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Constructing Wetlands in the Desert: An Example of Sustainable Produced Water Management in Oman

Mohamed Al-Rawahi, Stephane Prigent, and Tom Headley, BAUER Nimr LLC, Muscat, Sultanate of Oman; Roman Breuer, BAUER Resources GmbH, Edelhausen, Germany; Rainer Paetzelt, BAUER Emirates Environment LLC, Abu Dhabi, United Arab Emirates

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Abstract

Large volumes of produced water are generated as an associated co-product of oil production in Oman and other countries; the management of which often imposes a limitation on oil production. In many cases, a portion of this water is re-injected into reservoirs to maintain pressure for the oil wells. The remaining volume is typically disposed of into shallow aquifers or via Deep Well Disposal (DWD) which are environmentally undesirable and operationally energy intensive. Constructed wetlands represent an alternative option for treating produced water and have been trialled in Oman since 2000 with large-scale implementation since 2010. Wetland technology is a phytoremediation process in which native wetland plants facilitate microbial degradation of hydrocarbons. Volume reduction is also achieved through the high evapotranspiration rate of the plants. The advantages of wetland technology include: no or low-energy requirement, low operating cost, no chemical inputs, long life expectancy, high-level treatment performance & reliability. Based on these advantages, Petroleum Development Oman (PDO) decided to proceed with a large-scale application of wetland technology for management of produced water in its Nimr oil field in southern Oman. In 2008, BAUER was awarded a Design, Build-Own, Operate and Transfer (DBOOT) contract to develop the Nimr Water Treatment Plant (NWTP), which was commissioned in 2010. The capacity of the NWTP has been expanded over time and now has a capacity to treat 115,000 m^3/day of produced water within 350 ha of Surface Flow Constructed Wetlands (SFCWs,) followed by 500 Ha of evaporation ponds (EP) for volume reduction and salt production. The entire process operates via gravity without any pumps. The inlet produced water is brackish (TDS 7,000 mg/L) and oil-in-water is 400 mg/L on average. More than 90% of the oil (260 bbl/day) is recovered at the front-end of the system using hydrocyclones and skimmers. The remaining hydrocarbons are biologically degraded within the wetlands, producing an effluent with oil-in-water below detection ($<$ 0.1 mg oil/L) and brackish salinity (approximately 10000 mg/L TDS). Research and field trials are currently underway to develop options for reusing the wetland-treated water for irrigation of salt tolerant plants (biosaline agriculture) in order to produce biomass, bio-fuels, fibre and other products. The project has effectively created an "oasis" in the desert, providing valuable habitat for bird life ($>$ 117 species identified at the site).

Introduction

Located at the south eastern part of the Arabian Peninsula, Oman is recognized as a country which depends mostly on the oil and gas sector which contributes about 81% to the GDP of the country (OABINVEST, 2012). Petroleum Development Oman (PDO) is the largest hydrocarbon exploration and production company in Oman. Large quantities of produced water are generated as an associated co-product of oil production. The disposal of this water from on-shore activities can be very challenging. In previous years, part of this water was re-injected into the oil reservoir to maintain pressure for their oil wells (Al-Rawahi, 2005). The remaining volume was typically disposed into shallow and Deep Well Disposal (DWD) which was considered environmentally undesirable. Due to the environmental risks, shallow water disposal was phased out in Oman in 2005 leaving PDO with only the deep well disposal option (Al-Masfry et al., 2007). Hence, many oil companies have been exploring alternative and innovative ways to manage produced water in a sustainable way.

