SPE 126265

Nimr Water Treatment Project – Up Scaling A Reed Bed Trail To Industrial Scale Produced Water Treatment

Roman Breuer, SPE, BAUER Nimr LLC; Said Rashid Al-Asmi, Petroleum Development Oman LLC

This paper was prepared for presentation at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production held in Rio de Janeiro, Brazil, 12–14 April 2010.

Abstract

The Nimr Water Treatment Project is to develop and set up an effective water treatment plant for the residual waters produced from the Petroleum Development Oman (PDO) oil wells in its Nimr Oil Field with a capacity to process a minimum of 45,000 m³/day produced water.

PDO initially established a pilot project 10 years ago in the Nimr Oilfied in the Sultanate of Oman; see Figure 1 Map of Omani Oilfields – The Nimr Cluster. The technology used was based on a constructed wetland followed by an evaporation pond to remove the produced water contaminants and reduce the effluent. Using the experience of the pilot a Design, Build, Own, Operate and Transfer (DBOOT) tender process was started to upscale the pilot from a capacity of 1,000 m³/d to 45,000 m³/d in 2007. The project was awarded late in 2008 and based on PDO and the contractor's experience one of the biggest commercial constructed wetlands is build for water treatment.

Main technology changes were made based on pilot test results, an extended study of the water characteristics and climate data. The result is the construction of an approximately 600 ha large facility comprising of an Oil/Water Separator to recover remaining crude oil, a surface flow Constructed Wetland and finally an engineered salt works facility to include the option for salt recovery. Additionally, potential benefits of biomass utilisation and carbon credit values are investigated to be potentially included into the project after commissioning. Construction works have commenced in May 2009 and water is bound to flow in January 2011.

Introduction

In Oman PDO generates about 800,000 m³/d produced water in their oilfields all over the country. The Nimr oilfield itself has a daily waste water output of more than 240,000 m³, which is likely to increase to more than 270,000 m³ by the end of 2009 (PDO 2007) . The water treatment project is bound to set up a facility with a capacity of 45,000 m^3/day produced water by means of Oil/Water Separation, a Constructed Wetland and finally Evaporation Ponds to initially treat 1/5 of the daily water output.

The main means of produced water disposal in the Nimr Oilfield have been deep wells where the water is disposed by booster pumps into the Deep Water Disposal (DWD) wells. Shallow water disposal was phased out in 2005 due to environmental issues (Al-Masfry et al.) leaving PDO with the deep water disposal option only. The main disadvantage of this technology is the high energy consumption in an environment with limited power supply which is dedicated for oil production rather than disposal of waste water

On average, per barrel oil produced in the world about nine barrels produced water will be pumped to the surface. This water has to be handled, treated and disposed off. Worldwide a daily crude oil production of 87 Million barrels per day was recorded (in 2005 (Khatib et al. 2003)). The Nimr oilfield produces between 120,000 to 140,000 barrels of oil per day which translates to an oil water ratio of 1/10.

For example the United States of America produced 2.9 Billion m^3/a (18 billion barrels, bbl) of produced water in 1995 onshore and operated about 600,000 oil production locations. Worldwide a discharge of 33.4 Million m^3/d respectively 12.2 Billion m^3/a (1999) produced water was recorded (Veil et al. 2004).

A trail project by PDO in the Nimr Oilfield (Al-Lamki et al.; Al-Mahruki et al. 2006; Denney 2006; ICBA 2002; Jackson et al. 2003; Schrevel et al. 2004; Sluiterman et al. 2004) focusing on contaminants removal and feasibility, pilot projects in the USA (Khatib et al. 2003; Myers et al. 2006; Nijhawan et al. 2006) and one research programme in Sudan (Gill et al. 2006) have shown that Constructed Wetlands are capable of treating produced water at low costs compared to other options and in a sustainable approach.

PDO Project Strategy

PDO is the premier hydrocarbon Exploration & Production Company in the Sultanate of Oman. PDO has been actively experimenting with environmentally sound alternatives such as Reed Bed technology where production water could become an asset rather than a liability.

