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The first year's operation of the Nimr Water Treatment Plant in Oman-Sustainable Produced Water Management using wetlands

R. Breuer, SPE, BAUER Umwelt GmbH; T.R. Headley and Y.I. Thaker, SPE, BAUER Nimr LLC; Badar Al Sharji, Petroleum Development of Oman LLC.

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Abstract

One of the largest industrial constructed wetland systems in the world was commissioned at the start of 2011 to sustainably manage more than 45,000 m^3/day of produced water from the Nimr oilfields in Oman. This natural treatment system consists of a passive oil-water separator, 234 hectares of surface flow wetlands and 300 hectares of evaporation ponds and has been instrumental in reducing the amount of hydrocarbon polluted produced water being disposed to the deep well aquifers. The Nimr Water Treatment Plant (Nimr WTP), being a gravity flow system uses minimal fossil fuel for its operation and therefore results in an enormous saving in energy consumption compared to the conventional, energy-intensive disposal method of pumping the water more than 1.5 km below ground into deep aquifers under high pressure. Maximizing the use of locally available and naturally occurring materials for construction, treating and reusing oil contaminated soil from the oilfields and minimizing electricity consumption has decreased the carbon footprint, greenhouse gas emissions and environmental impacts of the oilfield, thus helping to protect people and the environment. The average operational power consumption for running the NWTP measured for 2011 was only 0.06 kWh per m^3 of produced water treated, compared to 3.6 – 5.5 kWh/m^3 for the deep well disposal that has traditionally been used. This equates to an energy saving of 98.3 – 98.9 % for managing the produced water and represents a huge saving in energy costs, fossil fuel consumption and subsequent green-house gas emissions making the project not only environmentally friendly but also economically successful for the oil producer. The reduction in CO_2 emissions in 2011 was between 40,700 and 62,600 tons. The wetlands and ponds also provide a valuable habitat for migratory birds, with close to 100 different bird species having been identified at the site to date. During 2012, an extension to the wetland system (additional 120 hectares) is being constructed to increase the capacity of the plant to 95,000 m^3/day. As part of this extension, approximately 167,000 m^3 of oil contaminated soil has been biologically treated and reused as soil substrate in the wetland, providing additional environmental benefits. This paper discusses the details of the plant performance, data analysis and the challenges experienced in the first year operation of the Nimr WTP.

Introduction

Nimr oilfield, part of Petroleum Development of Oman's (PDO) concession area is located approximately 700 kms south of Muscat in the Sultanate of Oman. The Nimr WTP is located in the desert climate conditions with high daily and annual temperature variations. The temperatures in the Nimr WTP can be as high as 50°C. The region experiences plenty of sunny days and very little rainfall (around 25mm for 1 hour). The extraction of oil results in the generation of large quantities of hydrocarbon-contaminated, brackish produced water, which is expected to increase in the future. In the past, the produced water was handled by disposing it to the shallow aquifers. However due to stricter environmental regulations, shallow water disposal was slowly phased out in 2005 (Al-Masfry et.al, 2007). Therefore, Deep Well Disposal (DWD) was chosen as an alternative which resolved the management of produced water. DWDs, however, could not address following issues:

1) Loss of revenue by disposing oil along with the produced water,
2) High fossil fuel consumption and emission of greenhouse gases by the high pressure DWD pumps,
3) Operation and Maintenance of DWD facilities and equipment, and
4) Unknown environmental consequences of disposing salty produced water with hydrocarbon over period of time.

Realizing the facts listed above, PDO decided to seek a more sustainable option for managing produced water. In 2000, PDO started to build a pilot constructed wetland and developed a research and development team to evaluate and analyze the degradation of the hydrocarbons, heavy metal removal by plant uptake or soil sorption as well as potential to reuse water for agriculture in an effort to green the dessert. In 2007, PDO decided to extend this research into a commercial treatment plant and released a tender for Design Build Own and Operation of treatment process of the produced water obtained from the Nimr Oilfields. In November 2008, PDO awarded a Design Build Own and Operate contract for constructing the world's first commercial constructed wetland for produced water treatment. The construction of the Nimr Water Treatment Plant started in May 2009 and has been in operation since November 2010. From the perspective of utilizing a natural treatment process there were two major challenges associated with the produced water from the Nimr Oilfield. These were the total dissolved solid (TDS) concentration, in the range of 6000 ppm – 7000 ppm, and the oil content with an average Total Oil and Grease (TOG) concentration in the order of 400 - 500 mg/l. A typical analysis of the produced water quality from 2011 is shown in Table 1.