In the past decades, more attention has been paid to constructed wetland technology as a natural process for water quality improvement. One of the most common applications of constructed wetland is the treatment of primary or secondary domestic sewage effluent. However, constructed wetlands are also used to improve water quality of different pollution sources. In general, constructed wetlands are shallow sealed ponds filled with some sort of filter material (substrate), usually sand or gravel, and planted with vegetation which tolerate high levels of chemical or organic pollutants, withstand water-logged conditions, have active microbial sites within their root rhizosphere, and have capacity of absorbing and biodegrading the pollutants. The removal process mainly depends upon the microbial activity inside the wetland. Comparing with mechanical treatments, constructed wetlands have relatively low operating costs; require minimal inputs of electricity and chemicals; and require only simple maintenance and management. In 1998, PDO introduced this technology to the oilfield industry (Gurden and Cramwinckel, 2000) through establishing a constructed wetland experiment at the Desert Agricultural Project (DAP). The experiment was conducted with about 800 m^2 of reed bed capable of treating 20 m^3/day of produced water. The results were very encouraging with substantial removal of hydrocarbons and heavy metals from Marmul production water. The volume of production water was reduced by approximately 50% across the wetland because of the high rates of evapotranspiration under the arid desert conditions. Based on the results of this experiment, PDO established a 6 hectare pilot project in the Nimr Oilfiled with a capability of treating 3,000 m^3/d of produced water (Al-Rawahi, 2005).

In November 2008, PDO has awarded a Design Build Own Operate Transfer (DBOOT) contract to BAUER Nimr LLC to develop a system for sustainable management of produced water in the Nimr Oil Field using wetland technology in constructing the Nimr Water Treatment Plant (NWTP) (Breuer et al., 2012).

Objectives

The main objective of building the NWTP was to replace the high energy consumption disposal techniques by an environmentally sound technology. During the past decades, several disposal techniques have been used in Oman, such as shallow aquifer disposal which was phased out in 2005 and Deep Well Disposal (DWD) where production water is injected in wells of up to 2 km depth. Some of the drawbacks of DWD include the high fossil energy consumption which is costly and leads to high CO_2 emissions, and the possible underground aquifer contamination. Furthermore, repair and maintenance of the large pumps required for DWD often leads to interruptions to produced water management, which in turn can impose a bottleneck on the oil production process. In contrast, the wetland solution provides an environmental and sustainable alternative for biologically degrading hydrocarbons using gravity flow, creating an “oasis” in the desert and creating a habitat for migratory birds. The main objectives of the NWTP are:

