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Greening the Desert – Recent Developments

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1 INTRODUCTION

In mid-2007 an invitation to public open tender was announced by Petroleum Development Oman (PDO) for treating water from its Nimr field in central Oman. The successful bidder(s) would Design, Build, Own, and Operate (DBOO) the treating and re-use facilities for a period of 20 years, and PDO would pay a service fee, agreed by contract, to the successful bidder to essentially take the water off of their hands. The Invitation to Tender (ItT) stated that the quantity of water to be treated is 45,000 m^3/day. (Other basic conditions of the produced water at Nimr Water Treatment Plant (NWTP) for (ItT) are shown in the Table 1.) PDO would make available a rectangular area of 10 km x 3.5 km for reed beds or farming. The objective of the ItT was to encourage vendors to submit proposals that would provide a use for the treated water.

Current practice in Nimr is to use Deep Water Disposal pumps to inject the produced water into deep aquifers. Previous experience with produced water treating and re-use for the Nimr field was based on reed beds. However, for the ItT, no preferences or stipulations were given as to the treating technology or re-use options. The vendors were given essentially a year to develop proposals. As hoped, several well developed technical bids were submitted.

In the Nimr field alone, roughly, 240,000 m3 of water is produced per day and the produced water volumes are growing at an annual rate of roughly 10 %. PDO has for several years been involved in a "Greening the Desert" initiative for produced water from the Nimr field. The term Greening the Desert indicates an approach to water treating that would utilize the water in some beneficial way such as for the production of biomass, or in the case where the water can be cleaned to a high standard for the generation of cattle fodder, or vegetables or fruit crops. The Nimr pilot initiative has pursued reed bed treating and re-use. However, the technology involved in water treating in general, and reed beds in particular, are not the typical strengths of a primary hydrocarbon producer such as PDO. Thus, little progress has been made beyond the Nimr pilot. For this and various other reasons, the initiative had all but died within the corporate organization. Thus, the ItT was an expedient means of pushing forward the concept of Greening the Desert.

On the basis of the quality of the tenders received, the ItT was a success. World-class vendors submitted proposals that were based on what appears to be the best available technology in the areas of produced water treating and re-use options. In addition, by utilizing a DBOO strategy, the vendors went to significant lengths to ensure that the facilities are operable and sustainable.

Given the strategy of an open tender for a DBOO project, the tendering process from the PDO standpoint became an exercise in data mining, literature review, consultation with experts (both within the vendor organizations and outside), working with regulatory authorities, and defining clearly the value of sustainable and local community development.

This paper gives the technical learnings in the process of tender development and evaluation. As anticipated, there was a wide diversity of technical approaches that were submitted. Each proposal could be broken into two parts, a water treating part, and a treated water re-use part. For water treating, two reed bed systems were submitted which were quite different in their design. Several "conventional" water treating systems were submitted. However, most of the conventional approaches would deliver potable water quality.

Regarding re-use options, biofuel appeared to be one of the most attractive options from the reed bed systems. Among the conventional technology re-use options, a number of crops were considered from forage for animals to vegetables and fruits.

Since the technologies submitted remain the proprietary property of the vendors, specific technical details of any one technical proposal shall not be discussed. While specific technical details are interesting, it turns out that there are several general and complex issues that must be addressed in determining viable treatment and re-use strategies.

Therefore, this paper discusses the existing gaps in technology that must be filled with experiment, measurements, or field experience in order to make the selection of viable strategies for produced water treating that is intended for re-use.

While there are many reed bed units for processing waste water around the world, there are relatively few reed bed units for processing produced water (oily formation water).

2 NIMR WATER HANDLING CHALLENGE

The Nimr field is roughly 700 km from the coastal area where the capital of Oman (Muscat) is found and where almost all of the petrochemical industry resides. Nimr is remote from the standpoint of a construction site and from the standpoint of oversight of any process operations. It is also remote from the standpoint of providing opportunities for using water or sale of agricultural products. The road system is minimal with narrow two-lane roads and there is no railway system.

The Nimr field produces roughly 28,000 m^3/day of oil with minimal gas volume. It also produces 240,000 m^3/day of produced water. Most of the production is from a few reservoirs of similar composition. Hydrogen sulfide, from geochemical origins, exists in the produced oil.