Table 1. Produced Water Characteristics

Parameter	Concentration	Units
Aluminum	0.07	mg/l
Barium	0.16	mg/l
Boron	4.59	mg/l
Calcium	62	mg/l
Iron	<0.01	mg/l
Lead	<0.001	mg/l
Lithium	0.11	mg/l
Magnesium	22	mg/l
Manganese	0.063	mg/l
Phosphate, Total as P	<0.01	mg/l
Phosphorous, Total as P	<0.1	mg/l
Potassium	53	mg/l
Sodium	2470	mg/l
Zinc	33.87	mg/l
Bicarbonate Alkalinity	189	mg/l
Ammoniacal Nitrogen	1.8	mg/l
Chloride	3201	mg/l
Nitrate, as N	<0.2	mg/l
Nitrogen, Total as N	<0.1	mg/l
Dissolved Organic Carbon	6.3	mg/l
Total Sulphur as SO_4	283	mg/l
Total Dissolved Solids	6200	mg/l
Total Suspended Solids	8	mg/l
Chemical Oxygen Demand	65	mg/l
Biological Oxygen Demand	38	mg/l
Total Oil and Grease	480	mg/l
Sulphide, as S	0.73	mg/l

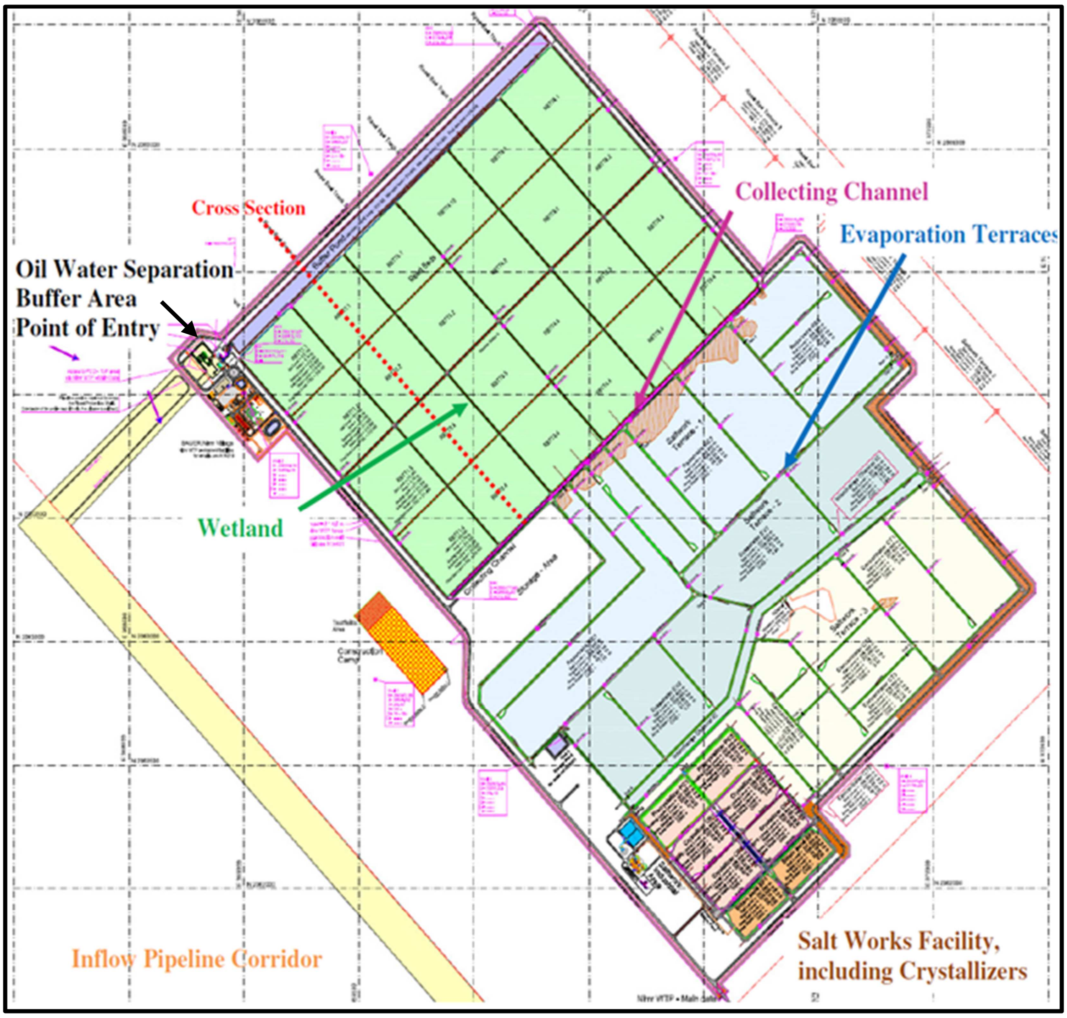
Treatment Plant Technical Details

Nimr WTP was initially designed for treating 45,000 m3/day of produced water from the Nimr oilfield. However, by the end of 2012 the total capacity of the Nimr WTP will be 95,000 m3/day. There are three main stages of the treatment plant:

- Bulk oil-water separation
- Constructed Wetlands and
- Evaporation Ponds and Salt crystallization to achieve zero effluent process

The overall layout of the treatment plant is shown in Figure 1.

Figure 1. Overall Layout of Nimr Water Treatment Plant



The produced water from PDO's central processing station comes through a pipeline to the Nimr Water Treatment Plant where the water is sent through the oil water separator in order to remove bulk oil. The produced water with residual hydrocarbon flows into the buffer pond lined with HDPE liner. The buffer pond has two days of residence time before being distributed by gravity through the 24 surface flow wetland cells (each 10 ha). The large surface area of the wetland, harsh climatic conditions, and keeping the theme of reducing the carbon footprint, a natural mineral sealing layer was used rather than HDPE liner for protecting infiltration of polluted water into the underground aquifers. This