1. To provide a robust and reliable system for management of produced water, capable of operating

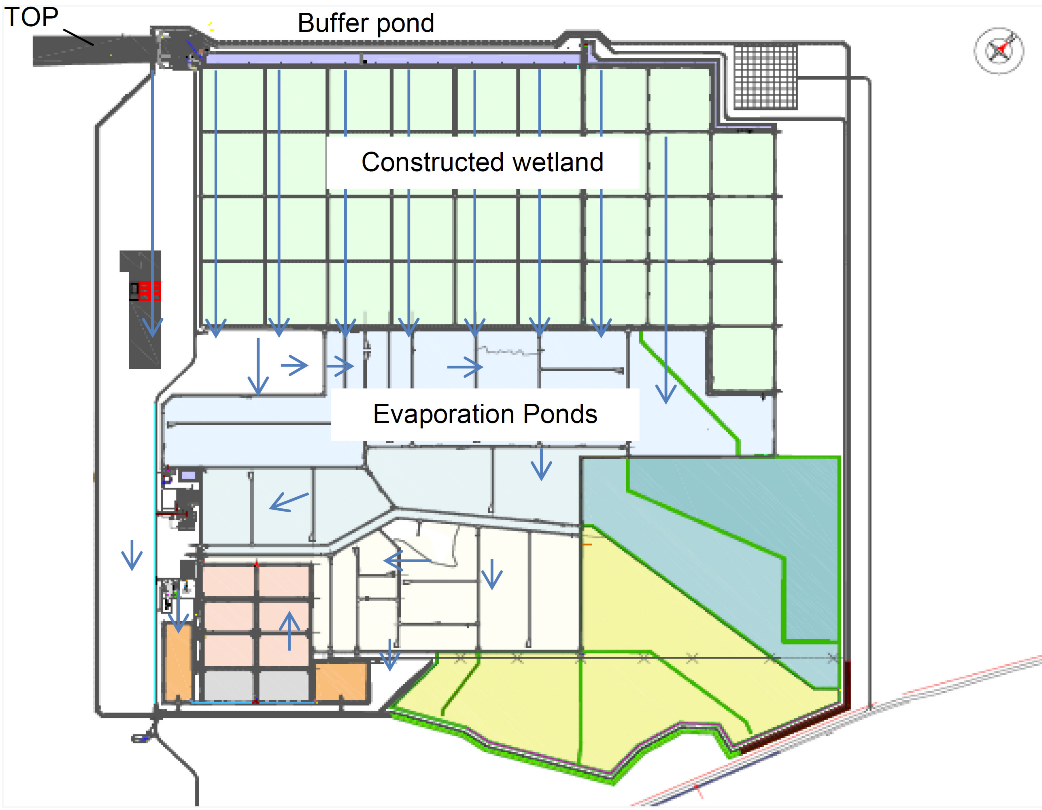

Figure 1—Layout of the NWTP showing each stage in the system

without shut-down.

2. To ensure gravity flow of the water allowing the system to operate with a minimum external power requirement using the local topography.
3. To treat produced water through removing hydrocarbons and dispose water through evaporation.
4. To create opportunities of reuse such as Bio-saline agriculture, algae cultivation, Drilling operation, aquaculture, reverse osmosis treatment for high value uses, shallow aquifer recharge.
5. To create a wildlife habitat within an industrial site.

Project Overview

The NWTP is one of the world's largest constructed wetlands, located in Nimr, approximately 700 kms south of Muscat the capital of Oman. The NWTP has the capacity of treating 115,000 m^3/day of produced water using 350 ha of Surface Flow Constructed Wetland (SFCW) and 500 ha of Evaporation Ponds (EP) (Figure 1). Produced water is sent through a pipeline to the Turn-Over-Point (TOP) of the NWTP. The TOP includes flow control and metering, and aims to separate and recover the majority of oil from the produced water using a series of hydro-cyclone oil separators and floated skimmers. Then, the produced water is distributed in the SFCW via a long buffer pond. The 350 ha of SFCWs are divided into 9 parallel tracks, each consisting of four 10 ha wetland terraces in series, operating with gravity flow (Figure 2). Samples of native wetland plant species were collected throughout Oman (Wadis, Coastal lagoons), propagated in the Bauer Nursery and then planted in the SFCW. Approximately 3 million plant seedlings have been planted to date.

Some of the treated water exiting the wetlands is reused in drilling operations, for dust surpression and for irrigation of salt tolerant plants. The remaining treated water flows into a series of EPs which are used for disposing of the majority of the production water through evaporation resulting in salt formation which can be used for drilling operations and other industrial uses.

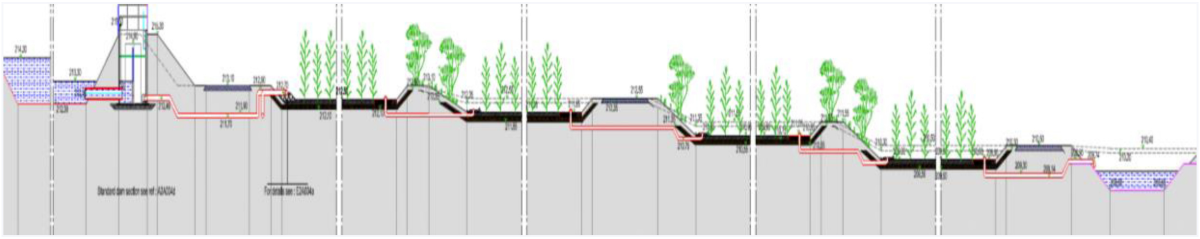

Figure 2—Cross-sectional profile through NWTP system indicating the water pathway through the four stages wetland (Terraces) treatment.

Table 1—Summary of meteorological parameters recorded at NWTP during the year 2013.

