Potential for up-scaling Nimr reed bed facilities, Oman

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Feasibility Study

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ABSTRACT

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This report describes the findings of a feasibility study to treat oil contaminated water using reed beds, and consume the treated saline water using forestry. The feasibility study focused on the social, technical and economical feasibility of a project designed to process 45,000 m3 of water per day. Possible effects of a large scale operation on interactions between Petroleum Development Oman and local population are listed, and suggestions on the social processes involved are made. The economics of reed bed water treatment and water consumption through the use of forestry are determined and compared with the current practise of deep well disposal. The economics of the treatment-forestry system are more favorable than the economics of the deep well disposal. The technical analysis shows that the reed beds are able to treat water to remove hydrocarbons, and suggestions for management, design and development of the system are given.

Keywords: biological water treatment; oil contaminated water; saline agriculture; reed bed technology; Eucalyptus forest; cost-benefit analysis; local population involvement; Oman; greening the desert; feasibility study

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Executive summary

1. Upscaling of the Nimr biosaline agriculture facilities, Oman, into a large scale Reed Bed and Eucalyptus Combination is technically, financially, and socially feasible:
    a. technically, because by directing the flow (45,000 m3/day) of oilcontaminated water through reed beds and subsequently feeding the treated water to Eucalyptus trees requires technology that is available and because the water downstream of the Eucalyptus trees will be of manageable quality
    b. financially, because at 0.05 $/m3 (with a range of 0.075 $/m3 in the worst case and 0.025 $/m3 in the best case) the contract price – the amount that PDO has to pay to allow the contractor to break even – compares favourably to disposing oil-contaminated water in deep aquifers, as is standard practice presently (the present total value of DWD is 0.11 $/m3, consisting of 0.075 $/m3 operating cost and 0.028 $/m3 capital cost)
    c. socially, provided that the local population is directly involved in decision making and their access to water as a resource to improve their standard of living is improved, to this is added that
    d. the environmental impact were not studied separately, but were included in the technical analysis; separate detailed environmental impact statement needs to be done, but from this feasibility study it is not expected that major problems will appear.
2. A new design is required for the upscaled reed bed and Eucalyptus combination project, rather than an inflated design of the existing pilot project. Points of attention in this design are water use reliability and treatment reliability of the reedbed and eucalyptus system, health and safety of this system, salt movement and salt accumulation, and limited soil depth.
3. Different objectives exist for PDO and a contractor bidding on the tender. While PDO wants to evapotranspire the water at high reliability, thus not necessarily at a financially optimal design, a contractor running a financially profitable farming operation wants to design their operation at minimal cost.
4. The contract price of water is very sensitive to a change in the capital costs of reed beds. Mechanical pretreatment seems to be an interesting option, as it reduces the required size of reed bed area (and consequently the associated capital costs) considerably. Included in the financial assessment are all costs from the tap point from which processed water is obtained onwards; not included are the costs of bringing the processed water to the tap point (over a distance of possibly 20 km).
5. The envisaged project has three beneficiaries (rather than the two that prevailed in the plans thus far): PDO, the contractor that will win the tender, and the local people. Although the water even after treatment is unsuitable for many uses, it still is water that is applied in a desert environment. Local people will show an interest in it. Not to recognise this interest could lead to relation problems; not to use this project to

contribute to the improvement of standards of living of the local people means that an opportunity is missed.

6. The standard PDO procedure to engage the stakeholders (local people) can be started, albeit with an important alternative objective: the aim is to work out with the people and their representatives how the project can be used to structurally improve the living conditions of the local people (water is the medium). The people and their representatives must be allowed to decide for themselves which actions they consider appropriate, given the potential and limitations of the project.
7. Monitoring of the technical, financial, environmental and social aspects of the project is important, especially because the project will be a new experience. Monitoring should be organised in such a way that conclusions are drawn during the course of the project and can lead to changes in project implementation (action research, rather than ex-post evaluation).
8. Decommisioning the project implies i) removing physical assets and waste products (soil, liner, salts) and ii) communicating with local stakeholders. With respect to the latter the team advices to agree on details in a Service Level Agreement at the start of the project

