1

Integrated Produced Water Management in a Desert Oilfield Using Wetland Technology and Innovative Reuse Practices

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1.1 Introduction

The water that is produced during the exploration and production of oil and gas represents one of the largest industrial waste streams worldwide [1]. This water occurs not only during the crude oil recovery, but also during other forms of fossil energy recovery including shale gas, oil sands and coal bed methane [2]. Produced water may include water from the reservoir, natural formation water and water injected into the formation, along with any chemical substances used during the production and treatment processes. Even after the majority of the oil and gas has been extracted, produced water is typically contaminated with residual hydrocarbons. Stricter environmental policies drive the vision of environmentally friendly treatment of produced water. The North American region is the largest market for produced water treatment; more than 20 billion bbl (barrels of oil) of produced water are annually produced in the USA alone [3]. The worldwide production of produced water associated with hydrocarbon recovery exceeds 77 billion bbl per annum [4]. The Middle East market remains a key growth area due to increasing awareness and fresh water shortage.

In the oil and gas industry, produced water management represents a major challenge, since if it is not properly managed it can have an adverse impact to the environment [5, 6]. Produced water quality varies among different oil fields and wells, depending on the produced hydrocarbon type and the geological formations [2]; however, specific compounds are usually present in this water, such as oil and grease, salts (i.e., total dissolved solids, salinity) and other organic and inorganic compounds (e.g., emulsion breakers, chemical additives, solvents, heavy metals etc.). The levels of these constituents in produced water usually define the required management options to be selected. Due to the high salt content and petroleum hydrocarbons, produced water cannot be released to the environment, since it can affect the soil salinity and plant productivity [7]. As the levels of salinity increase, so does the treatment cost. Therefore, desalination of produced water is a widely applied method to improve its quality and make it appropriate for reuse options [8].

Large volumes of produced water are generated as an associated co-product of oil production in many 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

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remaining volume is typically disposed of into shallow aquifers or via Deep Well Disposal (DWD), which are environmentally undesirable and operationally energy intensive. The most common practice for produced water management is disposal either into the ocean (mainly for offshore production activities) or underground deep injection (for onshore activities) [9, 10].

However, produced water is gradually viewed as a useful by-product, while its environmental impact lead to more stringent discharge standards [11]. Various produced water handling methods have been developed such as mechanical/chemical technologies including membrane filtration technology [2, 12–14], thermal technologies [11, 15, 16], aerated filters [11, 17], flotation [11, 18, 19] and electroagulation and electrodialysis [2, 11, 15, 20, 21], among others. However, the main disadvantage of these methods is the high operational and maintenance costs due to high-energy consumption and frequent mechanical failure, which respectively affects their performance [22]. Mechanical wastewater treatment methods, such as activated sludge and sequential batch reactor, also require high-energy consumption technologies with high operating costs. Experience of implementing conventional technologies throughout remote areas in developing countries (where many oil resources are found) shows inadequate treatment due to high maintenance cost, lack of local expertise and poor governance [23].

Constructed Wetlands (CWs) are natural wastewater treatment systems and have the advantage of significantly decreasing the capital and operation costs compared to mechanical systems. Especially over the last two decades, the green technology of CWs attracted attention as a natural process for produced water treatment. CWs are well-accepted as a reliable wastewater treatment technology in Europe and North America to treat a wide range of wastewater, such as domestic and municipal wastewaters [24–27]. The realization of their high treatment capacity enabled the use of this technology for the treatment of various industrial wastewaters [28].

The petrochemical industry is one of the fields where wetland technology is rapidly developing, as this sector is looking into new approaches and technologies to improve water efficiency. Existing knowledge and experience indicates that CWs can provide an effective, cost-efficient and ecological solution for the treatment of water contaminated with petroleum hydrocarbons, additives and phenols [29], as well as for produced water [30, 31]. Wetland systems are particularly appropriate as a remediation technology for oil production fields in remote areas, where land availability is usually high. Currently there are only a few wetland systems in various facilities such as refineries, oil and gas fields and pumping stations [29, 33] and a few others in the USA [34], in Sudan [35] and in China [36].

As water scarcity is becoming more and more topical around the world, water reuse opportunities have become of great interest [37, 38]. Wastewater, either municipal or industrial, is increasingly viewed as an additional source that can be added to the water balance and provide a new source of good quality water. Industrial wastewater reuse represents a high technical challenge, considering the varying nature of the different pollutants found in industrial effluents. Among the various types, produced water from oil fields is probably the most challenging due to the toxic and inorganic pollutants present in this water and the fact that most of these water sources occur in remote and/or desert environments. Water reuse for agricultural irrigation is often viewed as a positive means towards water recycling due to the potentially large volumes of water that can be exploited in this way. Recycled water can have the advantage of being a constant and reliable water source, while it reduces the amount of fresh water extracted from the environment [39, 40]. The major concern, however, has to do with the potential impact of the quality of the recycled water, both on the irrigated crop as well as on the end users of the crops [40]. Water reuse applications are usually viewed as an environmentally friendly practice, serving the sustainable water management approach and as economically beneficial [41, 42].

