Chapter 40

Promoting sustainability in the oil industry: The benefits of using constructed wetlands for oily wastewater treatment

Alex Stefanakis

School of Environmental Engineering, Technical University of Crete, 73100 Chania, Greece

Keywords: circular water economy, constructed wetlands, greenhouse gas emissions, industrial effluent, oil and gas industry, oily wastewater, produced water, surface flow, sustainability

40.1 CONSTRUCTED WETLANDS TECHNOLOGY

Natural processes are widely applied in wastewater treatment. Most of the established technologies and methods are based on these processes (e.g., sedimentation, filtration, biological activity), but they are usually associated with complex and energy-consuming electro-mechanical equipment (Stefanakis, 2020a). The main difference between nature-based solutions and conventional technologies is the use of only natural components and processes for the treatment. Among the various natural treatment systems, such as facultative and oxidation ponds, Constructed Wetlands (CWs) is the most promising sustainable treatment method with increasing worldwide interest. Natural wetlands have been utilized as disposal sites for secondary or tertiary wastewater effluents for thousands of years (Stefanakis *et al.*, 2014). The transition from Natural to Constructed Wetlands was based on the exploitation of naturally occurring processes under a controlled environment for beneficial human and environmental usage. Thus, man-made wetlands are designed to mimic and enhance the functions and operations of natural wetlands. Their excellent treatment performance, the environmentally friendly character, and the lower overall costs placed CWs at the forefront of the scientific and market interest. In addition, they offer the benefits of design flexibility and replicability, low and simple maintenance, low operation cost, and small environmental impact, all of which are consistent with the principles of a 'circular water economy' (Stefanakis, 2019; 2020a).

DOI: 10.2166/9781789060676_0427

40.1.1 Comparison with established treatment technologies

CWs represent one of the most attractive developments in ecological engineering. Their philosophy is based on the decentralized approach in contrast to what had been regarded as the centralized conventional biological treatment methods which dominate the wastewater market. This new approach introduces new parameters and views in wastewater treatment, such as sustainability and overall environmental impact (Stefanakis, 2019). Conventional treatment systems typically include large, end-of-the-pipe facilities and extended sewer networks, which translate to respectively high investment costs not only for their construction but also for their operation. On the other hand, CWs are generally easier to build and simple to operate, while they provide a treatment process robust to flow fluctuations and pollutant concentrations (Stefanakis, 2018). Due to the use of natural materials and processes and the minimum use of electro-mechanical equipment, CWs require only a small energy input since renewable energy sources are used by plants (solar, wind energy) for the treatment processes. At the same time, maintenance needs are low, while global experience from many countries has demonstrated that operational costs of CW facilities can be reduced by more than 90% compared to conventional plants (Stefanakis *et al.*, 2018a). This also translates to a significantly reduced carbon footprint for these facilities. However, the main limitation of CW systems is that they have a larger area demand compared to conventional technologies. Moreover, although issues with odor and/or surface ponding have been reported in the past, this is usually the result of false design and improper construction (Stefanakis *et al.*, 2014).

40.2 CASE STUDY: WETLAND TREATMENT OF OILY WASTEWATER IN OMAN

40.2.1 Wastewater in oilfields

The exploration and production of oil and gas generates a polluted water volume that represents one of the largest industrial waste streams worldwide (Aditya, 2016). This water occurs not only during crude oil recovery, but also during other forms of fossil energy recovery including shale gas, oil sands, and coal bed methane (Jain *et al.*, 2017), and 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. Large volumes of oily wastewater (also known as produced water) are generated as an oil production co-product in many countries, while its management imposes a limitation on oil production in many cases. This water stream is typically contaminated with residual hydrocarbons, salts, and various organic and inorganic compounds (e.g., emulsion breakers, chemical additives, solvents, heavy metals etc.). Due to the salt content and the hydrocarbons, oily wastewater cannot be freely discharged to the environment, since it can affect soil salinity and plant productivity and damage the human nervous system (Kim *et al.*, 2013).