1 Background and study objectives

PDO – Petroleum Development Oman – is the main oil and gas exploration and production company in Oman. All oil and gas is brought to the surface in the interior of the country. Here, desert conditions prevail: the average annual temperature reaches 28 degrees Celsius, annual rainfall is less than 40 mm, and this falls only during the summer; plant growth is limited to so-called wadi's, depressions in the desert where soil moisture is relatively high; population densities for Oman are at a low 7.6 people/km2, and even lower in the interior; and the prevailing livelihood system is of the nomads camel and goat raising type (Bedouins). Water is pumped along with oil production at a rate of more than five barrels water for each barrel of oil. At the Nimr exploration site, which is the site that is focal to the present study, every day 220,000 m3 of water is produced. This – oil-contaminated – water is currently injected into deep well disposal reservoirs (deep well disposal, hereafter DWD). PDO has been investigating low cost alternatives for the deep water disposal. Over the past five years PDO has experimented on a pilot scale with the reed bed technology at the test facilities at Nimr (5 ha layout). Oil-contaminated water is fed to the reed beds, where the oil is largely disintegrated. The water that flows out of the reed bed is still contaminated , but can be used for growing e.g. trees. Some experiments have been carried out to grow various shrubs and other plants with the treated water (for a discussion on the advantages and disadvantages of DWD see Appendix A).

The test phase has more or less come to an end and PDO has invited Alterra-ILRI and LEI to assess the potential for treating much larger quantities of oil-contaminated water using the reed bed technology. To further dispose of this water trees or other plants will be grown with it. The present study describes the results of the assessment. The following aspects were considered:

- the design of a large scale (input 45,000 m3/day of oil-contaminated water) reed bed treatment facility and crop production facility;
- the costs per m3, and the costs of the header system, the reed bed facilities, and the crop production facility;
- the consequences for the environment, and the requirements to make the reed bed and crop production facilities environmentally sustainable;
- the impact that a development at such a scale will have on both the economy and welfare of the surrounding population – camel and goat rearing Bedouins – plus suggestions for remedial actions.

The study was carried out in five steps: reading and information gathering prior to departure to Oman, introduction to the reed bed project by staff of the Department of Corporate Environmental Affairs, PDO, site visit to the Nimr experimental facilities, data and information processing including expert consultation both in Oman and the Netherlands, and report writing. Fieldwork started on May 4 and the report was submitted in the first week of June 2004.

The report describes the assessment methodology in section 2, the technical analysis section 3, the relations of the project with the local people in section 4, and the financial analysis in section 5. Section 6 contains two sections, one on the tender procedure and the other on monitoring. The conclusions are formulated in the executive summary, at the beginning of the report. Appendices complete the report.

2 Methodology

The study team has interpreted the assessment (whether large scale treatment of oil-contaminated water in reed beds combined with using the water to grow crops is technically and financially feasible against environmentally and socially acceptable 'costs') as a linear process with loops. Figure 1. is a diagram, which shows the relation between the technical design (of an up scaled reed bed cum crop production unit – hereafter referred to as the Reed Bed Eucalyptus Combination, or REC), the environmental and social consequences, and the overall costs.