Produced water reuse is a challenging task due to the variety of pollutants present in this water, e.g., high levels of salinity (i.e., total dissolved solids – TDS), oil and grease, dispersed oil, heavy metals, dissolved organic compounds and chemicals that may have been used in the production. However, irrigation with treated produced water could be an attractive and sustainable option for produced water management. This option could represent an innovative approach, especially if it is applied in regions with limited water resources that would offer added value to this water source. Treated wastewater availability for reuse purposes is highly dependent of the water balance of the system. In arid climates where rainfall is low or non-existent, ET is the most important factor in water balance and leads to a decrease of the outflow [43] and an increase of the pollutant levels and HRT [24, 44]. At the same time, the reuse of treated produced water for irrigation of beneficial plants could close the loop of resources use, and eliminate waste production. Under this frame, there is a need to identify plant species that can be irrigated with treated produced water containing a relatively high salt content.

To the best of our knowledge, the number of scientific publications in the international literature is limited for this industrial application of wetland technology. The good treatment capacity of the existing systems worldwide for produced water applications have enabled some research efforts [45–47]. One of the largest wetland systems worldwide treating produced water from an oilfield exists in Oman [30–32, 48]. Therefore, the aim of this chapter is to present this unique case study of one of the largest Constructed Wetland facilities in the world, located in Oman, designed and built for the treatment of produced water from an oilfield and also to highlight how different approaches to integrate reuse practices of the treated water will make this facility a global example of circular economy.

1.2 Constructed Wetland for Produced Water Treatment

1.2.1 Location and Description

Oil production in Oman is associated with large volumes of water (oil production water, OPW), where the ratio of water to oil can be as high as 1:10 after separation. Only 40% of the production water is utilized for the maintenance of the reservoir pressure by injection while the remainder was disposed of into shallow aquifers in the past, and now into deep aquifers. The Nimr oilfield itself is located in the southern part of Oman about 700 km away from its capital Muscat and produces an oil water ratio of 1/10. Deep wells have been used in the Nimr oilfield, where the water is disposed by booster pumps into aquifers. However, over the last three decades, both methods of disposal progressively became unacceptable for various environmental reasons. This activity demands high-energy consumption in an area with limited power supply [31]. One of the major concerns was the possibility of contaminating the exploitable groundwater resources with toxic organic and inorganic contaminants. Disposal into shallow aquifers was phased out in 2005 due to environmental issues, leaving Petroleum Development Oman (PDO) with a deep water disposal option only [31, 49]. This stipulated the prime need to re-assess disposal practices and evaluate potential methods of treatment and utilization.

PDO decided to proceed with a large-scale application of wetland technology for management of produced water in its Nimr oil field. In 2008, BAUER was awarded a Design, Build-Own, Operate and Transfer (DBOOT) contract to develop the Nimr Water Treatment Plant (NWTP) and a 32 km^2

plot was made available for the purpose of setting up the facilities as well as a pipeline to connect the oil production facilities with the water treatment plant, which was commissioned in November 2010 and will operate for at least 20 years (Figure 1.1).

The Nimr treatment facility is a hybrid system, incorporating elements of natural systems (green infrastructure) with traditional treatment technologies (grey infrastructure). The reed beds form a wetland built in a previously arid desert. This wetland is now a habitat for migratory birds, fish and other wildlife, providing a series of ecosystem services, which in combination create a system that offers the most resilience.

The NWTP is currently treating 115,000 m^3/day of produced water from a nearby oilfield using 360 ha of Surface Flow Constructed Wetland (SFCW) and 500 ha of downstream evaporation ponds (EPs). The size of this system makes it is one of the world's largest constructed wetlands. Produced water is sent through a pipeline to the Turn-Over-Point (TOP) of the plant, where separation and recovery of the majority of oil from the produced water takes place, using a series of passive hydro-cyclone oil separators. Then, the produced water is distributed in the SFCW via a long buffer pond. The 360 ha of SFCWs are divided into nine parallel tracks, each consisting of four (90 ha terraces with 10 ha wetland cells) wetland terraces in series, operating with gravity flow without any pumps (Figure 1.2). The treated water flows into a series of EPs, which are used for disposing the majority of the treated produced water, where evaporation results in salt formation, which can be processed into industrial grade salt as an end product.

A special mineral sealing layer has been developed using locally available soil material to reduce the environmental and cost impact of High Density Polyethylene (HDPE) liner. The mineral sealing layer was used in all wetland cells, while the HDPE liner is only used in the inlet buffer pond. Figure 1.3 shows the installation of the mineral sealing layer and the HDPE liner in the buffer pond and the installation of the mineral sealing layer in the wetland cells.