40.2.1.1 Established technologies for treating oily produced water

Internationally, the most common management practice of oily wastewater is the deep well disposal (DWD) and in some cases disposal into the ocean (for offshore production activities). A smaller volume is often re-injected into reservoirs to maintain pressure for the oil wells (Arthur *et al.*, 2005). However, these practices pose a significant environmental risk, while they are operationally energy intensive. Several mechanical and chemical technologies have been tested and applied as a treatment step before the final disposal such as membrane filtration (Jain *et al.*, 2017; Munirasu *et al.*, 2016), thermal technologies (Igunnu & Chen, 2014), aerated filters (Su *et al.*, 2007), flotation (Igunnu & Chen, 2014; Saththasivam *et al.*, 2016), and electrocoagulation and electrodialysis (An *et al.*, 2017).

However, almost all these technologies are characterized by high operational and maintenance costs due to the high energy consumption, and frequent mechanical failure, which affects their performance. Mechanical treatment methods, for example, activated sludge and sequential batch reactor, are also energy intensive with high operational costs. Moreover, the implementation of such systems in remote areas in developing countries (where many oil resources are found) often results in inadequate treatment due to the high maintenance cost, lack of local expertise, and poor governance (Daee *et al.*, 2019).

40.2.1.2 Use of constructed wetlands for oily water treatment

Internationally, the technology of CWs has gained attention as a sustainable and cost-effective treatment method. CWs have the advantage of significantly decreasing the capital and, especially, operation costs compared to mechanical systems. They are well established in Europe and North America to treat a wide range of wastewater, such as domestic and municipal wastewaters (Stefanakis *et al.*, 2014, 2019; Wu *et al.*, 2014). The realization of their high treatment capacity enabled their use for the treatment of various industrial effluents (Gholipour *et al.*, 2020; Gomes *et al.*, 2018; Ramírez *et al.*, 2019; Stefanakis, 2018; Wu *et al.*, 2015).

Existing knowledge and experience indicate that CWs can provide a reliable ecological solution for the treatment of water contaminated with petroleum hydrocarbons, additives and phenols (Breuer & Grissemann, 2011; Stefanakis, 2020b; Stefanakis *et al.*, 2016). Wetland systems are particularly appropriate as a remediation technology for oil production fields in remote areas, where land availability is generally high. Currently there are only few wetland systems in various facilities such as refineries, oil and gas fields, and pumping stations (Knight *et al.*, 1999; Stefanakis *et al.*, 2016), located in the USA (Wallace *et al.*, 2011), in Sudan (Saad *et al.*, 2009) and in China (Ji *et al.*, 2007). In general, reports on CWs research and/or applications for oily produced water in the international literature are limited (Alley *et al.*, 2013). One of the largest CW systems worldwide exists in Oman for the treatment of oily produced water from a nearby oilfield (Stefanakis *et al.*, 2018a).

40.2.2 Case study

40.2.2.1 Design and construction

The Nimr oilfield is located in the southern of Oman and produces an oil water ratio of 1:10. Deep wells are used in the area for oily wastewater disposal, an activity that has a high energy demand and that poses many environmental concerns. Hence, there is always a need to reassess the disposal practices and to evaluate other potential methods for treatment and utilization. In 2008, the government oil company of Oman awarded a Design, Build-Own, Operate, and Transfer (DBOOT) contract to the company Bauer Nimr LLC to develop an oily water treatment plant (Stefanakis *et al.*, 2018a). The facility started its operation in December 2010 with a treatment capacity of 45,000 m^3/day. Nine years and three expansion phases later, the current treatment capacity has reached 175,000 m^3/day, a figure accounting for more than 65% of the total oily water generated at that oilfield (Stefanakis, 2020c).