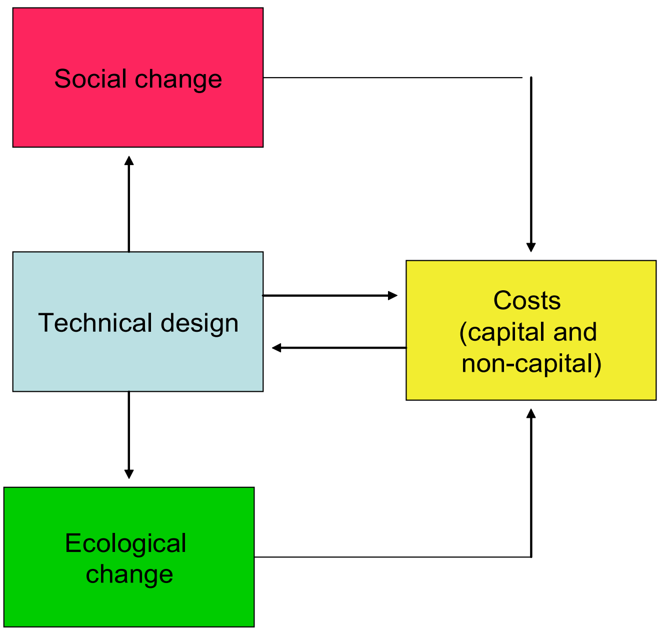


Figure 1. Assessment logic: relation between technical, ecological, social and financial aspects.

Starting point of the assessment is the technical design. The reed beds and the production unit further downstream are designed in such a way that the required water quantities and the required water quality standards are met. This can only be done at certain costs, which are to be kept as low as possible.

The consequences for both the local population and the environment are considered of each design alternative that meets the financial criteria. It is important to remark that the social and environmental consequences are not like financial costs that can be minimized. It is inevitable that a large-scale development as foreseen will bring along changes in the social fabric of the surrounding population (if they get access to the water or to the products or revenues that are generated with it) and in the physical environment. The livelihood system of the Bedouins will change. Flora and fauna will change. Even the microclimate will change. The extent to which such changes are considered acceptable must be the outcome of a dialogue – negotiation process – between the parties involved; PDO, the Ministries of Agriculture and Fisheries, Department of Irrigation, the Ministry of Municipalities, Department of Environment, and last but not least the local population. Whatever the outcome of this dialogue, it will have to lie within the framework of existing laws and regulations.

Some of the assumptions made in this report are based on limited or incomplete measurements. Where possible, the limitations of existing data is discussed in this report, and a range of possible results is given. The most likely results have been used to formulate conclusions of this study.

The assessment does not imply a detailed technical design of a REC. Only one tree crop has been assessed, Eucalyptus, and this crop only with regard to its the technical and financial feasibility. Eucalyptus was chosen because of its potential to survive under the conditions created in the production unit. In discussions with the Ministry of Agriculture and Fisheries, department of irrigation, and the Ministry of Municipalities, department of the environment, it was clear this project is supported and seen favorable by the Omani government. The dialogue with the local population has not yet been started. The team wishes to stress that other crops may also meet the criteria.

The team looked at the project as the possible starting point of a series of similar projects in the interior of Oman. One can imagine a development that in addition to the Nimr REC more of such projects will see light, namely at all sites where presently oil-contaminated water is pumped back into deep aquifers. If this is to happen – and this depends to a large degree on the success of reed beds as a financially attractive alternative to deep water disposal – the environmental and societal consequences will be multiplied. A local economy quite different from the present would emerge. Agricultural production (probably not food crops) and possibly recreation would be the corner stones of the new economy. Oil and gas production would be the engine, at least during the first decades. If such a development were to happen without appropriate attention being paid to the position of the local population and the environment from the first moment onwards the latter run the risk of being marginalized (examples from other cases exist). The present assessment indicates the first steps to be taken in this regard.

At the present level of knowledge and technology PDO does not permit the use of treated water for food and fodder crops, as the quality of water may constitute a potential health risk. Should other information become available or should other techniques be put in place, PDO's view may be changed. The study team did not look into this issue any further. PDO is also careful not to make local people or others dependent on what is created, and as a consequence places itself into a situation that at the end of oil exploration at Nimr or in Oman it still has obligations related to the REC project. The study team has understood that oil, and therefore water, will be pumped to the surface for at least the coming 20 years, even under conservative estimates. The REC project described in the present assessment has taken this period as point of departure. The time dimension of the project should be a core issue at the stakeholder engagement sessions (and possibly a core issue in a service level agreement with the local people as well).