In 2000, PDO started to build a pilot constructed wetland and integrated a comprehensive research program to evaluate hydrocarbon degradation, heavy metal removal by plant uptake and soil sorption as well as potential use of the treated water for agriculture. The so called “Greening the Desert Study” (Schrevel et al. 2004) was the kick-off for the research development which led to a final Design, Build, Own and Operate (DBOO) tender process (PDO 2007).

The main criteria and the fundamental idea for the whole tender was to open the project to a wide range of technologies and international companies to implement the best technical option combined with the most economical solution.

Tender announcement took place in July 2007 with the aim to award the project by April 2008. The tender was released with specific contract conditions and basic technical information such as climate conditions, water quality and treatment goals. No technical specifications were given for the technology to be used. The wide range of bidders had to undergo a comprehensive pre-qualification process including an outline of the technologies to be used. Subsequent to the pre-qualification, the technical proposals had to be specified in detail and approved by the local authorities as well as the client, thus reducing the number of applicants. PDO’s technical and commercial team was leading the process using tools like written clarification and clarification meetings to evaluate the bidder’s capabilities and technical proposal. Due to limited local knowledge of the bidders and the interactive approach by PDO the initial time schedule could not be fulfilled as shown in Table 1. This was caused mainly by the fact that for the evaluation of various technologies the technical clarification process lasted longer and additional information had to be obtained by the client as well as by the bidders to reach a sufficient information level.

Proposed technologies varied from Constructed Wetland technology to drinking water production by means of desalination.

The remaining "pre-qualified" bidders of the technical tender stage were invited to submit a commercial bid based on a cubic meter-fee to recover investment and operation costs for the given operational period of 20 years. The construction period of the facility was contractually limited by PDO to a maximum of two years. The cubic meter-fee had to be split into a fixed base rate and a variable rate comprising the operational cost, which are subject to fluctuations on the economic markets. Both fees together determine the final fee to be paid.

Table 1: Summary of Tender Process

Tender Process Steps	Scheduled Date	Final Date
Announcement		July 2007
Pre-qualification	October 2007	October 2007
Technical Tender	December 2007	February 2008
Commercial Tender	February 2008	September 2008
Award		November 2008

After the commercial bid the submission evaluation was carried out and results were presented to the tender board without the influence of the technical qualifications. As a result of the process all bidders offering a solution based on constructed wetland had quoted a significantly lower price than bidders offering technically higher sophisticated solutions.

The project was finally awarded in November 2008 to a German/Omani bidder consortium lead by the German environmental specialist company BAUER Resources GmbH. Subsequently BAUER has established a local company in charge of the final design, procurement and construction of the plant and later to operate the Nimr Water Treatment Facility.

Scope and Technical Background

PDO defined the scope of their tender for the setting up of Nimr Water Treatment Plant to have a processing capacity of 45,000 m^3/day of effluent water produced. The contractor is responsible for treating and reuse of the treated water for a period of 20 years. A 32 km^2 plot was made available by PDO for the purpose of setting up the facilities.

The plant will be installed under desert climate conditions with high daily and annual temperature variations see Table 2.

Table 2: Climate Conditions Nimr Oilfield

Item	Minimum	Maximum
Shade temperature	5°C	60°C
Daily variation in temperature		25°C
Hourly wind speed, average	15 m/s	
Relative humidity	30%	98%
Rain fall	0 mm	25 mm for 1 hour
Solar radiation	120 mW/cm^2	
Prevailing wind direction	Mar-Apr:NW; May-Jun:SW; Rest:SE	

Furthermore the produced water characteristics typically show high dissolved solid content as well as high Sodium and Chloride concentrations and some very specific elements like Boron and Strontium, see Table 3.

Table 3: Produced Water Data, Nimr Oilfield

Parameter		**Concentration**	
Conductivity @ 21 °C		11.18	ms/cm
pH @ 20 °C		7.9	
Aluminium	Al	2.2	mg/L
Boron	B	4.1	mg/L
Calcium	Ca	86	mg/L
Magnesium	Mg	31	mg/L
Manganese	Mn	0.19	mg/L
Potassium	K	29	mg/L
Silicon	Si	10	mg/L
Sodium	Na	2450	mg/L
Strontium	Sr	4.3	mg/L
Sulphur	S	99	mg/L
Chloride	Cl^-	3058	mg/L
Sulphate	SO_4^{2-}	260	mg/L
Bicarbonate	HCO_3^-	488	mg/L
Total Dissolved Solids(TDS)		6980	mg/L
Total Suspended Solids(TSS)		20	mg/L
Oil in Water		150	ppm

On average, the remaining oil concentration is at 150 ppm but can be as high as 1,000 ppm at peak times. The proposed technical solutions had to cope with all these circumstances and provide a comprehensive solution.