This treatment facility consists of 490 hectares of Surface Flow Constructed Wetland (SFCW) and 780 hectares of downstream evaporation ponds (EPs) (Stefanakis, 2020c). The size of this system makes it is one of the world's largest commercial constructed wetlands (Figure 40.1). The oily wastewater is sent through a pipeline to the plant. First, separation and recovery of most of the oil content takes place in passive hydrocyclone oil separators without the use of energy or chemicals. Then, the water is distributed into

Figure 40.1 Aerial view of the Constructed Wetland facility for oily produced water treatment in Oman. (*Courtesy*: Bauer Nimr LLC)

the SFCW via a long buffer channel without the use of pumps (Stefanakis, 2020c). The water flows through the SFCW by gravity, and the treated clean water flows into the EPs, where water evaporation results in salt formation that can be processed into industrial grade salt (Stefanakis *et al.*, 2018a). The climate in the area is a typical desert climate, with average air temperature in June–July exceeding 50°C. Lower humidity values are usually observed during warmer months (April to October). It is also noticeable that practically no rainfall takes place in the area.

The SFCW beds are sealed with a bottom mineral layer made of locally available clay material in order to reduce the environmental and cost impact of High-Density Polyethylene (HDPE) liner. The HDPE liner is only used in the inlet buffer channel. The wetland beds are planted with various local reed species widely used in SFCWs worldwide such as *Phragmites australis* (common reed), *Typha domingensis*, *Schoenoplectus littoralis*, *Juncus rigidus,* and *Cyperus* spp (Stefanakis, 2020c). All plants were collected from nearby water resources and were propagated at the onsite nursery. The presence of different plant species enhances the biomass production and the resilience of the created ecosystem, which makes this wetland a polyculture (Stefanakis *et al.*, 2018a).

The inlet water is brackish with total dissolved solids concentration exceeding 7000 mg/L (Stefanakis *et al.*, 2018a). Oil in water (OiW) is the target pollutant with an average inlet concentration close to 350 mg/L (in some cases it exceeds even 500 mg/L), while the oily water is low in nutrients, that is, total nitrogen and phosphorus concentrations are lower than 4 mg/L. Each treatment element was selected to maximize the overall effectiveness of the entire system (Stefanakis *et al.*, 2018a). More than 85% of the oil is recovered at the upstream passive hydrocyclones and skimmers. The water with the residual oil hydrocarbons (up to 100 ppm) that flows with gravity to the SFCW cells is biologically degraded there, producing a treated effluent with OiW below the limit value according to the national standards (<0.5 mg OiW/L) (Stefanakis *et al.*, 2018a; 2020c).

40.2.2.2 Advantages

The CW system provides excellent polishing of the pretreated oily water, resulting in complete removal of the oil content in the final outflow. It has been found that the rhizosphere in the wetland system is rich in hydrocarbon-degrading bacteria (Abed *et al.*, 2014), resulting in high rates of oil removal. Additionally, 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.

Due to the operation of this wetland facility, many high-pressure deep well pumps that are used to dispose the oily wastewater into deep-lying aquifers in the area have been shut down. Considering that this facility is a gravity-based system, the energy demand for the treatment processes is close to zero. Energy is only consumed during the operation for the instrumentation (flow metering), office and accommodation facilities (water supply, air conditioning, kitchen, etc.), and the small onsite reverse osmosis system (Stefanakis *et al.*, 2018a). 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. The estimated reduction of carbon emissions reaches 99% compared to the other management options (Breuer & Grissemann, 2011; Stefanakis *et al.*, 2018a). It should be mentioned that it is estimated that this facility alone contributes by more than 5% to Oman's overall Intended Nationally Determined Contributions to reduce emissions by 2% (Stefanakis, 2020c).

It is also worthy to mention that the large CW and the series of evaporation ponds provide a series of ecosystem services, which in combination create a system that offers the most resilience. The whole facility is nowadays a valuable habitat for migratory and resident birds and other wildlife. The SFCW is well integrated in the local environment and accepted by the wildlife, since it provides a comfortable stopover for more than 120 migratory bird species that travel between Asia and Africa (Stefanakis *et al.*, 2018a).