The Wetland system was initially planted with common reeds (*Phragmites australis*) as the only plant species. Currently, four more local plant species have already been introduced into the system, i.e., *Typha domingensis*, *Schoenoplectus littoralis*, *Juncus rigidus* and *Cyperus* spp., to enhance the biomass production and the resilience of the ecosystem, which makes this Wetland system a polyculture. These plant species are widely used in SFCWs worldwide [50]. Samples of native wetland plant species were collected throughout Oman (from wadis and coastal lagoons), propagated in the onsite nursery and then planted in the SFCW. More than 2 million plant seedlings have been planted to date. It should be noted that the SFCW is now well integrated in the local environment, accepted by the wildlife and provides a comfortable stop-over for more than 120 migratory bird species between Asia and Africa (Figure 1.4).

1.2.2 Weather Station

Weather data are recorded through a Davis Vantage Pro 2 weather station located onsite (Figure 1.5). Each weather station contains a rain collector (self-emptying tipping-bucket), temperature sensor (platinum wire thermostat), humidity sensor (film capacitor element), an anemometer (vane anemometer with wind cups) and a solar radiation sensor. An integrated sensor collects the outside weather conditions by a Vantage Pro 2 console in 30-minute intervals. The data was recorded by a USB Data Logger and thereafter readout by the DAVIS software Weather Link. The data are downloaded off the weather station at the beginning of each month. Monthly average from 2013 to 2016 air temperature, humidity, wind speed, solar radiation and rainfall are then calculated

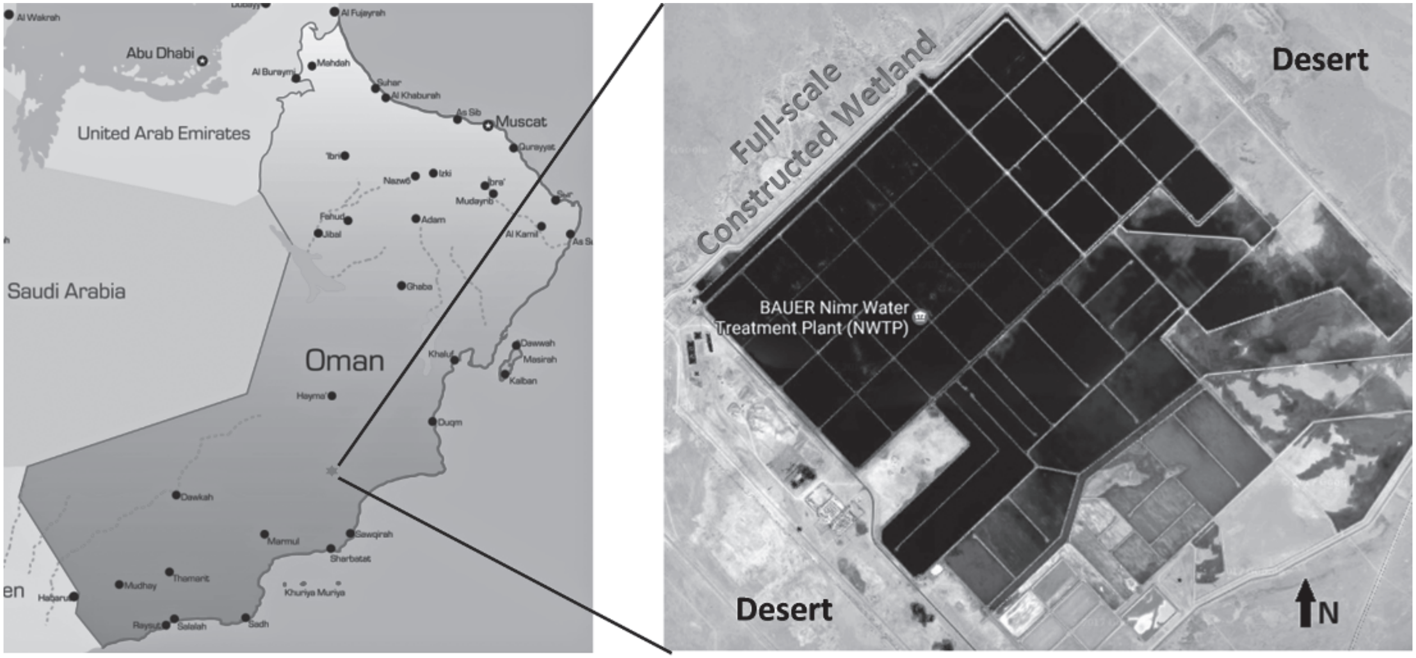

Figure 1.1 Location of the Constructed Wetland treatment plant in the desert of the south eastern Arabian peninsula in Oman (left) and aerial picture of the Constructed Wetland system and the surrounding desert (right).