The BAUER Reed Bed Concept was finally not only designed for treatment purposes but also to consider and address the higher salt content and to utilise the water to grow biomass as a secondary benefit, which became a decisive factor in the final tender process. Additionally, the before mentioned salt content provides an opportunity to create benefits by recovering the Sodium Chloride content as a source for industrial salt.

Technical Outline of the Project

The concept developed by BAUER during the technical evaluation phase of the tender is based on well approved technical features utilised for many years like Reed Bed Technology and Oil/Water Separation. The core of the system is an advanced and innovative, technically upgraded Reed Bed treatment system based on the experience of an existing pilot plant at Nimr and experience from Reed Bed systems designed and build by BAUER in Germany, Europe and the Middle East, see Figure 2 Nimr Water Treatment Plant – Design Overview.

To improve the treatment process BAUER has thoroughly evaluated the disadvantages of the existing pilot system. The major deficiencies have been eliminated and the system has been designed with focus on minimising operational costs. Therefore emphasis was put on gravity flow allowing the system to operate with a minimum external power requirement using the local topography, see Figure 3 Nimr Water Treatment Plant – Reed Bed Cross Section. Special mineral sealing layers have been developed using locally available soil material to reduce the environmental and cost impact by HDPE liner.

Two additional technical features have been added to the proposed system compared to the pilot system:

a) An Oil/Water Separation unit which additionally serves as buffer capacity in case of incoming oil peaks from the client's production facility or higher inflow rates;

b) Engineered salt evaporation ponds to reduce outflow water volumes to zero, to minimise waste disposal, and to be able to set up salt crystallisers to produce technical grade Sodium Chloride.

Therefore, the system consists of the following technical units: Operation Building – Oil/Water Separation – Reed Bed Tracks – Evaporation/Salt Fields.

The operation of the system leads to a final mass balance producing zero effluent water, approximately 100,000 t of Sodium Chloride per year and 16,000 t (equal to 7,600 m^3) of salt residues per year. The utilisation of the residuals is currently under investigation. Technical grade salt can be used locally for various applications, e.g. as a drilling salt or in the chemical industry.

The Reed Bed will produce approximately 40 t of dry biomass per hectare and year due to the natural growth of the used Phragmites australis plant. This translates to an average production of more than 9,600 t dry biomass per year for the Reed Bed area of 2.34 Mio m^2 (234 ha).

The system is simple but innovative as it combines well approved technologies in an innovative way and will therefore be unique of its kind and size in the world.

Competencies carried out by BAUER are:

- Complete planning for an environmental sound and cost efficient water treatment system, preferably with the complete reuse of the treated water within the vicinity of the plant ;
- Complete financing, construction and installation of the treatment plant and reuse of the treated water;
- Complete operation and maintenance for the plant and for all facilities for the reuse of the water.

Additional Values of the Project

Oil Recovery

Potentially an average of about 40 barrels of oil can be recovered per day. This translates to more than 14,600 barrels per year worth 730,000 US $ at a price of 50 $ per barrel. All recovered crude oil will be returned at a specified quality to the client PDO allowing the oil producer to recover approximately 0.04 US $/m³ of the paid water treatment fee.

Biomass Production

Reed Beds can achieve a high yield of 4 to 44 t/ha of dry biomass per year (Timmermann et al 2003), see Table 4. For the location at Nimr, a productivity above 40 t/ha was estimated which will produce a calculated quantity of 9,360 t/a dry biomass. As Reed has a caloric value of 4.2 kWh/kg dry mass this translates to 39,312,000 kWh/a heat energy content which can be related to Reed plants. The heat energy would be sufficient for fuelling a 4.5 MW per hour power plant. As biomass is not directly convertible into electrical energy and a poor efficiency of 20 % to maximum 30 % must be considered to determine the economic value.