Parameters	Mean	Max	Min	Total
Air temperature (°C)	26.6	45.4	7.8	-
Relative humidity (%)	58.5	96.3	5.3	-
Wind Velocity (m/s)	3.2	14.0	0.0	-
Solar Radiation (W/m^2)	238.3	1045.0	0.0	-
Rainfall (mm)	-	-	-	5.8

The construction phase of the project lasted for 2 years and was commissioned in November 2010. The NWTP will operate for at least 20 years. The weather conditions, size, influent produced water quality and the operation make this project unique around the world and challenging. The air temperature can reach up to 50°C during the summer months. The composition of the produced water from the Nimr Oilfield is brackish with influent Total Dissolved Solids concentration ranging between 7,000 and 8,000 mg/L and increasing along the wetland terraces. Moreover, the produced water is characterized with a low nutrient concentration, i.e. total nitrogen and total phosphorus lower than 1 mg/L.

Weather Conditions

Meteorological conditions are measured continuously using permanents weather stations located at the NWTP (Vantage Pro 2, Davis Instrument, USA). These stations were setup to record data at 30 minute intervals. Table 1 shows the means, maximum and minimum of different meteorological parameters.

Water quality

Water sampling is performed in quarterly basis. Composite samples are collected from the Oil separator (before and after separation) and from overall wetlands tracks (each track and terrace). Samples are analysed for physical and chemical parameters such as temperature, pH, electrical conductivity (EC), Total dissolved solids (TDS), Oil in water content (OiW), Boron (B), total Nitrogen (TN), total Phosphorous (TP), Sulphate (SO4), Sodium (Na), Chloride (Cl), Potassium (K). Water physical parameters are measured in-situ using the WTW MultiLine P4 universal meter with combined pH electrode and temperature probe, whereas TetraCon 325 probe is used for determining the conductivity. Water chemical analysis is performed onsite by BAUER Nimr lab technician (HACH DR 3900 spectrophotometer, Hach, Germany). Similar samples are also analyzed by accredited external laboratories such as Agrolab Laboratory GmbH (Bruckberg, Germany) and ALcontrol laboratories (Rotterdam, Netherland).

The NWTP constructed wetland serves two main functions for the management of produced water: (i) removal of residual hydrocarbons from the water, (ii) volume reduction via evapotranspiration rate of wetland plants. The results show that the Oil in water concentration ranges between 250 to 400 mg/L at the TOP. After oil separation through hydrocyclones and floated skimmers, oil in water concentration reduced to 10 - 30 mg/L before entering into the treatment wetland. The separated crude oil from the produced water is returned to the oil production process. The outflow is cleaned ($<$ 0.1 mg oil/L) but remains brackish as the salinity increased ($>$10000 mg/L) as a result of evapotranspiration, which

Table 2—Average water quality of the inflow and outflow of the NWTP during the year 2013

	Inflow (After oil separation)	Outflow (After wetland treatment)	Unit
Water Temperature	32.2	26.0	°C
pH	7.8	8.9	
Conductivity	10.5	>15.0	dS/m
B	4.9	8.0	mg/L
TNs	1.2	0.3	mg/L
TPs	0.03	0.01	mg/L
K	60	80	mg/L
Nas	2,500	4,000	mg/L
Cls	3,400	5,000	mg/L
SO4	300	500	mg/L
TDSs	6,600	>10,000	mg/L
OiWs	10-25	< 0.1	mg/L

removes water from the system and leads to an increase in the concentration of sodium chloride (NaCl) and other salts. In addition, boron increased from 4 – 5 mg/L at the inlet to 8 - 9 mg/L by the outlet. On the contrary, total Nitrogen concentrations in produced water are very low at the inlet (1.2 mg/L), and impose a limitation on the rate of plant growth in the wetlands. The total nitrogen concentration depleted rapidly over the length of the wetland terraces. Similarly, total phosphorous concentrations are very low throughout the whole system. The quality of water entering and exiting the NWTP constructed wetlands is summarised in Table 2.