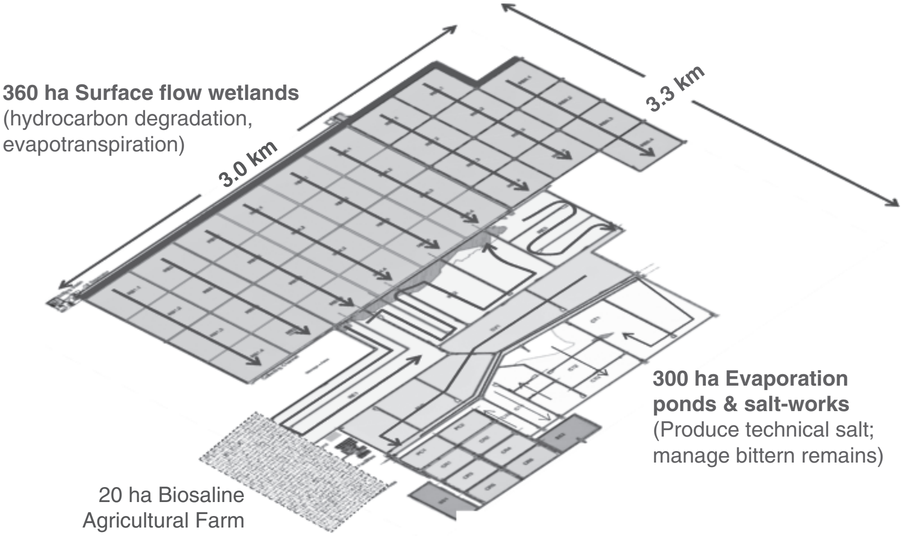

Figure 1.2 General schematic overview of the NWTP, showing each stage and all current activities in the system.

Figure 1.3 Installation of the HDPE liner in the buffer pond (left) and of the mineral sealing layer in the wetland cells (right).

1.2.3 Chemical Analyses

The Constructed Wetland facility is monitored on a quarterly basis and samples are collected at various points along the system (TOP, inlet terrace 1, inlet terrace 2, inlet terrace 3, inlet terrace 4, outlet terrace 4). Grab samples are collected in glass/polyethylene bottles of 400 mL volume to determine Oil in Water (OiW) content, physicochemical (water temperature, pH, electrical conductivity; EC, dissolved oxygen; DO, and oxidation reduction potential; ORP) and all other chemical

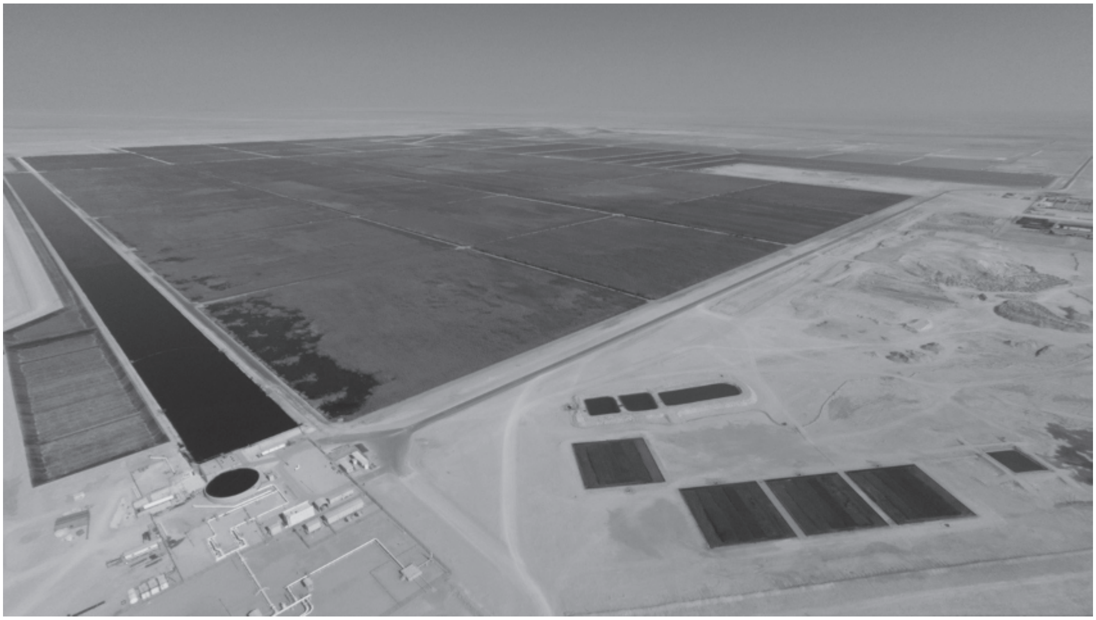

Figure 1.4 Aerial view of the inlet buffer pond and the SFCW cells. [4]

Figure 1.5 Weather station close to the SFCW cells. [5]

Table 1.1 Laboratory analyses and respective analytical method for samples taken in the NWTP during regular monitoring campaigns.