3 Technical analysis

3.1 Current situation

Deep well disposal
Current practice to dispose of produced water is deep well disposal (DWD). At the Nimr location, all oil-water produced is centrally separated through mechanical skimming. The setting of the mechanical skimming is adjusted manually, and variation in oil-water ratio at the pumps may therefore result in variations of oil in water (OIW) content in the disposal water. From the central treatment plant, water is distributed over 6 DWD-pressure stations (phase 1 through 6), each having two or three wells. Water is pressurized to 100 – 140 bar, and each well has a capacity of approximately 22,500 m3/day. A 7th DWD phase is expected to be needed in 2005, at a cost of 14 million US$ (compared to 11 million US$ for phase 5 and 6) (PDO, 2003a). A new skimming tank is planned to be in operation end 2004, which may reduce the OIW content of the effluent water.

Header system
The current reed bed trial takes water from a supply line to one of the DWD-phases. Since the capacity of the current reed bed is smaller than the supply of water, only a portion of the water is taken for biological treatment. The tap of the pipe is at the 6 o'clock position (tapping from the bottom of the supply line), which provides likely a lower OIW content then when the full flow from the supply line would be taken (since the density of water is higher than the density of oil, it is likely that separation of oil and water already occurs during the transport process from processing plant to disposal phase).

Weekly measurements of OIW content during the trial period showed an average OIW content in the water supplied to the reed beds of 127 ppm (ICBA, 2002). Oil in water content for the supply water during a 6 month period of measurements in 2003, while a redesigned reed bed layout was in operation, was higher, namely 217 ppm (varying between 44 ppm and 379 ppm) (Appendix B).

Two storage tanks were constructed at the header for storage of treated wastewater (fresh water supply) from the Nimr camps. These storage tanks are currently not in use and there is no fresh water demand since the establishment phase of the reed beds was completed successfully.

Reed beds
Subsurface flow reed beds were selected to treat the oil contaminated water. Arguments for using subsurface flow reed beds as opposed to surface flow can be found in report ONM/017/01 (PDO, 2001). Two trains (beds in series) of reed beds were envisioned during the initial trial, namely an A-train, where no liner was installed and where soil depth was shallow (0.8 m), and a B-train, where liner was used, and the soil was deep in the first bed (1.3 m). The philosophy behind the reed beds in series was that the first reed bed would treat the water for oil, while the subsequent reed beds would reduce the volume of water (Figure 2).