All of the produced water is processed through Free Water Knockout (FWKO) tanks, followed by Corrugated Plate Interceptors (CPI). It is then pumped to Deep Well Disposal stations for injection into a deep aquifer.

As shown in Figure 1, at the Nimr Production Station, the produced water is treated in three trains of Corrugated Plate Interceptors before being transferred by booster pumps to the Deep Water Disposal (DWD) sites. From the headers at the four DWD sites, the water is injected into deep water injection wells by deep water disposal pumps. At present there are four DWD sites 1, 2, 3 and 4. The Nimr Deep Water Disposal system has a capacity to dispose approximately 257,500 m^3/d of produced water.

Table 1.: Produced Water Supply Conditions at NWTP Battery Conditions

Parameter	Units	Minimum	Normal	Maximum
Quantity	M^3/day	0	45,000	50,000
Pressure	Bar (g)	0	2 to 16*(hold-1)	30 *(hold-2)
Temperature	º C	5	40	50
Oil In Water (OIW) (Hourly Average)	ppm (v/v)	50	150	1000
Total Suspended Solids	mg/l	20	30	100

*hold-1: It will depend on line size and operating conditions, to be confirmed during FED.
*hold-2: Pressure surge case – due to stoppage of flow at the NWTP, to be confirmed during FED.

Complex mechanical treatment technologies, large/distant areas or imported soil etc will involve high costs. Local, low-tech, robust solutions that have little requirement for imported materials or utilities, have better economics but they must have proven track record – they must work since technical support in remote locations is difficult.

2.1 Produced Water Characterization

In order to provide the vendors with reliable and accurate data upon which to base their proposals, PDO arranged to have 13 samples taken, roughly one per day, over a 15 day time period in mid to late May, 2007. The samples were taken at the discharge of the Nimr processing facility, at the entry point to the pipeline that transports the water to the Deep Well Disposal facility. The average results are given in the Table below. Table 1 gives the water characterization measurements. Table 2 gives elemental analysis results.

Table 1. Nimr Produced Water Characterization

Parameter	Average Value	Maximum Value
conductivity	12,236	13,000
total hardness	391	440
alkalinity	600	2,420
pH	8.11	7.72 – 8.24
total dissolved solids	7,430	8,660
total extractables (C11-C30)	31	79

The total dissolved solids are relatively low from a produced water standpoint. From the standpoint of membrane treatment, the TDS is in the range of brackish water. The pH is relatively alkaline.

Table 2. Nimr Produced Water Elemental Analysis

Parameter	Average Value	Maximum Value
bicarbonate	733	2,960
carbonate	0	0
chloride	4,122	4,320
iron	0.15	0.31
lithium	0.18	0.18
magnesium	32	35
manganese	0.18	0.23
potassium	37	49
sodium	2,453	2,950
strontium	4.7	5.2
sulfur	108	119
phosphorus	0	0
barium	0.41	0.51
silicon	11.3	11.5
boron	4.2	4.3
calcium	102	120
cobalt	0.002	0.004
copper	0.004	0.008
lead	0.000	0.004
antimony	0.000	0.000
molybdenum	0.002	0.004
nickel	0.007	0.017
selenium	0.05	0.07
arsenic	0.01	0.02
nitrate	0.00	0.00
nitrite	0.00	0.00
dissolved iron	0.07	0.32
total iron	0.15	0.31
sulfate	342	362

The Nimr produced water average OiW content was about 350 ppm with excursions peaking in the range of 800 to perhaps 1,000 ppm. The excursions would grow in oil concentration, have a peak and then subside as the operators would take corrective action. The whole excursion sequence would last perhaps a few days.

2.2 The Issue of Boron

There are two main reasons for limiting the concentration of boron in water that will be consumed by humans or cattle, or used for irrigation. In humans, boron is a suspected teratogen. The World Health Organization has set a preliminary limit of 0.5 mg/L for drinking water. The European Union is suggesting a guideline of 1.0 mg/L. The second main reason is that boron can pose a danger to crops. Although boron is essential as a plant growth trace element, it can be detrimental in concentrations greater than 0.3 mg/L in irrigation water. In citrus trees for example, boron causes leaf damage, and reduces the fruit yield.