Removal Processes

The NWTP performance was assessed through regular long-term monitoring of production water quality throughout the constructed wetland system since the start of 2013. The results demonstrate the high efficiency of the NWTP at removing hydrocarbons. Figure 3 shows the oil in water removal profile through the four terraces (stages) of the surface flow wetland. The removal of oil in water follows an exponential decrease in concentration (first order removal process). In general, hydrocarbon removal is achieved after the 3rd terrace of all monitored tracks. However, oil in water concentration varied spatially throughout wetland tracks. Track 1 receives the highest oil in water concentration at the inlet due to its location immediately adjacent to the outlet of the oil-water separator. Track 9 is the furthest distance along the buffer pond from the oil separator and receives the least amount of oil in the influent.

Hydrocarbons undergo several transformation and removal process during residence in the constructed wetland. Imfeld et al. (2009) have evaluated and listed the major removal process in constructed wetland system such as volatilization, photochemical oxidation, sedimentation, sorption and biological degradation. In addition, other processes such as plant uptake and contaminant accumulation, phyto-volatilization and metabolic transformation may be relevant for some plants and contaminations. In the NWTP surface flow wetlands, the hydrocarbon removal process is likely a result of a multi-stage process. First, any free floating oil adheres to surfaces within the system, such as wetland plant stems, microbial mats and soil. This trapped oil then becomes populated with microbial biofilms and undergoes degradation. This process leads to hydrocarbon degradation and transformation to carbon dioxide (CO_2) and other inorganic compounds. Abed (2010) assumed that heterotrophic bacteria associated with autotrophic cyanobacterial mats are responsible about the hydrolysis and mineralization of petroleum hydrocarbons in oil polluted sites.

Wildlife Habitat and Biodiversity

The Sultanate of Oman is a major pathway for migratory birds between Asia and Africa. The mix of shallow and deep water of the wetlands and ponds respectively, and the diversity of the wetland plant

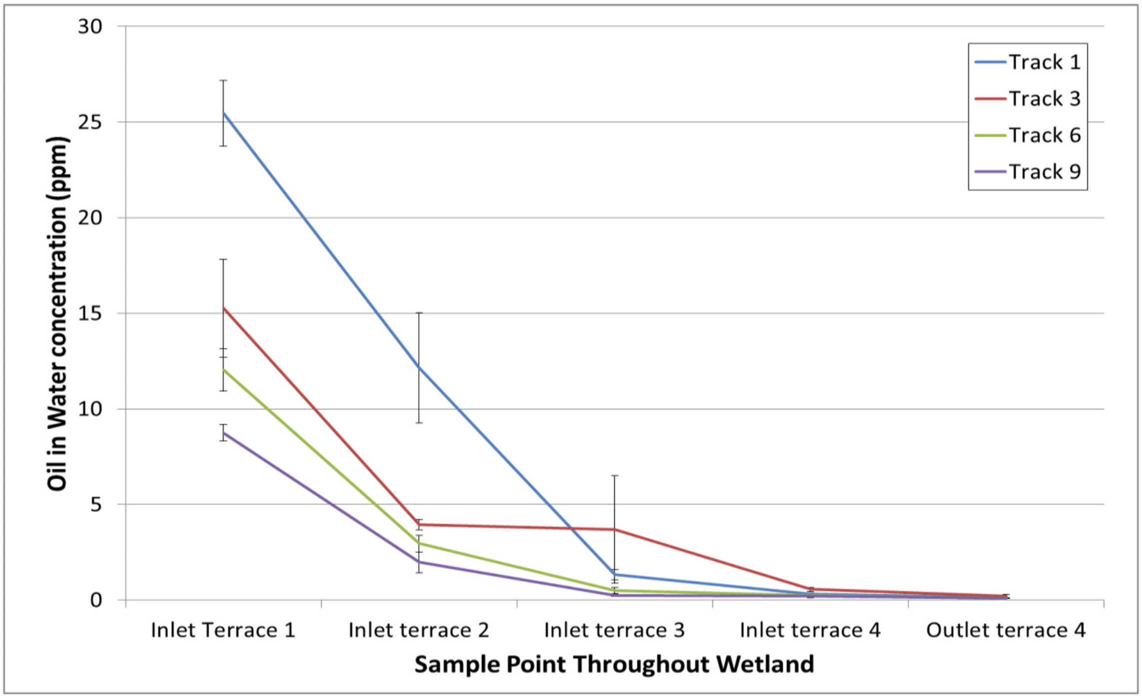

Figure 3—Average hydrocarbon concentration profile through Tacks 1, 3, 6 and 9 of the NWTP constructed wetland system for 2013 and 2014. Error bars indicate one standard error of the means.