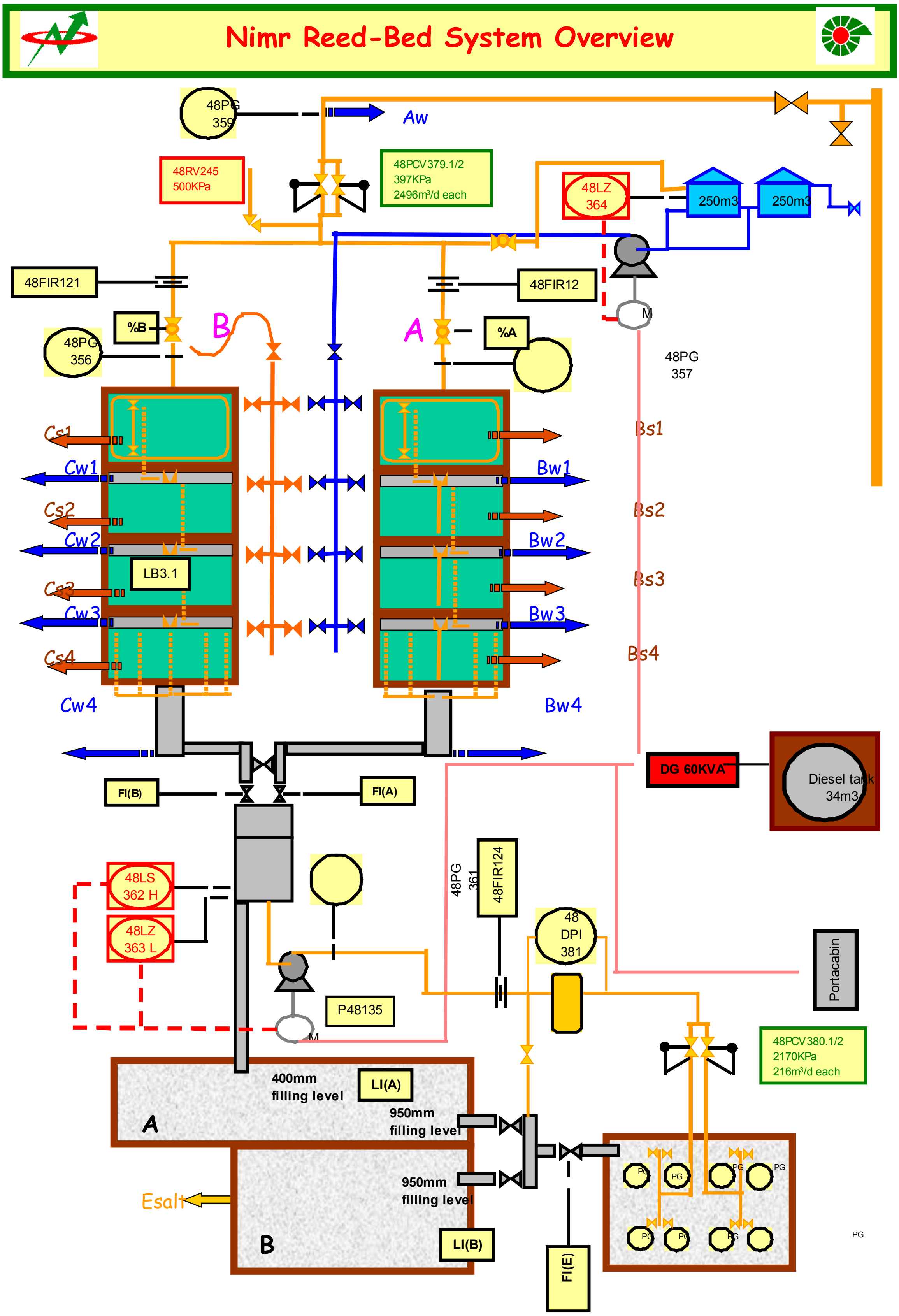


Figure 2 Schematic layout of train A and train B at the reed bed trial site in Nimr

As can be concluded from report ONM/017/01 (PDO, 2001), the expectations of the design where unrealistically high (evapotranspirations of 53 mm/day; impossible values considering agro-meteorological conditions). Problems were also encountered with the capacity of the reed beds, and based on lessons learned from the initial trials, an improved reed bed (A1) was constructed in April 2002. Preliminary analysis of a short period of data indicate that the treatment capacity of the reed bed more than doubled (Appendix B), to the potential to treat 17 ml oil per day, per square meter of reed bed.

Water disposal
Current practice of treated water disposal is a combination of evaporation pond and biosaline agriculture. The disposal capacity at the trial prevents the redesigned A1 reed bed to run at full design capacity (450 m^3/day).

The salinity of the treated water from A1 is only slightly higher than the influent, due to evapotranspiration losses of the water. Salinity of train B effluent is considerably higher than the inflow, due to additional evapotranspiration losses from the reed beds following the initial treatment in B1 (ICBA, 2002).

If the effluent water is to be used for agricultural production, reed beds should be designed to maximize oil reduction and minimize losses of water to maintain influent water quality as much as possible.

Biosaline agriculture (salt tolerant crops and trees, including halophytes) were tested at the trial site, and several species proved to be successful.

Water quality
Water quality and composition of shallow groundwater (100 m depth), produced water (1000 m depth) and average effluent is shown in Appendix C.

3.2 Technical analysis of upscaling reed bed and eucalyptus combination

An upscaling of reed bed-eucalyptus combination (REC) requires design adjustments. The current trial size of 1 reed bed of 50 x 70 m would in a large scale design not be replicated, but redesigned. **Construction cost for an upscaled system cannot be directly multiplied by the increased ratio, since the economies of scale are applicable** (1 shovel can move 100 m3 of soil or 200 m3 of soil for almost the same cost, since the fixed cost for both cases is the same and outweighs the operating cost).