In water, boron is usually present as boric acid, a Lewis acid. Above a certain concentration, polymers are formed. However, for aqueous systems where the concentration is low (few tens of ppm), the polymer species are in low concentration and may be ignored. For Arabian Gulf seawater, for example, the typical boron concentration is 15 mg/L (elemental boron in the species below) and the following equilibria are accurate to describe the speciation.

$$\textit{Equation 1:}\ B(OH)_3 + H_2O \leftrightarrow B(OH)_4{}^{-} + H^{+} \quad \textit{with pKa} \sim 9.2$$

$$\textit{Equation 2:}\ B(OH)_3 + OH^{-} \leftrightarrow B(OH)_4{}^{-} \quad \textit{with pKb} \sim 4.8$$

The boron species on the left hand side is boric acid and the species on the right hand side is borate. It is apparent from the above that boric acid is the dominant species at low pH and that borate is the dominant species at high pH.

2.3 Reed Beds for Produced Water Treating and Re-Use

In this section we discuss the technical details of a reed bed design for application in an arid climate with poor soil conditions. We also discuss the options for using the water for some productive benefit. Complicating these options is the fact that Nimr is relatively isolated since it is roughly 700 km from any densely populated area that could be considered a suitable market for products developed there.

2.3.1 Reed Bed Design

Constructed wetland wastewater treatment systems have been in use for at least one hundred years, perhaps longer. Their primary application has been to treat agricultural, industrial, and municipal waste water. They are easy to operate and maintain and are extremely energy efficient, particularly when compared to conventional mechanical waste water treatment systems. While the operation of a constructed wetlands is almost trivial, the proper design to avoid capacity limitations or bottlenecks is still somewhat difficult and there remains a lack of consensus regarding some important design issues. Further, their application for produced water system (oily water) has been rather limited to date.

In designing a wetlands process, the parameters which must be considered fall into three broad categories:

- Produced water characterization and flow rate
- Soil characterization

- Hydrology of the system
- Selection and characteristics of the vegetation

The produced water must be characterized according to mineralogy, organic species (including water soluble organics (WSO), Benzene, Toluene, Ethyl-Benzene and Xylene (BTEX), acids and sulfur species), various types of oxygen demand, scale (precipitate) forming tendency, oil content (both dispersed and dissolved), volatility (C1-C5, and BTEX), toxicity, heavy metal content, treating chemical content. All of these parameters must be assessed over time to understand the expected loading of the beds. Special sampling and handling techniques must be used to prevent oxidation (or to prevent the effects of oxidation) and to prevent biological degradation. Some species such as cobalt, boron, cadmium must be measured accurately in the range of 1 mg/L.

In the conceptual stage of design, the main design considerations are:

- Design Life
- Subsurface Flow (SSF) or Free-Water Surface (FWS) configuration
- Application of pre-treatment, prior to reed beds (influent OIW)
- Bed depth
- Hydraulic Retention Time (bed length and width)
- Hydraulic Loading Rate (bed length and width)
- Inflow and outflow distribution system design

As with any other type of water treating technology, design life is a factor in the design of reed beds. While this may not seem to be so upon first thought, a consideration of the fate of trace metals or accumulated components in general, will determine the life of a reed bed facility. If certain metals accumulate in the reed bed system, they may reach saturation at which point their concentration in the treated water will match that of the untreated water. If these same metallic elements are important for whatever reason such as toxicity, then the effective life of the bed is finished. The accumulation rate and saturation level are difficult to predict in the design stage. Bed life is discussed further below in the discussion of the Nimr Reed bed results.

There are two basic design types, FWS systems, and SSF systems. FWS systems introduce the waste water on the surface of the vegetated area which results in a flooded surface and in predominantly vertical flow of waste water through the plant root zone. SSF systems introduce the waste water below the soil surface and results in predominantly horizontal flow through the root zone.