mineral sealing layer was prepared from the naturally occurring soil and materials available in the region. The 240 hectares of constructed wetlands in Nimr WTP were planted with the Common Reed (*Phragmites australis*). Over 1.2 million seedlings were propagated and planted at a spacing of one seedling per square meter. The constructed wetland serves two main functions for the management of the produced water: removal of residual hydrocarbons from the water, and volume reduction via the high evapotranspiration rate of the wetland plants. The reed stems act as a physical filter for trapping floating oil, which is subsequently biodegraded through the action of microorganisms growing on the surface of the reed stems, roots and the soil surface. Due to the high transpiration rate of the reeds, the salinity gradually increases as the produced water moves through the wetland system. The treated clean brackish water from the constructed wetland then flows into a series of evaporation ponds and a final salt crystallization step to eventually produce salt for the drilling industry.

Performance of the System during the First Year of Operation

Oil and Hydrocarbon Removal

The total oil and grease (TOG) concentration measured in the produced water entering the NWTP was quite variable in 2011, ranging from 32 to 1112 g/m^3, with an average of 282 g/m^3. The vortex oil separator system was very effective, removing on average 88% of the residual oil in the produced water (Figure 2). The average TOG concentration entering the wetland system was 5 g/m^3, which was reduced to below the detection limit of 0.5 g/m^3 after the first wetland terrace (first 25% of wetland system) on the majority of sampling events. Thus, the wetland system was highly effective at polishing the pre-treated produced water and removing and residual hydrocarbons. This opens up greater opportunities for reusing the produced water for purposes such as irrigation of salt-tolerant crops or cultivation of beneficial algae.