Header system
The header system for an upscaled REC should be sufficient to supply 45,000 m3/day to the upscaled reed beds. This would result in a flow rate of 520 L/sec.

Since aeration of the water to be treated is important, a venture-type air injection system needs to be included into the header system.

Energy to move the water from the tap point to the reed beds can be obtained through the booster pumps of the supply line.

A reservoir at the header part of the system is not likely to be needed. The reed bed trial has shown that occasional spikes of OIW content will not be detrimental to the reed beds. An occasional spike of OIW in the effluent would not be detrimental to a forestry system, since the soil will act as an additional filter for the hydrocarbons in the water. Breakdown of this potential oil residue will occur naturally, although less efficiently than in the reed beds.

Reed beds

Based on a remediation potential of 17.1 ml oil per day per square meter of reed bed (allowing an outflow up to 5 ppm OIW), an inflow of 45,000 m^3/day, and an average OIW content of 250 ppm, approximately 65 ha of reed bed would be needed (see Appendix D).

Note that this value is based on preliminary measurements, and that no safety margin is included in the treatment capacity. A safety margin should be included as over-design of the actual reed bed system. Some additional reed beds could also be constructed to allow decommissioning reed beds for maintenance without losing treatment capacity.

Locations of the reed beds must be chosen such that the soil depth is sufficiently deep and soil type is sufficiently porous.

Reed bed reliability

The current REC design is based on the assumption that 45,000 m3/day will be treated by reed beds. Current water production in the Nimr area is 220,000 m^3/day, and 6 phases of DWD are currently active. It is expected that initially, the water production may increase due to a higher water to oil production, but that over time, water production may decrease due to a decrease of oil pumping.

It must be noted that when the reed bed treatment is an addition to the current DWD phases, there is no alternative to water disposal as a backup system (this is not different from a serious emergency with one of the DWD phases). The reliability of a reed bed treatment system can be improved by some over-designing of the reed bed system, as well as the forestry system (current design is based on optimal efficiency, and not based on optimal reliability).

This is a **conflicting objective** between PDO and a commercial contractor. PDO wants maximum reliability of water treatment, while a contractor would want to minimize reed bed treatment cost by minimizing surface area. The constant supply and fluctuating water demand by crops/trees also is a problem. To overcome this trees could be under-irrigated over summer and fully-irrigated over winter, making production less than optimum. Or alternatively large storage systems would have to be constructed, increasing salinity and causing additional seepage losses.

Phased reed bed (and forestry) development is another method to reduce the risk of sudden die-back of all reed beds at the same time. Re-establishment of a biological system needs more time (approximately 1.5 – 2 months to establish reeds) than repairing a mechanical system.

Recent water production predictions indicate that through improved technologies, the production of water may decrease below the capacity of the six existing DWD-phases (Sluijterman, pers. comm.). In this case, reed bed (and forestry) design could be optimized for economic profit. The water supply could be variable over time (since DWD will continue), and the water demand for forest production can be the driving force of the system (in the current assessment, the constant supply of 45,000 m3/day is used as the driving force of the system).

Reed bed safety

Although the reed beds have continuous water supply, a slight chance of fire danger may exist, due to the presence of dead plant material, oil in water and soil, and the combination of high temperatures and windy conditions, as well as, in theory at least, sabotage. To prevent the wipe-out of the whole biological treatment system, it is advised to locate the reed beds with sufficient inter-spacing that fire would not jump from one bed to another.

Standing water on the reed beds may cause health concerns, due to the presence of mosquitoes. Although malaria and West-Nile virus are not present in Oman, the conditions for mosquito breeding grounds should be considered in the design.

Standing water may also attract migrating water fowl. Some non-degraded oil residue was observed on the surface of the reed beds during a field visit, and this may cause problems with birds. Compensating wetlands/ecosystem may be considered as a parallel development to attract migratory birds as opposed to the treatment wetlands. This will be further discussed in paragraph 3.3. It must be noted that negative environmental impacts should be compared with the alternative to reed bed treatment, namely deep well disposal, and not to a "zero-impact" situation. Moreover, they should be evaluated for their own merit, agreed upon or rejected by all stakeholders.