Parameter	Unit	Analytical Method
Water temperature (T)	°C	PHC10101 probe, HACH
pH	–	PHC10101 probe, HACH
Electrical Conductivity (EC)	mS/cm	CDC40101 probe, HACH
Oxidation Reduction Potential (ORP)	mV	LDO10101 probe, HACH
Dissolved Oxygen (DO)	%	LDO10101 probe, HACH
Oil in Water (OiW)	mg/L	Hexane solvent extraction, HACH
Chemical Oxygen Demand (COD), Boron (B), Total Nitrogen (TN), Nitrite (NO2-N), Nitrate (NO3-N), Total Phosphorus (TP), Chloride (Cl), Suspended Solids (SS), Total Sulfur, Sulphide (S), Calcium (Ca), Magnesium (Mg), Sodium (Na), Potassium (K), Zinc (Zn), Bromide (Br), Barium (Ba), Lithium (Li), Iron (Fe), Lead (Pb), Manganese (Mn).	mg/L	External Laboratory

parameters (chemical oxygen demand, COD; boron, B; total nitrogen, TN; nitrite, NO2-N; nitrate, NO3-N; total phosphorus, TP; total dissolved solids, TDS; and heavy metals). Portable instruments (HACH HQ30d, Germany) are used for the onsite measurement of physicochemical parameters and OiW is measured onsite using the hexane solvent extraction method (HACH). All other chemical parameters are measured in an external laboratory in Europe according to European standards. Table 1.1 summarizes the main parameters and respective analytical methods for water analyses.

1.3 Results and Discussion

1.3.1 Weather Data

Table 1.2 summarizes typical mean monthly weather data for the area of the NWTP from 2013 to 2017. As it is obvious, average air temperature increases from January to June; after that, it decreases from July to December. Lower humidity values are usually observed during warmer months (April till October). It is also noticeable that practically no rainfall takes place in the area. These values are indicative for the local desert climate.

1.3.2 Water Quality

Since its start-up and until mid-2017, the NWTP has effectively received and treated more than 150 million m^3 of produced water. At the same time, the recovered oil volume reached approximately 660,000 barrels, proving the high performance of the various treatment infrastructures.

Table 1.3 presents the typical characteristics of the inflow produced water quality at the TOP. The inlet produced water is brackish with influent TDS concentration close to 7,000 mg/L [30–32]. The

Table 1.2 Mean monthly weather data (air temperature, relative humidity, wind velocity, solar radiation and total rainfall) collected at the project location between 2013 and 2017.

Month	Air temperature (°C)	Relative humidity (%)	Wind velocity (m/s)	Solar-radiation (W/m^2)	Total rainfall (mm)
January	19.8	59.5	2.5	186.5	0.1
February	21.4	60.7	2.7	247.0	0.5
March	25.1	52.8	3.2	243.0	0.3
April	28.3	60.6	4.7	271.1	0.7
May	31.6	54.5	2.8	266.1	0.3
June	32.8	40.9	3.1	235.5	0.0
July	29.6	60.7	4.1	223.2	1.7
August	29.8	61.9	4.0	217.9	1.1
September	28.7	64.0	4.2	220.1	0.3
October	28.1	61.9	3.0	225.6	0.7
November	24.7	66.9	2.6	208.0	0.0
December	21.2	57.5	1.8	204.5	0.1

main pollutant of concern in produced water is Oil in Water (OiW). OiW concentration at the TOP is on the average close to 350 mg/L (in some cases it exceeds even 500 mg/L), while the produced water is low in nutrients concentration, i.e., total nitrogen and phosphorus concentrations are lower than 2.5 mg/L. More than 85% of the oil is recovered at the front-end of the system using passive hydrocyclones and skimmers. The residual oil hydrocarbons concentration (on average 30 ppm) is routed with gravity from the inlet buffer pond to the SFCW cells and is biologically degraded within the wetlands, producing an effluent with oil-in-water below the limit value (<0.5 mg OiW/L) [32]. Figure 1.6 shows the gradual removal of OiW along the wetland length. As it is obvious, the wetland systems provide excellent polishing of the pre-treated produced water, resulting in complete removal of OiW in the final outflow. It has been found that the rhizosphere in the wetland system is rich in hydrocarbon-degrading bacteria [48], resulting in high rates of oil removal. The reed stems act as a physical filter for trapping floating oil, which is subsequently biodegraded by microorganisms growing on the surface of the reed stems, roots and the soil surface.