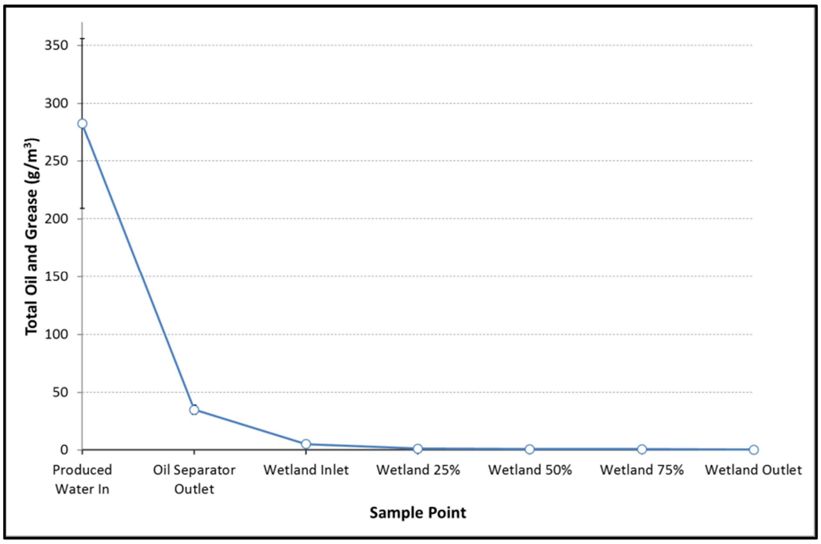


Figure 2. Mean concentration of total Oil and Grease throughout the NWTP system during 2011. Error bars represent +/- 1 standard error of the mean. *n* = 15 – 20.

TDS Concentration

The NWTP is currently operated as a zero-discharge system with the intention of producing industrial salt as an end-product. The system takes advantage of the high evapotranspiration rate of the wetland plants in the NWTP wetlands to bring about a significant reduction in the volume of produced water before subsequently flowing into the unplanted evaporation basins. As a result of the evapotranspiration (ET) rate of the reeds, the total dissolved solids (TDS) concentration increases throughout the wetlands and continues to increase in the first evaporation pond (Figure 3). As the reeds continue to grow and establish in the coming year, it is expected that the rate of water loss via ET will increase. This will also cause the typical TDS concentration in the system to increase. This increase in salinity due to wetland ET sets an upper boundary on the amount of reed-based constructed wetland that can be used in such a system, because eventually the salt concentration would become limiting for reed growth.

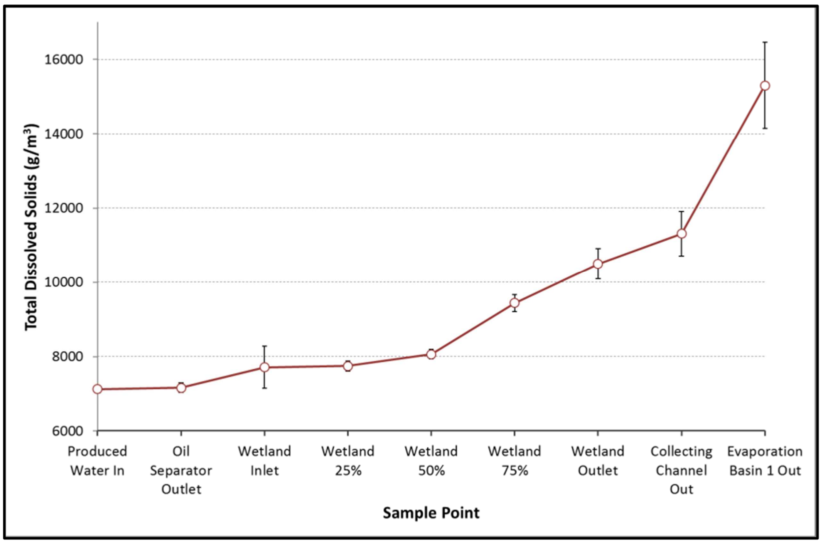


Figure 3. Mean concentration of total dissolved solids throughout the NWTP system during 2011. Error bars represent +/- 1 standard error of the mean. *n* = 15 – 20.

Water Balance

A monthly water balance was compiled for the constructed wetland system of the NWTP for the autumn-winter period of September 2011 to February 2012 (Figure 4). Prior to September 2011 there was no flow meter installed to measure the outflow from the wetlands.