Table 4: Productivity of Reed and Wetlands (Timmermann 2003)

Species	Productivity
	t ha−1 a−1
Common Reed (*Phragmites australis*)	3.6 - 43.5
Cattail (*Typha latifolia*)	4.8 - 22.1
Reed Canary Grass (*Phalaris arundinacea*)	3.5 – 22.5
Sweet Reed grass (*Glyceria maxima*)	4.0 - 14.9

Salt Production

An available quantity of approximately 100,000 tons per year was calculated for a proposed salt production facility. The salt is an essential content of the delivered produced water and shall be considered as an asset in the future of the project. At the current stage of the project, salt specifications are being verified in laboratory experiments as well as field experiments. The salt will be analysed in the laboratory to estimate the raw salt qualities and further evaluate potential later use. Preliminary results already indicate that a salt quality sufficient for technical applications can be achieved.

Carbon Credits – Energy Balance

With the Sultanate of Oman as a signatory of the Kyoto Protocol, the proposed treatment system would qualify under the Clean Development Mechanism (CDM) program of the United Nations to generate saleable CER's (Certified Emission Reductions), commonly known as Carbon Credits. However, this process will be proposed in the future once the plant is in operation.

Moreover, the interest at the tender stage for PDO was focused on cost and power reductions to reduce the load for the current facilities and avoid requirements for new facilities. Calculations of PDO concerning the power consumption and cost impact of their current operations (DWD) would have resulted in the construction of two 3 to 5 MW sub-power stations. Calculations for the consumption of the Reed Bed facility compared to the Deep Water Disposal Wells allow PDO to lay off these requirements.
Further to the power facilities a maximum budget for a DBOO facility to be operated by a contractor was determined by PDO and a maximum budget to be met by the bidders was set.
Table 5 compares the power requirements per m³ produced water to be disposed off for deep water disposal wells, as an example a common waste water treatment plant based on state of the art technology, and the chosen Reed Bed option. The figures clearly show that the Reed Bed has an overall advantage considering the power consumption and with a calculated value of 0.1 kWh/m³ is by far the best solution. Overall, the project will reduce the potential carbon emissions for produced water disposal in the Nimr oilfield within the next 20 years by more than 300,000 t CO_2. This figure becomes even more important if one determines the potential in the Nimr oilfield with more than 240,000 m³/d water.
It has also been calculated that the yearly production of dry biomass due to Reed growth will be approx. 9,500 t, which equals to 40,000,000 kWh carbon neutral energy potential.

Table 5: Compared Power Consumption for Disposal Options

Disposal Options	**Power required (Operation)**	**Total Power Used in 20 years**	**CO_2 Emissions in 20 years**
	kWh/m³	MWh	Tons
Deep Well Disposal	3.6 - 5.5	1,180,000 - 1,800,000	220,000 - 330,000
Waste Water Treatment Plant	0.8	~ 255,000	47,000
Reed Bed	0.1	~ 32,850	6,100

Conclusions and Forecast

The project approach by PDO has shown on a commercial basis that the Reed Bed / Constructed Wetland technology is a highly competitive solution when it comes to disposal of produced water under desert climate conditions.

Furthermore, the project setup as a DBOOT tender does relieve the client of risk related to commercial and technical responsibilities which have to be taken over by the bidder.

Especially the idea of creating additional value show the potential to generate further benefits for the client as well as for the bidder out of a former waste product. So far a number of potential benefits have been identified, such as:

- Oil recovery from the produced water, which may add up to a value of 730,000 US $/a;
- 10,000 t/a biomass equal to 40,000,000 kWh energy to be utilised for energy production or other purposes ;
- Salt production retained from the elevated salt content of the produced water generating up to 100,000 t/a Sodium Chloride;
- Energy savings by using a gravity flow system of up to 1,800,000 MWh during the whole project period compared to the current disposal mechanisms;
- CO_2 emission reduction to be potentially more than 300,000 t and additional carbon fixture in biomass.

Further options to add value have been already proposed and are under evaluation. Therefore in the progress of the project the number of benefits is most likely to increase further and both parties do work closely together to guarantee the success of the project.

Literature

(1) Al-Lamki M., Sluijterman A., Al-Asmi S.: Water Management in PDO. An experiment to re-cycle water using Reed Beds and Saline Agriculture.

