be noted that these are preliminary results and need to be investigated further to see whether this change can be implemented on the plant. One of the factors that need to be considered is that the aerators have a dual function. They transfer oxygen to the sludge as well as keeping it well-mixed. Thus it needs to be investigated how reducing the air input to the tanks will affect the mixing of the tanks.

Table 3
Breakdown of the global warming impact of providing 200 000 new consumers in the eThekwini Municipality with water and sanitation by maximising the base case (Option 1)

Unit	Volume produced (ML)	Impact (kg/kL)	Scenario A	Scenario B
			Total impact (kg)	Total impact (kg)
Inanda Dam	52	3.40E−02	1768	1768
Wiggins Waterworks	52	2.19E−01	11 388	11 388
Distribution	52	1.39E−01	7228	7228
Collection	24	1.50E−01	3600	0
Primary treatment	24	1.12E−01	2688	0
Total			26 672	20 384

Another option that requires further investigation is the pre-treatment of the entering effluent. Mels et al. [12] showed that by introducing a pre-treatment step the energy requirements of the activated sludge could be dramatically reduced. Two pre-treatment options were considered. The first used the addition of coagulant and flocculent, followed by a pre-precipitation step. The second option used the addition of coagulant and flocculent, followed by a flotation step. For a South African treatment system these options are not used, as the cost of chemicals outweighs the electrical savings. However, the environmental improvements are potentially large.

5.3. *Option 3: construct new infrastructure*

The last option considered was one where to meet increasing demand, new infrastructure is constructed. When modelling this