Flow meters were used to measure the flow volume entering the oil-water separator and leaving the collection channel after the surface flow wetlands. Class-A evaporation pans were monitored at the site on a daily basis since October 2009, initially for purpose of design of the system. From November 2010 until June 2011 the ET rate from Class-A pans vegetated with reeds was also monitored on a daily basis. An average crop coefficient was then calculated for the *Phragmites australis* reeds under the site conditions which provides the ratio of reed ET to Class-A pan evaporation measured at the site (evaporation:ET = 1:1.1). This was then used to calculate the ET losses from the NWTP constructed wetlands, using the mean monthly evaporation rate measured from the adjacent class-A pans multiplied by the mean crop coefficient.

Figure 4 shows that approximately half of the water entering the wetlands was lost to ET during September 2011 to February 2012 (autumn – winter period). The gap between the inflow rate and the sum of wetland ET and outflow rate represents a combination of measurement inaccuracy and the small amounts of infiltration from the wetlands that is likely to be occurring due to the fact that the wetlands were lined with a specially developed mineral sealing layer rather than a completely impermeable membrane. The calculated infiltration rate during the water balance monitoring period is only 1.3 mm/day (1.5×10^{-8} m/s), which is substantially less than the rate of 5×10^{-7} m/s which was stipulated by the environmental regulation organization.

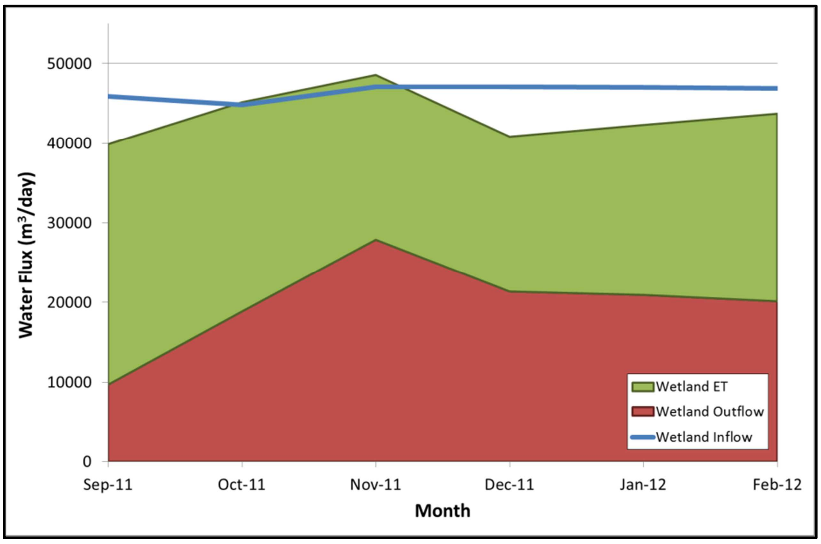


Figure 4. Monthly water balance for the NWTP wetland system.

Reed Growth and Biomass Production

Based on visual observations, the growth rate of the reeds in the constructed wetland during the first year of operation has been slower than expected compared to other constructed wetland systems. This was confirmed by measurements of the above-ground biomass standing stock in a series of 3 m^2 quadrats monitored throughout the wetlands in May 2012. The average above-ground biomass throughout the wetlands was measured as 0.62 tons/ha (dry weight), compared to 14 tons/ha measured in an adjacent pilot plant. The higher amount of biomass in the pilot plant can be partly explained by the fact that it is several years old (reeds are longer established), there is a greater edge-effect in the 100 m^2 which typically leads to higher plant productivity, the pilot bed received large amounts of sewage (nutrients) during its initial establishment period and it receives very little oil and hydrocarbons.