There does not appear to be a consensus regarding the advantages of the SSF configuration versus the FWS configuration. Obviously, SSF is more costly than FWS. SSF also involves design risks. It requires the design an installation of an inlet distribution system. If the design is inadequate for the given flow, or if the distribution system should become fouled or partially plugged, then the system will become a bottleneck to processing capacity or must be re-engineered. The obvious question is, what advantages are worth such risks.

Oxygenation is important to support high biological activity. The major sources for oxygenation in any configuration are surface exposure to the atmosphere and by transmission of oxygen by the plant, from the leaves to the root zone. SSF systems have been claimed to provide better oxygenation of the water because the majority of the water flow is through the root zone [1]. Redox potential (oxidation/reduction potential) is a more accurate way to characterize the situation [2] since there are mineral species such as nitrates which contribute significantly to the respiratory process of most plants.

The total bed size depends on the assumed evapo-transpiration rate (ETR). As discussed below, the assumed ETR rate for the design of the Nimr pilot was 53 mm/day while the actual ETR rate was measured as 15 mm/day. Needless to say, such a magnitude of underestimated error in this parameter results in a significant performance deficit.

Bed volume and shape are important design parameters. In deciding the values of these parameters, the main consideration is the Hydraulic Retention Time (HRT). This parameter is important because the processes that degrade the oil are somewhat complex and time consuming. They include microbial and fungal decomposition of organics (including hydrocarbon) in the rooted soil layer, and adsorption by vegetation and subsequent decomposition and assimilation into the plant structure. These are slow processes that require significant time. Further, good results are typically achieved by slow and uniform transport across the bed which is most easily achieved by mild flow gradients and are therefore promoted by long HRT. Other processes, typically requiring less time are mineralogical precipitation, and adsorption of dissolved and precipitated constituents on clay particles.

The bed Depth is set largely by root depth. This is discussed elsewhere. Once the depth is set, then the length and width of the bed must be determined. In comparing the performance of existing beds, they are likely to have different shapes so the fundamental parameter to consider is the HRT. In addition, the HRT is a physical variable that takes into account the degradation processes that occur in the root zone. A certain amount of time is required for these processes to occur.

$\mathrm{HRT} = \mathrm{Mu} * V / Q_{in}$
where Mu is the soil porosity, V is the bed volume, and Q_{in} is the inflow of water.

Bed porosity is a function of the soil. As described below, in the Nimr pilot beds, the bed porosity was increased by adding gravel. This is an expensive option. In the case of the Nimr beds, the re-design was constrained so increasing the bed porosity was a sensible alternative.

The inflow of water (Q_{in}) is the feed rate of produced water to the beds. In bed design, this is a given.

Bed volume (V) is calculated from:
$V = W * L * D$
where W = width, L = length, D = depth. Bed depth should be determined by considering the plant root depth. In practice, the value of HRT is determined from the physical processes of hydrocarbon degradation, as discussed above. Thus, the HRT equation is typically used to determine the design plot area. The plot area ($Ap = W * L$) is then the unknown in the HRT equation.

The Hydraulic Loading Rate (HLR) is the flux of water through the bed. It is calculated as the volumetric flow (m^3/day) divided by the cross sectional area in the direction perpendicular to the flow (m^2). The final units of the HLR are m/day. As with the HRT, values are reasonably well established for constructed wetlands to handle waste water but not for handling produced water.

There are many times more Constructed Wetlands systems for waste water treating than there are for produced water (oily formation water). The difference is of course that produced water tends to have higher salinity, higher scaling tendency, and contains hydrocarbons which together with short chain fatty acids, resins, and aromatics tends to form oil in water emulsions which makes separation of the oil and water more difficult. The application of Constructed Wetlands systems for produced water treating are becoming more common. Examples of the later include the Amoco Mandan refinery in North Dakota, the Chevron refinery in Richmond, CA, and the Jingling Petrochemical facility in Nanjing, China. However, this is still a very short list and given the significant variation in climate, soil, and water properties from one application to another, there is a relative scarcity of documented experience for constructed wetlands processing of produced water. Since some experience does exist within PDO from the Nimr reed bed pilot, that experience is reviewed here.