(2) Al-Mahruki A., Alloway B., Patzelt H. (2006): SPE 98548-PP The Use of Reed bed Technology for Treating Oil Production Waters in the Sultanate of Oman, Society of Petroleum Engineers Inc. (Abu Dabhi).

(3) Al-Masfry, R., van den Hoek, P., Verbeek, P., Schaapveld, M., Baaljens, T., van Eijden, J., Al-Lamki, M., Biezen, E.: Technology reaches water disposal, Water Management.

(4) Denney, D., (2006): Reed-Bed Technology for Treating Oil-Production Water in the Sultanate of Oman, JPT, S. 47 – 48.

(5) Gill, Dr. Lucian, et al, (2006): 20th IPMA World Congress on Project Management, Shanghai, Paper No. 265.

(6) ICBA - International Center for Biosaline Agriculture, (2002): Evaluation of Reed Beds, Dubai.

(7) Jackson L. M., Myers J. E. (2003): SPE 84587 Design and Construction of Pilots Wetlands for Produced-Water Treatment, Society of Petroleum Engineers Inc. (Denver).

(8) Khatib, Z., and P. Verbeek, (2003), "Water to Value – Produced Water Management for Sustainable Field Development of Mature and Green Fields," Journal of PetroleumTechnology, Jan., pp. 26-28.

(9) Myers J.E., Nijhawan N. (2006): SPE 94329 Constructed Treatment Wetland Plant Monitoring Parameters, Society of Petroleum Engineers Inc. (Texas).

(10) Nijhawan N., Myers J.E. (2006): SPE 98567 Constructed Treatment Wetlands for the Treatment and Reuse of Produced Water in Dry Climates, Society of Petroleum Engineers Inc. (Abu Dhabi).

(11) Petroleum Development Oman (PDO, 2007), Nimr Water Treatment Tender Document, C310631.

(12) PDO, Description of "Nimr Reed Bed Project.

(13) Schrevel, A., Hellegers P.J.G.J., Soppe R.W.O. (2004), Potential for up-scaling Nimr reed bed facilities, Oman, Alterra-ILRI and LEI, Wageningen, Den Haag.

(14) Sluiterman, A.C., Al-Lawati, Y., Al-Asmi, S., Verbeek, P.H.J., Schaapveld, M.A.S., Cramwinckel, J. (2004): SPE 88667, Opportunities for re-use of produced water around desert oil fields, Society of Petroleum Engineers Inc., Abu Dhabi.

(15) Timmermann, T. (2003): Nutzungsmöglichkeiten der Röhrichte und Riede nährstoffreicher Moore Mecklenburg-Vorpommerns. Greifswalder Geographische Arbeiten 31, p.31 - 42.

(16) Veil, John A., Puder, Markus G., Elcock Deborah, Redweik Jr, Robert J. (2004): White Paper Describing Produced Water from Production of Crude Oil, Natural Gas and Coal Bed Methane Argonne National Laboratory, US Department of Energy, National Energy Technology Laboratory.