Nutrient limitation is most likely one of the main factors restricting reed growth in the full-scale wetland, especially in combination with the range of other stress factors (salinity, oil, extreme exposure to sun, heat and wind) that the plants are subjected to. It is also believed that some of the plants suffered excessive stress during the initial planting, as the seedlings were transported some distance from a nursery and in some cases left for a day or two without water, either prior to or following planting due to logistical limitations. Measurements of the nitrogen and phosphorus concentration in both the produced water and soil substrate have shown that their availability is extremely low. Thus, in April 2012, a fertilizing program was instigated to bolster the reed development and establishment. This has proven somewhat challenging in such a large-scale operating wetland system, since any added fertilizer is potentially flushed out of the wetland within a few days due to the flow through the system. Thus, a regime of fertilizing the parallel wetland streams one at a time and taking the given wetland off-line for one week immediately after fertilizer addition has been implemented. The planting process for the wetland extension being constructed during 2012 has also been optimized by establishing a reed nursery on-site, ensuring that seedlings receive water within a few hours of being planted and integrating fertilizer into the soil substrate at the time of planting.

Despite the slow reed growth and establishment, the constructed wetland is still effective at performing its task of removing hydrocarbons, as seen in the previous sections. In areas where the reeds are less dense, it has been observed that mats of algae and cyanobacteria proliferate, which are also likely to play an important role in supporting biological hydrocarbon degradation. A secondary impact of the slow reed establishment during the first year is that the rate of evapotranspiration reduced accordingly. However, this can easily be tolerated during the initial two years of operation of the NWTP due to the extremely large hydraulic buffering capacity provided by the 300 ha of evaporation basins which will take several years to completely fill in any case, due to their large volume.

Bird Habitat and Biodiversity

The large constructed wetland and pond system provides a valuable habitat for migratory and resident birds and other wildlife. Through routine monitoring campaigns and incidental observations, 94 different bird species have been identified to date in and around the wetlands and ponds. The site is located in the middle of the EastAsia/East Africa flyway. Such a large water body in the middle of the desert represents an important island refuge, especially for those birds migrating between Asia and Africa. It is anticipated that the number of birds using the wetlands will increase over time as the vegetation becomes more established and the earthwork activities for the construction of the adjacent extension are completed.

Energy Consumption

The amount of energy consumed during 2011 for the operation of the NWTP was calculated. This included the energy used in the following segments:

- the camp where the operations staff live (approx. 30 resident staff)
- the reverse osmosis plant supplying water to the staff
- the instrumentation, flow control and laboratory facilities of the NWTP
- operations vehicles used at the site (7 light vehicles, 1 ten ton truck, 1 back-hoe)

Most of the electricity is supplied by diesel powered generators, which are monitored routinely as part of the environmental monitoring plan for the site. Fuel receipts for the operations vehicles were examined to determine the average fuel consumption (diesel and petrol) of the vehicles during routine operations. The main energy consuming devices are air conditioning units, kitchen, vehicles and the reverse osmosis plant. It is worth highlighting that most of the power consumption of the NWTP can be considered as baseline power use for the staff and vehicles that would be consumed in an equivalent way by any produced water management facility. As shown in Table 1, The power consumed by the actual produced water treatment process is limited to a flow control system (computer, valves, flow meter), which is almost negligible (0.007 kWh/m^3).

Table 1. Operational energy consumption of the NWTP during 2011.

Energy Consuming Element	kWh/day	kwh/m3 of water treated	kWh/year
Control System, Laboratory	318	0.007	115980
Camp	1576	0.035	575240
Reverse Osmosis System	128	0.003	46769
Vehicles	677	0.015	247180
TOTAL	2699	0.060	985168

Owing to the fact that the NWTP operates via gravity and utilizes ecological treatment processes essentially driven by natural solar power (photosynthesis), the energy and fossil fuel consumption of the facility is only 0.06 kWh per cubic meter of produced water managed. This equates to a saving of 98.3 – 98.9% of the fossil energy consumption of the conventional disposal method of injecting the produced water into deep aquifers under high pressure (Table 2). By using the natural approach of the NWTP to dispose of its produced water, the oil producer (PDO) is effectively reducing their CO_2 emissions by up to 3.9 kg/m^3 of produced water treated, which equated to as much as 63,000 tons of CO_2 for 2011 based on the amount of produced water managed through the NWTP.

Table 2. Energy consumption and CO_2 emissions from the NWTP and conventional deep well disposal in 2011.