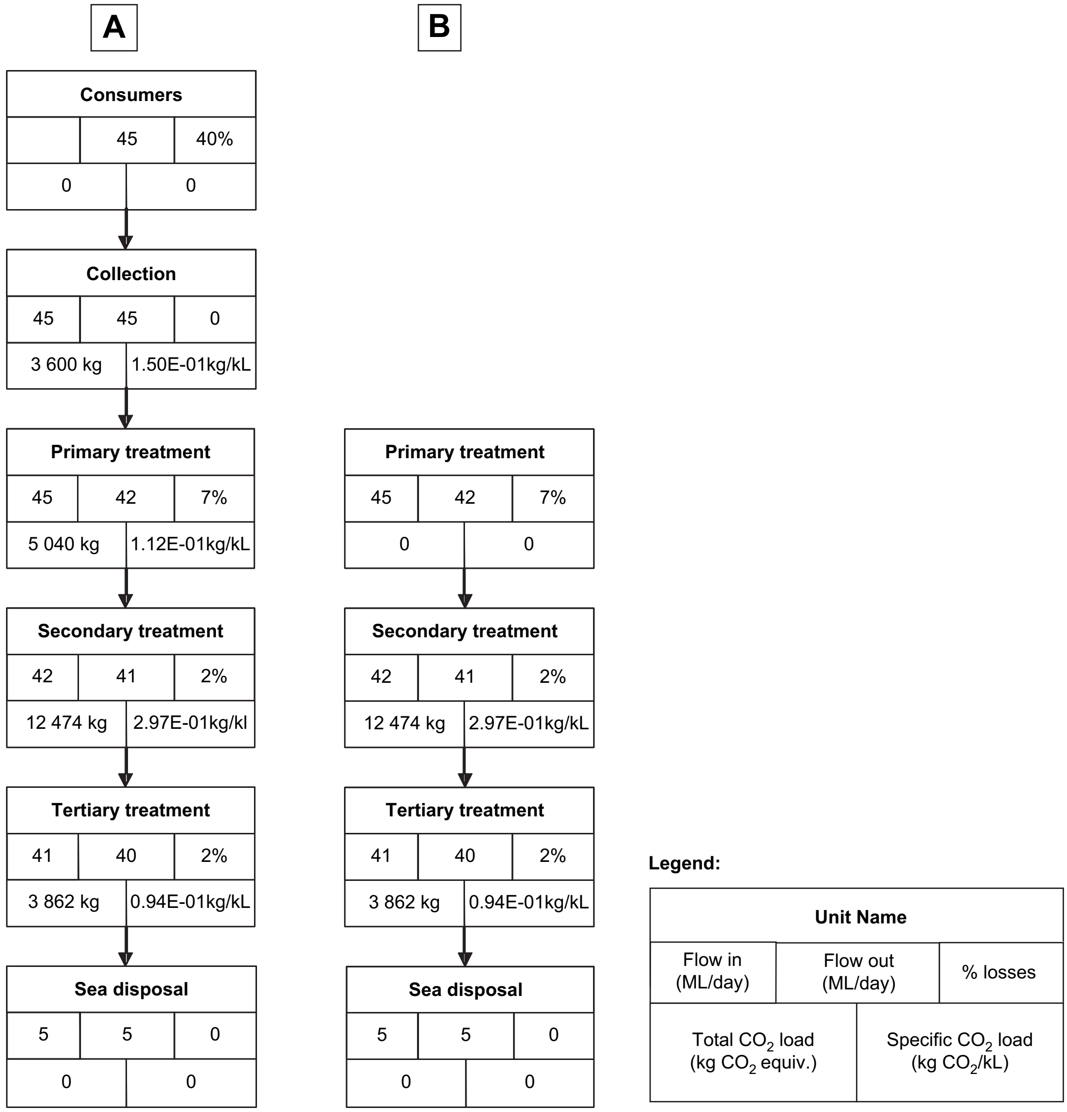

Fig. 4. Simplified flowsheet of Scenarios A (waterborne sanitation) and B (on-site sanitation) for Option 2 (the recycling case).

option it was taken that the same technology would be used, except for the treatment of the wastewater. A flowsheet for this option is presented in Fig. 5.

In calculating the global warming scores, the following assumptions have been made:

- The environmental burden for the new dam would increase per kilolitre. It was assumed that at the start of operations only 50 ML/day would be abstracted from the new dam. This would result in a global warming burden of 2.40E−02 kg/kL CO_2 equivalents.
- There are no plans to build new waterworks to supply the Durban region. There have been no major technological advances that have dramatically reduced the environmental loads of large-scale water treatment plants; however, one has to assume that best available technology will be applied. In this case the reduction in environmental burden comes from the new plants being energy efficient. Thus using Wiggins as a base case, it was assumed that a new plant would incorporate the same treatment units but be energy efficient. Currently the ozone process at Wiggins uses 4341 kWh/day (34%) from a total of 12 613 kWh/day. It was shown in the improvement analysis (see Ref. [4]) that this figure could be reduced by up to 80%. This would reduce the electricity consumption of Wiggins to 9140 kWh/day. An improvement of 27%.
- The recycling plant is essentially a water treatment plant employing all the same units as Wiggins Waterworks. It is a state-of-the-art design employing all the latest energy efficient technology. The global warming burden of the recycling plant is 1.01E−01 kg CO_2 equivalents/kL water produced. The global warming burden of Wiggins is 1.85E−01 kg CO_2 equivalents/kL water produced. Thus the recycling plant is able to

Table 4
Global warming impact of Option 2 – recycle water

Unit	Volume produced (ML)	Impact (kg/kL)	Scenario A	Scenario B
			Total impact (kg)	Total impact (kg)
Collection	24	1.50E−01	3600	0
Primary treatment	24	1.12E−01	2688	0
Secondary treatment	42	2.97E−01	12 474	12 474
Tertiary treatment	41	0.94E−01	3862	3862
Total			22 624	16 336