Besides the removal of residual hydrocarbons from the produced water, the constructed wetland also allows for the volume reduction via the high evapotranspiration rate of the wetland plants. The current design of the NWTP is at a zero-discharge system with the intention of producing industrial salt as an end-product. The goal is to exploit the high evapotranspiration (ET) rate of the wetland plants in the wetland cells to significantly reduce the produced water volume, before its discharge into the unplanted evaporation ponds. As a result of the high ET rate in the wetland (which results on average in 40% of water loss), the TDS concentration increases along the wetland length and reaches a value of up to 12,000 mg/L at the wetland outflow [31, 32]. Despite this high level of salinity, the lack of nutrients and the general climatic conditions in the area, especially at the downstream cells of the wetland system, the wetland plant species used in the system are so far capable of surviving.

Table 1.3 Inflow produced water quality at the TOP (Turn-Over-Point).

TOP-Water Analysis (2011–2016)			
Parameter	**Unit**	**Average**	**St dev**
Total Dissolved Solids	mg/L	6810	648
Electrical Conductivity	μs/cm	13,073	1,045
pH	–	7.55	0.07
Temperature	(°C)	23.65	0.49
Chloride as Cl	mg/L	3991.0	493.3
Suspended Solids	mg/L	18.9	21.2
Oil in Water	mg/L	280	150
BOD	mg/L	15.7	14.7
COD	mg/L	121.6	93.0
Total Nitrogen as N	mg/L	2.46	1.66
Ammonia Nitrogen as N	mg/L	1.30	0.93
Nitrite as N	mg/L	0.03	0.03
Nitrate as N	mg/L	0.08	0.07
Total Phosphorus as TP	mg/L	0.03	0.03
Boron as B (Dissolved)	mg/L	4.5	1.2
Total Sulphur as SO_4 (Dissolved)	mg/L	488	773
Sulphide as S	mg/L	9.3	15.5
Calcium as Ca (Dissolved)	mg/L	96.4	31.3
Magnesium as Mg (Dissolved)	mg/L	41.1	43.0
Sodium as Na (Dissolved)	mg/L	2580	651
Potassium as K (Dissolved)	mg/L	39.7	10.9
Zinc as Zn (Total)	mg/L	1.38	6.77
Bromide as Br	mg/L	13.0	7.6
Barium as Ba (Dissolved)	mg/L	22.7	111.7
Lithium as Li (Dissolved)	mg/L	0.16	0.10
Iron as Fe (Dissolved)	mg/L	0.24	0.22
Lead as Pb (Total)	mg/L	0.00	0.00
Manganese as Mn (Total)	mg/L	0.18	0.20

BOD_5 concentration is always very low at the inflow (around <50 mg/L) and is completely removed in the outflow. COD is also removed in the system, which could be attributed to the potential release of organic matter in the wetland system (e.g., algae, plant litter, bacteria). However, it should be noted that the COD/BOD ratio in the wetland system is around 8–10, indicating that the majority of COD in the produced water is likely not readily biodegradable. Moreover, produced water is naturally low in nutrients concentration (2.5 mg/L of total nitrogen and 1.3 mg/L of ammoniacal nitrogen), which is also completely removed in the bed. Phosphorus is practically absent in the produced water (<0.5 mg/L).

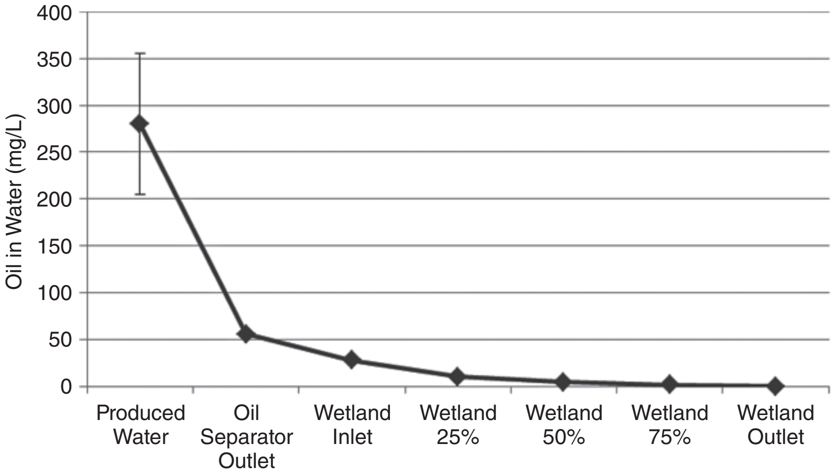

Figure 1.6 Mean OiW concentration along the different treatment stages of the NWTP.

1.3.3 Environmental Performance

Due to the operation of the NWTP, PDO has been able to shut down five of the twelve high pressure pumps that are used to dispose produced water from the oil field into deep-lying aquifers. Considering also that the NWTP is a gravity-based system with close to zero energy demand for the water treatment processes, it is estimated that the energy saved could add up to the equivalent of around 23 billion ft^3 of gas over a 10-year period.