2.3.2 Nimr Pilot Reed Beds

In April 2000, pilot reed beds were commissioned in the Nimr field. In that area, the average annual temperature is 28 ^{o}C. The average annual rainfall is less than 40 mm and precipitation only occurs in the summer.

From an agricultural standpoint, the soil in the Nimr area is poor. The soil conditions are significantly worse than typically found in natural wetlands. The soil is relatively shallow in some areas ranging in depth from a meter or so to only a few centimeters. It has high permeability with a low clay content (hence low nutrient value), and a high content of sand and calcium carbonate. Neither sand nor calcium carbonate have nutrient value. Further, calcium carbonate is undesirable since it will dissolve over time raising the pH of the water being processed through the bed which will precipitate minerals and nutrients and further reduce the solid depth.

The Nimr pilot facility is composed of eight beds, each roughly 50 x 75 m, with two trains of four beds each (A1-A4 and B1-B4). It was originally designed such that each train (A and B) was comprised of one treatment (hydrocarbon reduction) bed (A1 and B1) followed by three evapotraspiration beds (A2-A4 and B2-B4). Both trains were designed as SSF with subsurface feed and drainage piping.

At the time that the beds were designed, little was known about proper design of reed beds for produced water in such a desert environment in an area with such poor soil. As a result, the initial performance of the Nimr reed beds was poor.

In early 2001, PDO commissioned the International Center for Biosaline Agriculture (ICBA) to develop recommendations to improve bed performance [3]. By August 2001, most of the recommendations had been implemented. Performance of the reed beds was improved dramatically, as described in an ICBA report issued in December 2002 [3].

The treatment beds (A1 and B1) were significantly redesigned. The subsequent beds (A2-A4 and B2-B4) were left unchanged. The following design changes were made to the A1 and B1 beds:

- Soil was dug up and mixed with gravel to produce a courser soil structure
- Decreased soil depth to reduce bypass of water under the root zone
- Reduced number of drainage lines
- Reduced number of irrigation lines

The optimum soil depth depends on the depth of the plant roots. If the soil is much deeper than the root depth, then a significant volume of water will bypass the root zone thus not having the benefit of optimal microbial action and oxygenation. In the Nimr pilot, the plant root depth was determined by direct measurement. The root depth was measured at roughly 0.8 m and the original A1 bed depth was 1.25 m. The A1 bed was then redesigned with a bed depth of 0.8 m.

An important point to keep in mind in this discussion is that the re-design of the A-1 and B-1 beds was constrained by the bed size. The ICBA team considered the possibility of expanding the beds from their original bed size but decided to keep the bed length and width constant. It is not altogether clear why this decision was made [3]. However, once made, the bed capacity could only be improved by other means such as a change in the bed porosity and inlet/outlet water distribution systems.

These changes improved the oil handling capacity of the B1 bed from 7 mL/m^2/day to 17 mL/m^2/day [4]. These results were obtained in the last six months of 2001. During that time, the Nimr produced water had an average OIW concentration of 350 ppm [3]. The B1 reed bed effluent ranged in OiW from 5 to 10 ppm. The HRT was in the range of 3 to 6.5 days. The average flow rate of produced water to Nimr was 5,000 m^3/day. Recent OiW measurements indicate that over several months the average OiW concentration is roughly 150 ppm.

An analysis was conducted of soil samples from the B1 bed. Two samples were taken and analyzed consistently over a period of one year. Actually a third analysis was conducted but the analysis procedure was different from that of the other two samples so the results are not comparable. The two samples that were analyzed consistently were analyzed using a saturated paste extract technique. This technique measures the amount of heavy metals, and other elements that can be released (extracted) by contact with reed bed effluent. The results indicate that the extractable metals content of the soil decreased significantly in the one year time period following the ICBA modifications to the bed. Elements such as arsenic, boron, iron, lead, and vanadium had extractable values that decreased by 90+ %. Based on the lack of change to the production profile, it is assumed that the elemental analysis of the feed water changed little over the time period. Thus, the reduction in extractable elemental analysis indicates that the soil was incorporating these elements in strong chemical interactions that effectively eliminate them from the effluent stream.