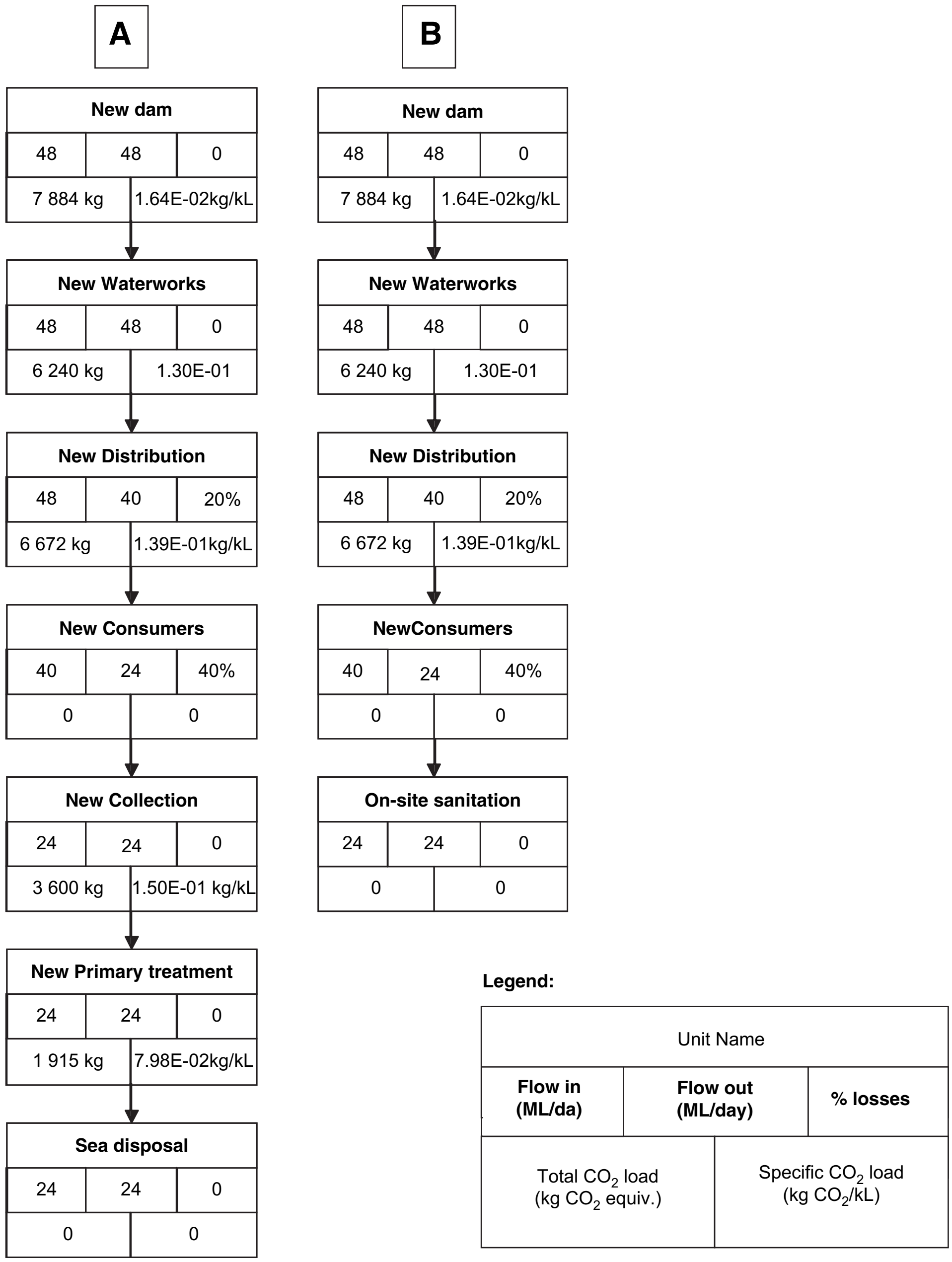

Fig. 5. Simplified flowsheet for Scenarios A (waterborne sanitation) and B (on-site sanitation) for Option 3 (the new infrastructure case).

treat a lower quality influent to an almost equal standard at a 45% reduction in the global warming load.