Plate 1—Flamingos at the NWTP

species combined with areas of open water provide a good habitat for a wide range of birds. A permanent population of birds showed the first breeding time period in summer 2012. The NWTP is now well integrated and accepted by the wildlife and provide a desirable stop-over for migratory birds. There are two main seasons for migratory bird visitation each year at the site, during May and October. The shallow water depth of the NWTP attracts wading birds such as Flamingos (Plate. 1). Moreover, breeding was observed in 2013 for Black winged stilt and Kentish plover. Over 117 bird species, dragonflies, foxes, snakes and scorpions were recorded at the NWTP since the construction phase.

More than 2 million *Phragmites australis* (Common reed) were originally planted into the NWTP between 2010 and 2012. However, a caterpillar invasion (*Schoenobius gigantella*) reduced drastically the

Plate 2—An example of the diversity of plants and habitat within the NWTP wetlands.

plant vigour. It was subsequently decided to increase the biodiversity in order to decrease the susceptibility to pests and disease. Therefore, specimens of native wetland plant species were harvested locally from wadis and coastal lagoons such as *Typha domingensis, Cyperus laevigatus, Juncus rigidus*, and *Schoenoplectus litoralis*. These species were propagated in a nursery on-site and then planted in a mixed mosaic pattern throughout the NWTP wetlands. The system now resembles a diverse natural wetland ecosystem (Plate 2).

Potential treated water reuse

One of the initial objectives of NWTP was to recover salt by evaporating the treated produced water in a series of ponds. However, the lack of groundwater in arid regions, especially in Oman, has led to a shared reflexion of all stakeholders involved in the produced water treatment to develop concepts for the reuse of the treated produced water. Different options are under evaluation: (i) bio-saline agriculture for bio-fuel, wood, fibre, and other uses; (ii) algae cultivation to produce bio-fuel or animal food by-product; (iii) fluid for drilling operations; (iv) aquaculture to grow shrimps or fish; (v) creation of mangrove swamps for biodiversity and carbon sequestration values; and (vi) aquifer recharge. Utilizing Nimr oilfield treated water for irrigating bio-saline agriculture has already been described in previous trials (ICBA, 2002). Moreover, the limiting factors for plant selection are salinity and boron content of the treated production water and the adaptation to the harsh desert conditions. The treated water from the NWTP wetlands has a salinity range between 8000 to 12000 ppm and boron concentration between 4 and 9 ppm (Tudose and Headley, 2012). Research is underway at the NWTP to evaluate the growth and productivity of a range of salt-tolerant plant species with commercial potential which can withstand the high levels of salinities as well as the harsh desert climate. Expected results will create new opportunities for the existing business by introducing economically valuable crops to the system. This will lead to sustainable development and reflect positively on national economy and social sustainability through the contribution to NWTP sustainability objectives.

Conclusion

The constructed wetlands at the NWTP is a proven, energy-efficient system combining naturally-occurring physical, biological, processes to effectively treat production water at significantly less cost than conventional disposal technologies. The NWTP is designed for flexibility and ease of construction and operation. The modularized design is robust and provides redundancy, as well as incorporates hydraulic flexibility for optimal operation. Consequently, the facility has operated for four years without any unscheduled shut-downs in operation. Compared to the Deep Well Disposal, NWTP uses less than 2% of the energy consumed, including all infrastructure facilities, while opening up multiple opportunities for beneficial reuse of the treated water.

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