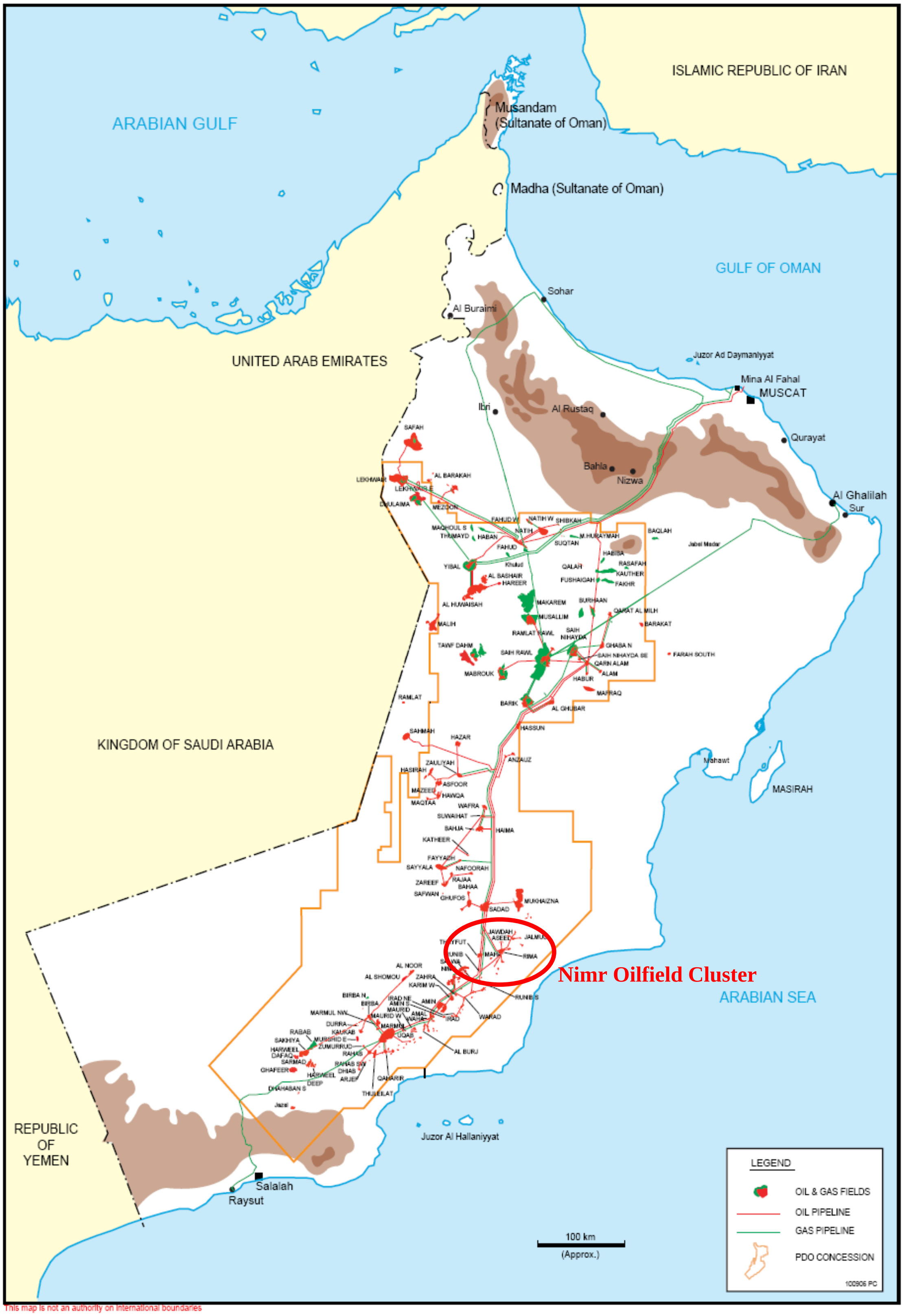

Figure 1: Map of Omani Oilfields – The Nimr Cluster

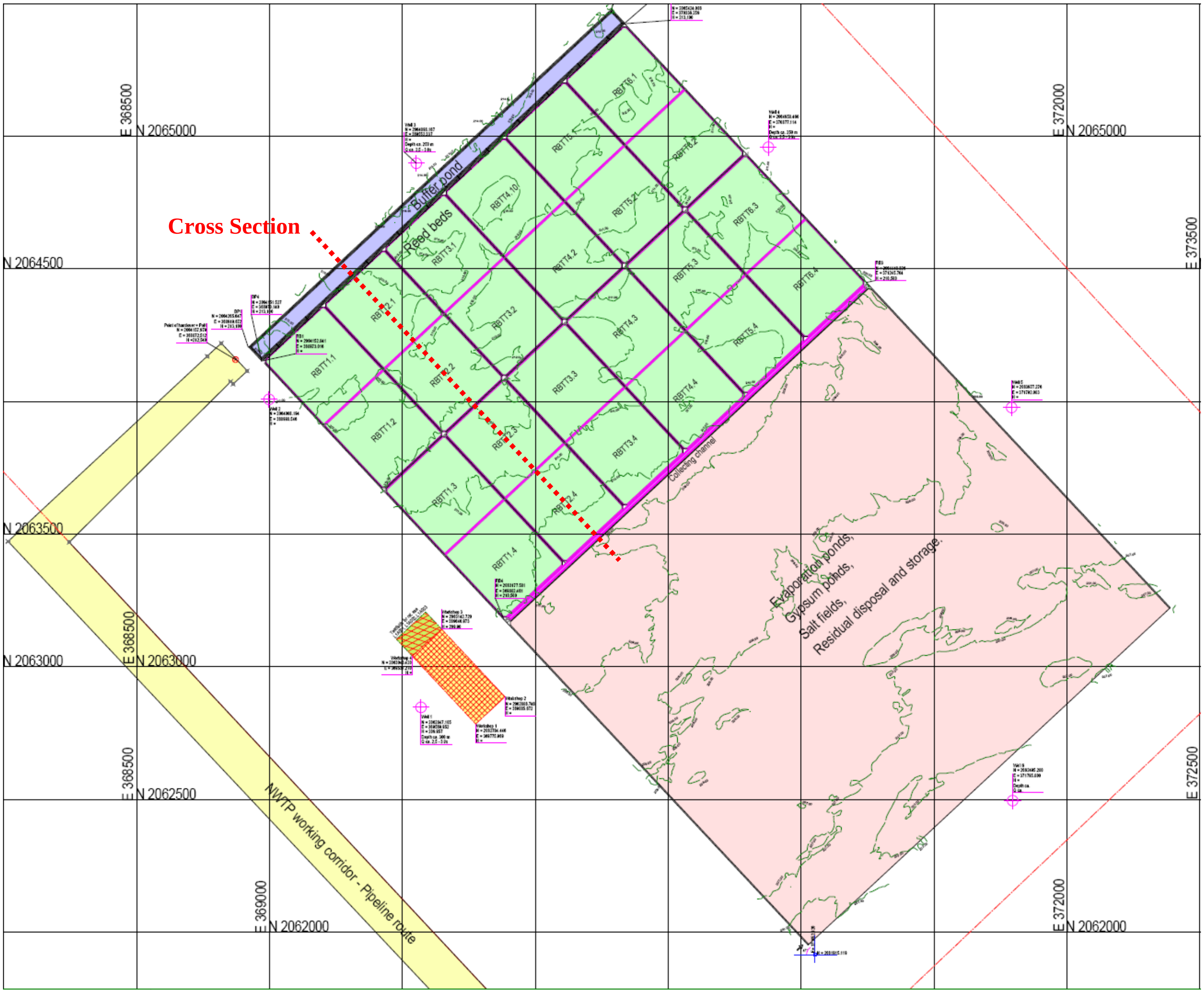