- It was thus assumed that using energy efficient measures and even using the same technology a minimum environmental improvement (in the global warming category) of 30% could be achieved for a new water treatment works. This would translate to a global warming load of 1.30E−01 kg CO_2 equivalents/kL water produced.
- A series of measures are being implemented to reduce leakage and the losses in the distribution network. The aim of eThekwini Municipality's Water Services is a leak rate of 20% and this was the rate that was assumed when considering the new infrastructure case.
- In Durban, the municipality has set a boundary outside which it will not provide waterborne services as it cannot afford to build and maintain a system to serve dispersed communities. In these areas Durban is increasingly promoting the use of a double alternating pit urine diversion toilet.

The total environmental impact of providing 200 000 additional consumers with water and sanitation by constructing new infrastructure is presented in Table 5.

Table 5
Breakdown of the global warming impact of providing 200 000 new consumers in the eThekwini Municipality with water and sanitation by using Option 3 – construct new infrastructure

Unit	Volume produced (ML)	Impact (kg/kL)	Scenario A	Scenario B
			Total impact (kg)	Total impact (kg)
New dam	48	1.64E−02	7884	7884
New waterworks	48	1.30E−01	6240	6240
Distribution	48	1.39E−01	6672	6672
Collection	24	1.50E−01	3600	0
New primary treatment	24	7.98E−02	1915	0
Total			26 311	20 796

The global warming score for Option 3, Scenario A is marginally smaller than that of the base case.

5.4. Discussions of the different scenarios

Fig. 6 presents the greenhouse gas emissions in all the options and scenarios.

Examining Fig. 6 it is clear that for both Scenarios A and B, Option 2, the recycling option is the best. All the options have a lower environmental burden than the base case (27 561 kg CO_2 equivalents – see Table 1). The study highlighted the importance of proper planning when constructing a dam. Dams should only be constructed if there is sufficient demand for the water that they can supply; otherwise they act as greenhouse emitters for no return. Thus one should always aim to use a dam to its maximum capacity to get the greatest return for the environmental damage being caused. The concept of using an asset to its maximum to get a lower environmental burden does not apply to sub-systems where the energy input increases in proportion to the volume treated (e.g. the waterworks).

The question that now must be asked is, for a municipality looking to increase its available water and sanitation, what is the best route? Should one go straight to recycling, like Durban, or are the better ways (environmentally) of doing so?

There are many variables to be considered when answering this question, the most important being:

- The type of sanitation to be provided to new customers. Since the burden of waterborne sanitation is the largest contributor to the environmental burdens, this should only be used when on-site treatment cannot be used.
- The location of the new customers. On-site sanitation can only be used in rural and peri-urban areas. If the new customers are in densely populated urban areas, then waterborne sanitation is the only option.
- The capacity of current infrastructure. Is the infrastructure being used to its maximum capacity, is there room for expansion?
- The quality of water required by the new customers. Are they industrial or domestic users? If industrial, then what is the water used for and what is the quality required? Is potable water really necessary? How far are the industrial users from a wastewater treatment works?
- The catchment capacity of the municipality. In the event of new infrastructure being required, is it possible to abstract more water through the construction of a new dam or must other options be considered?

Careful consideration of these issues led to some general guidelines for South African municipalities wanting to increase their supply of potable water and sanitation. These steps in increasing the water and sanitation capacity of a system are common to all municipalities regardless of their location (coastal or inland) and should be implemented even in municipalities which are not facing a water shortage. These steps are:

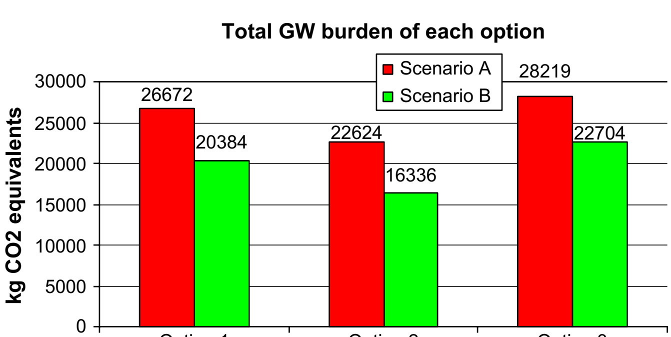

Fig. 6. The total global warming burden of each option to provide 200 000 people with water and sanitation for each day.