Produced water management method	Energy Consumption		CO2 equivalent[a]
	kWh/m^3	MWh/year	kg CO_2/m^3
NWTP (wetlands)	0.060	985	0.042
Deep well disposal	3.6 - 5.5[b]	56160 - 90380	2.5 - 3.9

[a] based on average of 0.7 kg CO_2/kWh for electricity in Oman (Solanki *et al.*, 2010)

[b] Breuer and Grissemann (2011).

Future Work

Owing to the success of the first year of operation of the NWTP, particularly in terms of providing a more environmentally sustainable, carbon-neutral and cost-effective solution for dealing with produced water, construction of an extension to the NWTP constructed wetland system was started in late 2011. The first phase, consisting of an additional 40 ha of surface flow wetlands came on-line in April 2012, increasing the capacity of the NWTP to approximately 65,000 m^3/day. By the end of 2012, the area of the NWTP constructed wetlands will total 350 hectares and will process 100,000 m^3/day of produced water from the Nimr oil fields.

BAUER is also actively developing techniques and expertise for reusing the produced water following wetland treatment for purposes such as:

- irrigation of bio-saline agriculture,
- creation of mangrove ecosystems for habitat creation and carbon sequestration,
- irrigation of high-value ornamental crops following reverse osmosis treatment,

Given that the oil industry worldwide generates huge volumes of produced water with moderate to high levels of hydrocarbon contamination and moderate to high salt concentrations, it is part of the vision of BAUER to continue to learn from the experiences from the operation of the NWTP and develop new and innovative sustainable solutions for managing produced water which can achieve substantial reductions in associated greenhouse gas emissions and enhance the opportunities for reusing this water for beneficial and productive purposes.

Conclusions

Experience over the first year of operation has shown that one of the main benefits of using such a natural water management system is the fact that is provides an extremely reliable and robust long-term solution for dealing with produced water, with minimal down-time or operating costs. The large, high-pressure pumps that are required for deep well disposal of produced water often means that significant time and expense can be lost during times of equipment repair and maintenance, especially if parts have to come from specialized suppliers abroad. In many oilfields, this results in substantial losses in productivity and revenue, because the ability to dispose of produced water is often a critical bottle-neck in the oil production process. Thus, the utilization of natural treatment process such as that implemented at the NWTP not only brings about multiple significant environmental benefits, but can also equate to substantial increases in oil production and savings in operating costs compared to conventional methods of land-based disposal of produced water from the oil and gas industry. Furthermore, the ability of the wetland system to remove hydrocarbons leads to greatly enhanced opportunities for reuse of the produced water for other productive and beneficial activities, such as irrigation of salt-tolerant bio-fuel crops. Nonetheless, many lessons have been learned during the construction of the NWTP and first year of operation which has brought to the surface many of the challenges associated with developing natural solutions for produced water management and highlight the importance of careful design and specialized knowledge and experience for the construction and operation of such facilities to ensure their success.

References

Al-Masfry, R, van den Hoek, P., Verbeek, P., Schaapveld, M., Baaljens, T., van Eijden, J., Al-Lamki, M., Beizen, E. (2007), Technology reaches water disposal, http://www.epmag.com/EP-Magazine/archive/Technology-reaches-water-disposal_530, July 30, 2007.

Breuer, R., and Al-Asmi, S. (2010). Nimr Water Treatment Project – Up Scaling A Reed Bed Trail To Industrial Scale Produced Water Treatment, in proceedings of: SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production. Rio de Janiero, Brazil, 12 – 14 April, 2010. Society of Petroleum Engineers.

Breuer, R., and Grissemann, E. (2011). Produced water treatment using wetlands - reducing the environmental impact of oilfield operations, In proceedings of: SPE European Health, Safety and Environmental Conference in Oil and Gas Exploration and Production, Vienna, Austria, 22–24 February 2011. Society of Petroleum Engineers.

Solanki, P.S., Mallela, V. S., Allan, M., and Zhou, C. (2010). Distributed generation to reduce carbon dioxide emissions: a case study for residential sector in Oman, *The Open Renewable Energy Journal*, 2010 (3): 26-32.