Moreover, the Constructed Wetland is a biological system and, thus, acts as a sink for CO_2 by fixing carbon in the plant structures through photosynthesis. The estimated capacity of an annual fixture is 15,000 t CO_2 [51]. At the same time, it is known that a wetland system can produce a yield of 4–44 t/ha of dry biomass per year [52]. Considering a conservative productivity of approximately 10 t/ha for the Nimr area, the dry biomass produced at the NWTP could be estimated at 360 t/year. This translates to 1,521,000 kWh/annum heat energy content related to the reed plants [30].

Energy within the NWTP is consumed during operation for the instrumentation (flow metering), office and accommodation facilities (including water supply, air conditioning, kitchen, etc.), as well as the Oil/Water Separator and the Reverse Osmosis system [30, 31]. The gravity flow along the wetland minimizes the power requirements down to zero. Table 1.4 presents a comparison of the power requirements for the deep disposal wells, for a mechanical wastewater treatment plant and for the Constructed Wetland system for the total operational period of 20 years. Compared to the deep disposal wells, the Wetland facility uses only 1/50 of the energy consumed including all related infrastructure facilities, which is directly related to significant reduction of carbon emissions. A reduction of carbon emissions of more than 1.5 million tons CO_2, or 99% compared to the other options, can be achieved using the Constructed Wetland technology [31]. It should be mentioned that the NWTP contributes by approximately 4.26% to the Oman's overall Intended Nationally Determined Contributions to reduce emissions by 2%.

The selection of the mineral sealing layer to line the bottom of the wetland cells instead of the HDPE liner is also considered a more environmentally friendly solution. Although the transport and installation of the HDPE liner has a lower impact than the sealing layer installation, the overall balance

Table 1.4 Energy consumed and respective carbon emissions by the Constructed Wetland system and other produced water management options, i.e., deep wells and mechanical wastewater treatment methods.

Energy consumption	[kWh/m^3]	CO_2 emissions in 20-year operation
Deep Wells	up to 4.0	3,200,000 MWh 1,700,000 t CO_2
Mechanical Wastewater Treatment Plant	0.8–1.0	700,000 MWh 390,000 t CO_2
Constructed Wetland	<0.1	4,000 MWh 2,150 t CO_2

showed that lining the cell bottom using local material accounts for only 21% of the impact caused by the use of the HDPE liner, due to the higher environmental footprint of the raw materials and the production process of the HDPE [30]. Therefore, this also contributes significantly to the reduction of the environmental footprint of the whole project. Specifically, the installation of the mineral sealing layer translates to a carbon footprint of 1 million tons, while the installation of a HDPE sealing layer would have resulted in a footprint of 5 million tons.

It is also worth mentioning that the large Constructed Wetland system and the series of evaporation ponds provide a valuable habitat for migratory and resident birds and other wildlife. The routine monitoring campaigns and incidental observations so far resulted in the identification of more than 120 different bird species in and around the wetland cells and ponds. Given that the site is located in the middle of the East Asia/East Africa flyway, such a large water body in the middle of the desert apparently represents an attractive island refuge, especially for those birds migrating between Asia and Africa.

1.4 Treated Effluent Reuse for Saline Irrigation

A large-scale experimental project, co-funded by PDO, is ongoing at the NWTP (Figure 1.4) covering 22 ha, to investigate the establishment and growth of 13 different plant species irrigated with oilfield produced water treated in the adjacent Constructed Wetland system under desert field conditions (Figure 1.7). Two main irrigation areas of 11 ha each, named flood irrigation and overhead irrigation, respectively, have been constructed in this area. Each irrigation area consists of three blocks of about 3.7 ha each, receiving three different water qualities with the use of a pumping system [53, 54].

As shown in Figure 1.6, the oil content decreases as the water moves through the wetland terraces. Thus, the OiW is significantly decreased at the downstream cells of the wetland after 50% of the wetland length. However, other parameters such as boron and salinity increase along the length of the SFCW and may have a potential impact on plant growth. Thus, it was decided to apply three different water qualities, pumping produced water from three respective points along the wetland length (Figure 1.2) with low/minimum hydrocarbon concentration: water after the second terrace,

Figure 1.7 Aerial view of the agriculture research project area at NWTP.

after the third terrace and the final effluent [53]. Two general methods of irrigation are used: flood and overhead. Sprinkler, drip and bubbler systems are three different techniques used for the overhead irrigation.

Perennial and annual plant species have been selected according to the climate and water characteristics, as well as the potential commercial value of the end products. Different methods of planting were implemented according to the agronomic recommendations for each type of plant species. Planting methods used were seed sowing and transplanting. The criteria to select plant species (Table 1.5) were:

- Tolerance to brackish water (up to 12,000 ppm TDS).
- Compatible with the hot and dry desert climate.
- Tolerance to water logging due to flood irrigation.
- Plants with valuable commercial end-product, e.g., biofuel, timber or carbon credits.
- Non-invasive and with limited risk for the local biodiversity.