1. In any system, the first step is to ensure the system is running efficiently. This entails a programme where losses in the system are identified and reduced. The same efficiency measures must be practiced throughout the system and a thorough improvement analysis should be carried out.
2. Institute a water demand management programme. This promotes cost savings and environmental savings, thus creating a win–win situation. This is an easy and environmentally friendly way of immediately increasing a municipality's water supply.
3. What must be avoided is using a dam as a storage facility without any abstraction, as this results in all the negative environmental effects for no return. Thus any dams in the system should be utilised at their maximum capacity.
4. As one of the largest burden accrues from the treatment of wastewater, where possible residents should use safe, on-site sanitation. This is the single most effective way of reducing the environmental load of a sanitation system.
5. Water recycling should be encouraged in cases where it is environmentally efficient. The water recycling should take place preferably close to large industrial customers who can accept a lower quality of water as the environmental burden of getting recycled water up to a standard for human use could be high. An important conclusion that is applicable to this analysis is that *if there is no need to use potable water then don't supply it*. Water recycling may become environmentally inefficient if the distance between the recycling plant and the user is considerable and the pumping requirements are increased and/or if the quality of the incoming water deteriorates to the extent that more energy intensive treatment processes are needed. Therefore, each new recycling initiative should have an LCA study undertaken.
6. Construct new infrastructure. This must be done using environmentally friendly processes. In the absence of a detailed LCA for a process, the following rule of thumb can be used: *in general, the less electricity a process uses, the more environmentally friendly it is*. In addition, care must be taken with the quality control of existing chemicals and the introduction of new chemicals for water treatment, since they may have an impact in terms of toxicity.

From a theoretical perspective for a city seeking to improve its environmental performance and become more sustainable there are three ways of achieving this:

- By incrementing or continual improvement; while this option may deliver substantial progress in the early stages by capitalising on small easy improvements. International experience has shown that marginal improvements become smaller and hence more costly through time. An example of this is leak detection. Initially the savings will be great, but will gradually taper off.
- By redesigning the product, product lines or the services being delivered. This approach leads to an organisation changing the actual products, processes or services to bring them in line with sustainability principles. Because redesign allows changes to be made earlier in the product cycle, the savings from increased resource productivity are often significantly greater than in the incremental approach. An example of this is the urine diversion toilet. It is an innovative solution to the city's

waste problem and greatly reduces the environmental burden of the city.

- By rethinking the way in which people obtain value from the products or services themselves. This is a more radical change and involves a complete reassessment of how an organisation generates value. Changing the business model may imply a shift in patterns of both production and consumption as an organisation moves from a 'product based' orientation to a service business model – seen as a flow of services rather than a flow of goods. An example of this is the provision of industrial grade recycled water. Instead of just providing water, the question that was asked was what service does the customer require? In this instance it was water for boilers and paper-making. Hence there was no need to treat water to a potable standard when recycled sewage could be used.

In the quest for urban sustainability all three approaches must be used concurrently.

5.5. Additional options and scenarios

There are a number of additional scenarios that can be considered which make minor changes to the four detailed scenarios considered in this paper. A qualitative analysis of these scenarios is presented.