2.3.3 Pre-Treatment for Reed Beds

The inlet OiW content is by far the most important factor in design for successful operation of a reed bed system. Its importance cannot be over-emphasized. If reed beds are to be used to de-oil the produced water, i.e. as one of the major initial processing technologies, then considerable thought must be given to the need for upstream processing to reduce and control the OiW concentration.

As discussed above, the Nimr produced water average OiW content was about 350 ppm with excursions in the range of perhaps 1,000 ppm. Such excursions would last less than a day or two. The experience in Nimr was that an oil slick developed in the feed area of the inlet beds. The oil slick, once formed, did not go away over the life of the reed bed trial.

Based on a review of experience at other constructed wetlands sites for produced water, it is recommended that the inlet OiW concentration be limited to an average value of 50 ppm with excursions of no more than 150 ppm and only for a day.

2.4 Conventional Treatment

There were several proposals to treat the Nimr produced water using conventional technology in systems such as gas floatation, filtration, chemical treatment, reverse osmosis (RO), and perhaps some polishing to reduce boron content. The use of reverse osmosis requires significant pump energy. It also incurs some operability risk since typical RO membranes foul readily upon contact with even small concentrations of oil. Relatively novel treatments were proposed to eliminate the oil content or to reduce the impact of oil on the membranes. Altogether, the proposals were sound from a technical standpoint. Case studies were submitted where the technology had been applied with success in similar situations. In effect, some of the most attractive conventional technology that was proposed appeared to be reasonably well proven and robust.

The evaluation team has noted that there was a press release entitled “Oilfield Produced Water Successfully Desalinated Using OPUS^{TM} Technology”, which appeared on Water Online dated on 14/2/2008 [2]. The press release confirmed that– N.A. Systems (based in Pittsburgh, PA), which is a Veolia Water Solutions & Technologies company, announced the successful full-scale demonstration of OPUS^{TM} Technology for produced water treatment at Chevron U.S.A. Inc.’s oil production in San Ardo. The system there is sized to treat 50,000 bbl/d produced water. It is believed that the system there is almost identical to what Veolia has proposed in the current application for Nimr produced water treatment.

Following the discovery of the above mentioned press release, a document entitled “Desalination of Produced Water Using OPUS^{TM} Technology” [7] was obtained. The paper discussed the demonstration of the OPUS^{TM} technology at an oil production facility in the United Stated. The paper concluded that the technology when combined with deoiling process can meet and exceed the product water quality.

The main problem encountered by all of the bidders who proposed conventional technology involved the question of what to do with the treated water effluent from their system. Depending on how many passes of RO membranes were proposed the water quality was anything from potable to pure.

The water quality standards was intended to reach potable re-use or food chain agricultural re-use options, was really not attractive economically to consider for a low value crop such as biofuel. To use the water for any other crop would require acceptance of the produce by the Ministry of Agriculture which has no experience to date in such an application. Standard A is the water quality standard which must be met in order for water to be used for irrigation of vegetables and fruits that are likely to be eaten raw. The most relevant parameters and the influent values from the Nimr produced water are given in Table 3 below. Unfortunately the bid process could not afford the opportunity to do pilot studies to determine whether the water product would be safe for animal and ultimately human consumption of the animal.

Standard A and the Nimr produced water discharge concentrations

Parameter	Standard A (mg/L)	Nimr Water range (mg/L)
Al	5000	10-1000
Ba	1000	0-800
Cr	50	10-100
Cu	500	5-100
Fe	1000	100-10000
Pb	100	5-60
Mn	100	80-120
Zn	5000	1-640
Li	70	75-281
B	0.5	2-7
Sr	N/A	3.8-6.6
Na	200	2000-2500
TOC	N/A	70-140
BOD_5 at 20 C	15	40-160

Parameter	Standard A	Nimr Water range
EC (dS/m)	2	12-15
pH	6-9	7-8.5

In addition, conventional technology suffers from a capitalization burden. The capital cost of the equipment is quite high compared to reed beds and must be amortized thus adding to the unit handling cost. Also, such equipment is somewhat complex to operate and requires a well trained staff of operators. Oman, like many other emerging economies has a critical shortage of competent well trained people in its workforce especially on produced water technologies and re-use options related to greening the desert. The N.W.T Project had to rely on external consultants in getting specialized assistance.