The project irrigation area is mostly covered with a bed rock, thus it was decided to backfill the flood irrigation area with approximately 65 cm thickness of local. The soil addition was necessary to provide substrate for plant root development. A 35 cm top soil layer of screened red soil (0-20 mm) was added above the construction material to enable the planting of the different plant species. Ridges were then created by cutting furrows with construction equipment. Local compost was placed at each marked plant station for the perennial trees at a rate of 1.5 kg per plant station. The same rate was also applied to the annual plant stations on the top of each soil pile. After the application, the compost was mixed with the soil at each plant station. Local compost was applied before planting in order to improve the soil structure and the water holding capacity of the soil as well as to release nutrients to the plants for optimum plant growth.

Table 1.5 Perennial, annual plant species and grasses investigated in the saline agriculture research project at NWTP [53, 54].

Plant species	Common name	End product	Growth form
Acacia nilotica	Acacia (Qarat)	Wood/honey wax	Perennial tree
Acacia ampliceps	Acacia	Wood/honey wax	Perennial tree
Casurina equisetifolia	Casurina	Wood/windbreak	Perennial tree
Conocarpus lancifolius	Kuwaiti tree	Wood/windbreak	Perennial tree
Eucalyptus camaldulensis	Red river gum	Wood/windbreak	Perennial tree
Prosopis cineraria	Ghaf	Wood	Perennial tree
Distichlis spicata	Distichlis grass	Forage – landscaping	Grass
Paspalum vaginatum	Salt grass	Forage – landscaping	Grass
Cotton spp.	Cotton	Textile	Annual
Brassica napus	Canola	Oil – Biofuel	Annual
Cyamopsis tetragonoloba	Guar	Guar gum	Annual
Ricinus communis	Castor	Oil – Biofuel	Annual
Salicornia bigelovii	Dwarf Saltwort	Oil - Biofuel	Annual

Table 1.6 Monitoring schedule for the different tasks during the project period [53].

Monitoring task	Frequency
Water flow rate	Daily
Water quality	Bi-weekly
Soil quality	Every year
Plant parameters	
Perennial plants	Every three months
Annual plants	Every four weeks
Leaf sampling (all plants)	Every six months
Dry weight (annual grasses)	Every three months

The project started in early 2016 and will run for three continuous years. During the operational period, regular monitoring of the water balance, water quality, soil quality and plant growth parameters and yield takes place, according to the schedule shown in Table 1.6. The project is currently in the second year of operation.

The first monitoring results indicate that flood irrigation method favors plant establishment. Perennial tree species present the highest survival rates, higher compared to those under bubbler irrigation method. Regarding all perennial tree species, the outcome is positive and the survival rates ranged between 60% and 90%, with the exception of *Acacia ampliceps*, which did not manage to survive [54].

Annual grass species established well under flood and bubbler irrigation method (establishment rates up to 99%). *Distichlis spicata* showed a lower establishment rate only under bubbler irrigation (14%). Cotton plants and *Ricinus communis* also present good establishment rates under both irrigation methods (flood and bubbler). However, the rest of the annual species, i.e., *Brassica napus*, *Cyamopsis tetragonoloba* and *Salicornia bigelovii* present a negative overall outcome under both flood and overhead irrigation methods, with low survival rates or no survival at all [54].

In general, so far 10 out of the 13 plants species have been established well in the field. Future tasks and experiments will determine the limiting factor of the germination/plant establishment (i.e., water salinity, water quality, climatic conditions). The successful implementation of this research project will provide significant information on the plant species that can survive under these specific environmental conditions (water quality, climate) and also provide a beneficial product, in order to minimize the waste production at the NWTP and close the materials cycle. Ultimately, the plant species that combine site condition tolerance with commercial value will be selected for irrigation with the total outflow volume of the Constructed Wetland system.

1.5 Conclusions

A large-scale Surface Flow Constructed Wetland (SFCW) has been designed, constructed and is currently operating by Bauer in Nimr, Oman for produced water treatment under desert climatic conditions. This facility has shown on a technical and commercial basis that the Constructed Wetland technology is a highly competitive solution for industrial applications. The highly energy-efficient and extremely reliable Natural Treatment system in Nimr provides a free-of-oil treated effluent, while it converted a previously arid desert into a massive reed-vegetated area of 360 ha where migratory birds, fish and other wildlife find habitat. Since the start-up of the Nimr wetland facility, five of the twelve deep well disposal sites have shut down, saving billions of cubic feet of gas. The technical and environmental performance of this unique facility has made it a landmark for the oil and gas sector and for the wider environmental community. Among the many international awards given to the project, has been the prestigious Global Water Award, which was presented in 2011 by former United Nations Secretary-General Kofi Annan. Ongoing research activities for the reuse of the treated effluent for saline irrigation of beneficial plants in the desert will further highlight the potential of wetland technology to be further integrated with sustainable activities, making the Nimr Water Treatment Plant a unique showcase of circular economy principles applied in practice.

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