- *The effect of sending untreated effluent directly to sea*. This will lower the overall environmental burden of the system for the global warming category but might increase the burdens in other impact categories such as toxicity and eutrophication potential.
- *The trade off between using activated sludge to reduce COD as opposed to granular activated carbon and ozonation for the treatment of wastewater.*
- *Sludge treatment scenarios*. Further research is needed to examine means of sludge disposal in the South African context. This is particularly applicable to inland municipalities which do not have the option of discharging wastewater to sea. Matsuhashi et al. [13] carried out a comparative LCA of different sludge treatment options. Methods of disposal considered included landfilling, incineration and composting. The study also considered using the sludge as a resource. One conclusion that the authors drew was that when the sludge is used for soil improvement the benefit is comparable to the production and use of chemical fertiliser. Neumayr et al. [14] carried out a study on six different sludge-recycling strategies. The main impacts associated with sewage sludge treatment were found to be energy use, diesel used in transportation and direct emissions of ammonia from composting and dewatering.
- *Supplying bottled water for food and drinking use and a partially treated supply for other use*. This method is currently used in some developing countries, where filtered water is supplied from a nearby river to households for general use and bottled water is supplied for drinking and food use purposes. A brief study was carried out using data available in the literature [15] to ascertain the viability of this option. The results calculated are presented in Table 6.

Table 6
Summary of the impacts for the bottled water option

Process	Volume produced (ML)	Impact (kg/kL)	Scenario A	Scenario B
			Total impact (kg)	Total impact (kg)
Production of water for bottling	0.6	7.03E+01	131	131
Production and distribution of bottles	0.6	2.19E−01	42 180	42 180
Production of semi-treated water	51.4	9.01E−04	46	46
Distribution of semi-treated water	51.4	1.39E−01	7145	7145
Collection	24	1.50E−01	3600	0
Primary treatment	24	1.14E−01	2736	0
Total			55 838	49 502

The results show the environmental impracticality of supplying bottled water due to the large burden accruing from the production of the bottles. Over 75% of the global warming impact can be attributed to the production and distribution of the plastic bottles. The global warming burden of the bottled water option is more than double that of any of the other options for increasing the water supply for both scenarios. Although the treatment of potable water is a large proportion of the overall system impacts (42%) in the base case, as shown in the case studies of Options 1 through to 3 there are better ways of mitigating this burden than using bottled water.

6. Conclusion and recommendation

This study illustrates that LCA in general, and global warming scores (carbon footprinting) in particular, are appropriate tools to evaluate the environmental performance of a complex system like the urban water supply and sanitation. The focussing capacities of these environmental tools are highlighted by the results presented and complete the range of applications as presented in the literature (for a review on the use of LCA in the water industry, see Ref. [16]).

The analysis process presented in this paper is able to identify major environmental contributors. By targeting these major contributors, the overall environmental performance of the system can be improved in the most efficient manner. This is particularly important for developing countries where limited financial resources should be used to achieve the best possible outcomes.

The lessons, from this research, for municipalities striving to achieve the Millennium Development Goals (MDGs) with regard to safe water supply and sanitation are summarised as follows:

- Water losses in the distribution of potable water have high-environmental burdens in addition to financial implications. It is the first and most important step in improving performance. This should be achieved by reducing consumer demand and supplier demand. Taking into account the high-proportion of unaccounted water (due to leakage, illegal connections, etc) reducing supplier demand will have the highest environmental and financial improvement impact without negatively impacting on the quality of the supply. Consumer demand should also be addressed (i.e. water saving devices and local by-laws or restrictions).
- Wastewater treatment plants, which have activated sludge units, have a high-impact due to their energy requirements. Therefore, where appropriate safe, on-site sanitation should be promoted because it has environmental advantages in terms of energy requirements (collection and secondary treatment are not necessary) and sustainability.
- Ozonation is seen as a clean technology for the disinfecting of water, however, due to its relatively high-energy requirements it has high-environmental burdens. The efficiency of the process itself is another issue to be looked at. In this study the ozonation unit in the recycling plant has a higher efficiency than the one in the potable water plant. This issue needs further investigation.