40.3 BEYOND THE OILFIELD

40.3.1 Limitations and challenges

The highly energy-efficient and reliable CW system in Oman provides a free-of-oil treated effluent, while it converted a previously arid and dry desert into a massive new ecosystem and habitat. Such a solution can be adapted not only to warm and dry regions but also to colder climates. However, the space requirement limits the application range of this particular system to regions with adequate space availability, as can be found in the Middle East, in many African countries, and also in North America. It should be noted that the higher space demand is counterbalanced by the significant energy savings and the sustainable character of this nature-based solution. Additionally, as with every biology-based treatment technology, higher salinity content will not allow development and growth of the microbial ecosystem inside the wetland system and will hinder plant growth.

40.3.2 Potential for additional research

The effective and ecological treatment of oily wastewater as demonstrated in this facility in Oman indicates the wide range of additional research that is needed towards not only optimizing the process design but also to better understand and measure its environmental efficiency.

Considering the large volumes of water generated during oil exploration, the effective ecological treatment can and should be combined with further beneficial reuse of the treated effluent. Particularly under hot and arid climates, such as the desert environment, there is the potential to reuse the treated water for irrigation. This practice, however, should be further studied considering that the effluent water remains brackish. A first research study was implemented in this wetland facility in Oman, where a research irrigation field of 22 hectares was established (Stefanakis *et al.*, 2017, 2018a). Due to the relatively high salinity of the irrigation water, salt tolerant plants were tested in order to avoid the need for a costly and nonsustainable reverse osmosis step for desalination. In addition, the crops tested had a related market value, for example, as biofuel and cotton crops. Moreover, research trials should be carried out to test the use of the reed biomass produced in the wetlands for compost production and biogas generation, aiming at closing the loop of materials and waste and promote circularity in this large-scale application (Stefanakis, 2020c).

Another aspect that needs to be studied is the range of ecosystem services provided by CW systems. A first such study was implemented at this massive wetland facility in Oman on the effect of the wetland beds on the microclimate of the area (Stefanakis *et al.*, 2018b). For the first time it was revealed that the presence of the wetland beds regulated the local microclimate: a 10°C decreased temperature value was detected between the wetland body and a radius around the wetland of up to 1 km distance. This study showed the first findings clearly indicating the positive effect of the constructed wetland system on its surrounding environment. Such findings are very helpful to understand the changes in the microclimate due to the wetland's presence. Further studies are needed to determine the impact on all organisms and humans of the temperature difference between a wetland facility and the surrounding area. The reduced temperature and the increased humidity can also modify the biodiversity and affect the energy consumption needed for cooling. Moreover, determining the mean temperature differences is important to communicate to specialists in other disciplines, such as ornithology and ecology, to identify further effects on biodiversity and people living and/or working in wetland surroundings.

40.3.3 Wetland treatment as a paradigm of wastewater treatment for circular economy

Proper and sustainable wastewater management is one of the Sustainable Development Goals (SDG 6) referring to water and sanitation for all. Globally, large volumes of wastewater are still discharged into the environment without proper or with no treatment at all. A main factor for this is typically the related treatment costs and the lack of respective expertise. This is an indication that when choosing a treatment technology, cost-efficiency and simplicity should be among the main decision-making criteria along with environmental performance and reliable technical efficiency. This approach is also enriched by integrating reuse and resource recovery in wastewater management following the circularity principle. The conventional wastewater paradigm views wastewater as a 'waste', focusing only on the treatment effectiveness. Nature-based solutions such as Constructed Wetlands bring a new perspective of integrated and comprehensive wastewater management. This green technology possesses the necessary characteristics envisaged by the new concept of circular economy, that is design flexibility and replicability, low and simple maintenance, low operation cost, small environmental and carbon footprint, use of natural material and processes, among others. In addition, nature-based solutions offer a series of ecosystem services, while their design and operational flexibility allows their installation in different contexts, from the desert environment to the urban environment, as green infrastructure elements. At the same time, the options for effluent reuse, resource efficiency, and nutrient recovery integrate circular economy principles in the water sector, where every 'waste' stream is now considered as a new raw material for new products. Facilities like this large treatment wetland in Oman demonstrate in an emphatic way the technical feasibility, the sustainable character, and circularity options of nature-based solutions under diverse environments and show the way for the transition to a circular water economy.