3 CONCLUSIONS

PDO is committed to further progress in the Greening the Desert initiative. This paper describes recent progress. In mid-2007 an invitation to public open tender was announced for a Design, Build, Own, and Operate (DBOO) strategy. PDO would pay a service fee, agreed by contract, to the successful bidder to treat the water.

On the basis of the quality of the tenders received, the ItT was a success. World-class vendors submitted proposals that were based on what appears to be the best available technology in the areas of produced water treating and re-use options. In addition, by utilizing a DBOO strategy, the vendors went to significant lengths to ensure that the facilities are operable and sustainable.

As anticipated, there was a wide diversity of technical approaches that were submitted. Each proposal could be broken into two parts, a water treating part, and a treated water re-use part. For water treating, two reed bed systems were submitted which were quite different in their design. Several "conventional" water treating systems were submitted. However, most of the conventional approaches would deliver potable water quality and it was evident that there is not sufficient market economics for fodder, fruit or vegetable crops to justify such high quality water. Among the re-use options, biofuel was the most attractive.

4 NOTATION AND ABREVIATION

BTEX – Benzene, Toluene, Ethyl-benzene and Xylene
CPI – Corrugated Plate Interceptor
DBOO – Design, Build, Own and Operate
ETR – Evapo-Transpiration Rate
FED - Front End Design
FWKO – Free Water Knockout
FWS – Free-Water Surface
HLR – Hydraulic Loading Rate
HRT - Hydraulic Retention Time
ICBA – International Centre for Biosaline Agriculture
ItT – Invitation to Tender
Mu - porosity
NWTP – Nimr Water Treatment Plant
OiW – Oil in Water
PDO – Petroleum Development of Oman
RO – Reverse Osmosis
SSF – Subsurface Flow

V - volume
Q_{in} - the water volumetric inflow rate
WSO – Water Soluble Organics

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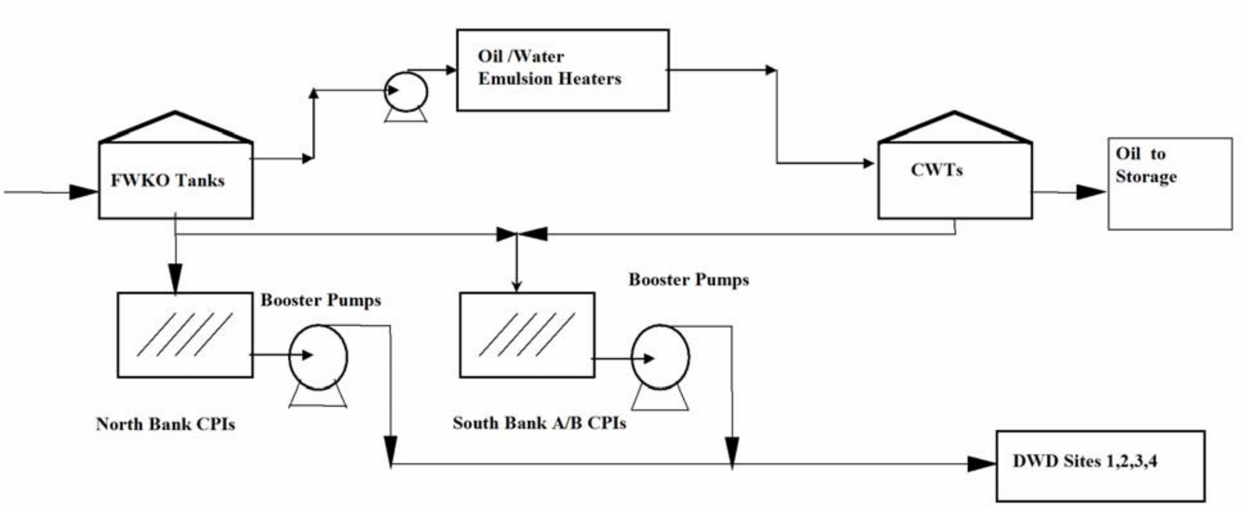

Figure 1. Oil and water treating schematic for the Nimr Production Station