- In general for developing countries, the environmental burdens of providing partially treated water together with bottled water are high and this method of supplying safe water should not be encouraged. In other words it would be more beneficial, environmentally, to treat all the water supplied for households to drinking water standards. The environmental costs of supplying water which is not properly treated are high, adding to the health costs, and it will affect mostly the poor since they are more likely to be in a position where access to bottled water is not existing (affordability, distribution, etc).

Acknowledgements

The authors wish to express their gratitude for supporting this research to following organisations: Water Research Commission of South Africa, Umgeni Water, eThekwini Municipality, Durban Water Recycling, National Research Foundation of South Africa and University of KwaZulu-Natal Research Fund.

References

[1] Department of Water Affairs and Forestry of South Africa. Strategic framework for water services. Available from: http://www.dwaf.gov.za/Documents/Policies/Strategic%20Framework%20approved.pdf; 2003 [accessed 21.11.05].
[2] eThekwini Municipality, Water and Sanitation Services. Water services development plan. Available from: http://www.durban.gov.za/eThekwini/Services/water_and_sanitation/policies_and_guidelines/WSDP; 2004 [accessed 21.11.05].
[3] Statistics South Africa – census 2001. website. Available from: http://www.statssa.gov.za/census01/Census/Database/Census%202001/Census%202001.asp [accessed 21.11.06].
[4] Friedrich E, Buckley CA, Pillay SD, Leske A. A life cycle assessment of a secondary water supply, water research commission of South Africa report. Project K5/1252. South Africa: Pretoria; 2005.
[5] Rosa LP, Santos MA, Matvienko B, Sikar E. Hydroelectric reservoirs and global warming. In: RIO 02 – world climate and energy event, January 6–11; 2002.
[6] Liikanen A, Flojt L, Martikainen P. Gas dynamics in eutrophic lake sediments affected by oxygen, nitrate and sulfate. Journal of Environmental Quality 2002; 31:338–49.
[7] Friedrich E. The use of environmental life cycle assessment for the production of potable water. MSc Eng Thesis. Pollution Research Group, University of Natal: Durban; 2001.
[8] Friedrich E. Life cycle assessment as an environmental management tool in the production of potable water. Water Science and Technology 2002;46(9): 29–36.
[9] Pillay SD. An environmental life cycle assessment of the provision of recycled water in Durban. PhD Thesis. Pollution Research Group, University of KwaZulu-Natal: Durban, South Africa; 2005.
[10] Pillay S, Friedrich E, Buckley CA. Life cycle assessment of a water recycling plant. Water Science and Technology 2002;46(9):55–62.
[11] Houk DH, Boon AG. Survey and evaluation of fine bubble diffuser aeration equipment. US EPA Report, EPA 600/2-81-222; 1981.
[12] Mels AR, van Nieuwenhuijzen AF, van der Graaf JHJM, Klapwijk B, de Koning J, Rulkens WH. Sustainability criteria as a tool in the development of new sewage treatment methods. Water Science and Technology 1999;39(5): 243–50.
[13] Matsuhashi R, Sudoh O, Nakane K, Hidenari Y, Nakayama S, Ishitani H. Life cycle assessment of sewage treatment technologies. In: Paper read at the IAWQ conference "sludge—waste or resource?"; June 26–28, 1997. Czestochowa, Poland.
[14] Neumayr R, Dietrich R, Steinmuller H. Life cycle assessment of sewage sludge treatment. In: Proceedings of the 5th SETAC annual conference; 2–4 December 1997. Brussels, Belgium.
[15] Ekvall T, Person L, Weidema BP. Life cycle assessment of packaging systems for beer and soft drinks. Environment Project No. 404. Denmark: Ministry of Environment and Energy; 1998.
[16] Friedrich E, Pillay SD, Buckley CA. The use of LCA in the water industry and the case for an environmental performance indicator. WaterSA 2007;33(4): 443–51.