REFERENCES

Abed R. M. M., Al-Kharusi S., Prigent S. and Headley T. (2014). Diversity, distribution and hydrocarbon biodegradation capabilities of microbial communities in oil-contaminated cyanobacterial mats from a constructed wetland. *PLoS ONE*, **9**(12), e114570.

Aditya R. (2016). Produced water treatment market by application (onshore & offshore), by treatment types (physical, chemical, membrane and others), & by geography. Global Trends & Forecast to 2019.

Alley B. L., Willis B., Rodgers J., Jr and Castle J. W. (2013). Water depths and treatment performance of pilot-scale free water surface constructed wetland treatment systems for simulated fresh oilfield produced water. *Ecological Engineering*, **61**(A), 190–199.

An C., Huang G., Yao Y. and Zhao S. (2017) Emerging usage of electrocoagulation technology for oil removal from wastewater: a review. *Science of the Total Environment*, **579**, 537–556.

Arthur J., Langhus B. and Patel C. (2005). Technical Summary of Oil & Gas Produced Water Treatment Technologies. ALL Consulting, LLC, Tulsa, Oklahoma, USA.

Breuer R. and Grissemann E. (2011). Produced water treatment using wetlands – reducing the environmental impact of oilfield operations. *Paper presented at the SPE European Health, Safety and Environmental Conference in Oil and Gas Exploration and Production*, Vienna, Austria, 22–24 February.

Daee M., Gholipour A. and Stefanakis A. I. (2019). Performance of pilot Horizontal Roughing Filter as polishing stage of waste stabilization ponds in developing regions and modelling verification. *Ecological Engineering*, **138**, 8–18.

Gholipour A., Zahabi H. and Stefanakis A. I. (2020). A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment. *Chemosphere*, **247**, 125966.

Gomes A.C., Silva L., Albuquerque A., Simões R. and Stefanakis A. I. (2018). Investigation of lab-scale horizontal subsurface flow constructed wetlands treating industrial cork boiling wastewater. *Chemosphere*, **207**, 430–439.

Igunnu E. T. and Chen G. Z. (2014). Produced water treatment technologies. *International Journal of Low-Carbon Technologies*, **9**, 157–177.

Jain P., Sharma M., Dureja P., Sarma P. M. and Lal B. (2017). Bioelectrochemical approaches for removal of sulfate, hydrocarbon and salinity from produced water. *Chemosphere*, **166**, 96–108.

Ji G. D., Sun T. H. and Ni J. R. (2007). Surface flow constructed wetland for heavy oil-produced water treatment. *Bioresource Technology*, **98**, 436–441.

Kim K. H., Jahan S. A., Kabir E. and Brown R. J. (2013). A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. *Environment International*, **60**, 71–80.

Knight R. L., Kadlec R. H. and Ohlendorf M. (1999). The use of treatment wetlands for petroleum industry effluents. *Environmental Science & Technology*, **33**(7), 973–980.

Munirasu S., Haija M. A. and Banat F. (2016). Use of membrane technology for oil field and refinery produced water treatment – a review. *Process Safety and Environmental*, **100**, 183–202.

Ramírez S., Torrealba G., Lameda-Cuicas E., Molina-Quintero L., Stefanakis A. I. and Pire-Sierra M. C. (2019). Investigation of pilot-scale Constructed Wetlands treating simulated pre-treated tannery wastewater under tropical climate. *Chemosphere*, **234**, 496–504.

Saad A. S. G., Khadam M. A. and Agab M. A. (2009). Biological method for treatment of petroleum water oil content in Sudan. University of Khartoum. Available at http://research.uofk.edu/multisites/UofK_research/images/ stories/research/PDF/BESBC/biological%20treatment.pdf.