Figure 2: Nimr Water Treatment Plant – Design Overview

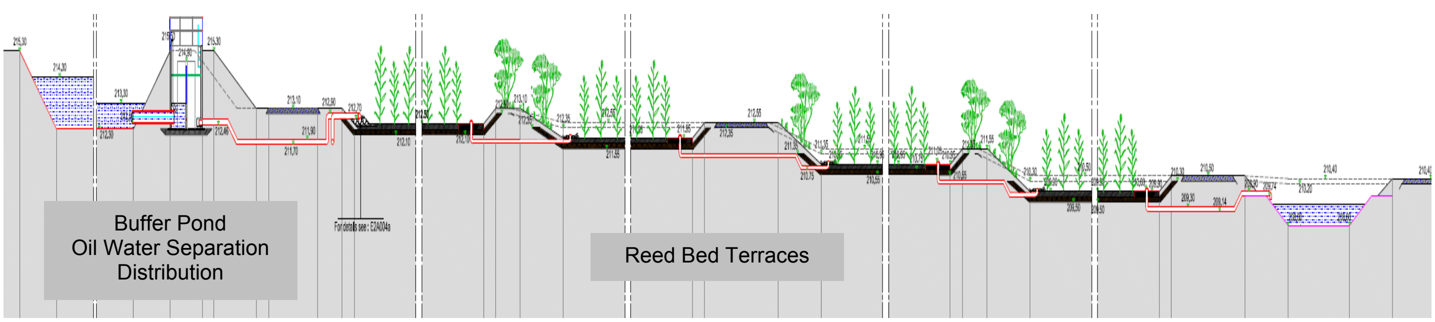

Figure 3: Nimr Water Treatment Plant – Reed Bed Cross Section