Stefanakis A. I., Khadam M. A and Agab M. A. (2009). Biological method for treatment of petroleum water oil content in Sudan. University of Khartoum. Available at http://research.uofk.edu/multisites/UofK_research/images/ stories/research/PDF/BESBC/biological%20treatment.pdf.

Saththasivam J., Loganathan K. and Sarp S. (2016). An overview of oil–water separation using gas flotation systems. *Chemosphere*, **144**, 671–680.

Stefanakis A. I. (2018). Constructed Wetlands for Industrial Wastewater Treatment. John Wiley & Sons Ltd, Chichester, UK.

Stefanakis A. I. (2019). The role of constructed wetlands as green infrastructure for sustainable urban water management. *Sustainability*, **11**(24), 6981. https://doi.org/10.3390/su11246981

Stefanakis A. I. (2020a) Constructed Wetlands: description and benefits of an eco-tech water treatment system. Waste Management: Concepts, Methodologies, Tools, and Applications, IGI Global, pp. 503–525. doi: 10.4018/978-1-7998-1210-4.ch025

Stefanakis A. I. (2020b) The Fate of MTBE and BTEX in Constructed Wetlands. *Applied Science*, **10**, 127. doi: 10.3390/app10010127

Stefanakis A. I. (2020c). Constructed Wetlands for Sustainable Wastewater Treatment in Hot and Arid Climates: Opportunities, Challenges and Case Studies in the Middle East. *Water*, **12**(6), 1665. https://doi.org/10.3390/w12061665

Stefanakis A. I., Akratos C. S. and Tsihrintzis V. A. (2014). Vertical Flow Constructed Wetlands: Eco-Engineering Systems for Wastewater and Sludge Treatment. Elsevier Publishing, Amsterdam.

Stefanakis A. I., Seeger E., Dorer C., Sinke A. and Thullner M. (2016). Performance of pilot-scale horizontal subsurface flow constructed wetlands treating groundwater contaminated with phenols and petroleum derivatives. *Ecological Engineering*, **95**, 514–526.

Stefanakis A. I., Al-Hadrami A. and Prigent S. (2017). Reuse of oilfield produced water treated in a Constructed Wetland for saline irrigation under desert climate. 7th International Symposium on Wetland Pollutant Dynamics and Control – WETPOL, August 21–25, 2017, Montana, USA.

Stefanakis A. I., Prigent S. and Breuer R. (2018a). Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In: Constructed Wetlands for Industrial Wastewater Treatment, A. I. Stefanakis (ed.), John Wiley & Sons Ltd, Chichester, UK, pp. 25–42.

Stefanakis A. I., Charalampopoulos I., Psomiadis E. and Prigent S. (2018b). The thermal regime of a large Constructed Wetland in the desert environment. 16th IWA International Conference on Wetland Systems for Water Pollution Control, September 30–October 10, Valencia, Spain.

Stefanakis A. I., Bardiau M., Silva D. and Taylor H. (2019). Presence of bacteria and bacteriophages in full-scale trickling filters and an aerated constructed wetland. *Science of the Total Environment*, **659**, 1135–1145.

Su D., Wang J., Liu K. and Zhou D. (2007). Kinetic performance of oil-field produced water treatment by biological aerated filter. *Chinese Journal of Engineering*, **15**(4), 591–594.

Wallace S., Schmidt M. and Larson E. (2011). Long-term hydrocarbon removal using treatment wetlands. SPE Annual Technical Conference and Exhibition, 30 October–2 November, Denver, Colorado, USA.

Wu S., Kuschk P., Brix H., Vymazal J. and Dong R. (2014). Development of constructed wetlands in performance intensifications for wastewater treatment: a nitrogen and organic matter targeted review. *Water Research*, **57**, 40–55.

Wu S., Wallace S., Brix H., Kuschk P., Kirui W. K., Masi F. and Dong R. (2015). Treatment of industrial effluents in constructed wetlands: challenges, operational strategies and overall performance. *Environmental Pollution*, **201**, 107–120.