Reed bed effluent

The effluent of the reed bed will be used for forestry production (Eucalyptus) in this scenario. Forestry is only one of the many options of water use. It is also stressed here that a combination of production systems may use the water. Alternative water uses that have been suggested are water for shallow drilling (salinity too high to continue use for deep drilling), water for fire protection (not a continuous demand, but in case of emergency, tree water supply could be reduced to allow water to be used for fire protection), water for a multitude of crops (sugarcane, honey producing trees, forages etc), water to be used for the local community.

At present, a PDO requirement for making the water available is that it will not enter the food chain, thus crops for direct consumption, or fodder crops are excluded from the water use potential at the current situation (If it can be proven that there is no health risk anywhere in the food chain, relaxation of the food chain rule may be possible. However, public perception of products grown with produced water may prevent marketing of these products).

Since the reed beds have treated the produced water for hydrocarbons, only salinity and boron remain as a concern. Produced water after treatment will likely have a salinity of 6,000-11,000 ppm, boron will likely have a value between 4 and 7 ppm, and OIW content will likely be less than 5 ppm. The boron concentration will limit the potential of the water for agricultural/forestry options, but is not a critical limitation (production with boron tolerant crops/trees will still be possible). The salinity concentration has the same concerns; the water will limit the potential, but not critically restrict water use.

Forestry header system

A fairly constant supply of water will be obtained from the reed bed outflow. The outlet of the reed beds cannot be restricted to manage the inflow for the forestry system, since this would limit the flow capacity of the reed bed system. However, due to seasonal variations in temperature, water demand by trees would be variable.

There could be several strategies to work with this offset between water delivery and water requirement. The most logical method would be to create reservoirs between the reed bed and the farming system. This would, however, result in a very large storage capacity required.

Another management option to avoid the necessity of excessively large storage capacity is to over design the area planted under Eucalyptus. The trees will grow with less water (and be less productive) than under optimal watering conditions during the hotter months. During the cooler months, a larger area can then be irrigated at the capacity of the tree uptake, and the requirement for large storage is reduced.

The header system of the forestry system will also be dependent on the irrigation method used. Any type of pressurized system (mini-sprinklers, drip irrigation, bubbler irrigation) would require a more expensive irrigation system than non-pressurized systems (furrow, basin, flood irrigation). A pressurized system often obtains higher water use efficiencies than non-pressurized systems. However, in the case of using a constant supply of water with variable demand, as described in the paragraph above, water use efficiency is not the major concern. There is enough water, and the main aim of the production is to dispose of the water in a safe manner.

This may be a conflicting objective between PDO and a commercial contractor, who will want to maximize profits of the forestry production by optimizing forest area. These different objectives may result in different irrigation system requirements.

Since the soil depth is generally shallow and the soil type is sandy/loamy, the potential exists to use surface irrigation using furrows. Using furrow irrigation, applications of 10 – 15 cm are common, and during peak demand, a 10-15 day irrigation interval could be obtained (this interval will be smaller when establishing trees are considered to prevent wilting, or larger during the winter period). This will create a wetting/drying cycle that may stimulate root development laterally. Bubbler or drip irrigation, besides the potential prohibitive costs in the proposed system, will deliver water very locally to the trees, which may restrict the stimulus for roots to develop, which may in turn create a danger of tree toppling.

When surface irrigation is used, gated pvc pipes could be used to transport water to the irrigation plots. An alternative is open channels. Topography of the area appears to be sufficient for non-pressurized irrigation (at the current location of the trial reed beds, a 2 meter difference of height over a 400 m length was measured before construction; this would be considered a high slope for surface irrigation).

Forestry system

The forestry system should be adjusted to local conditions. Two limiting factors for tree selection are the salinity of the available water, and the shallow soil depth.

The salinity of the available water after biological treatment could range between 6,000 and 11,000 ppm. There are several Eucalyptus species (and other tree species) that can survive these salinities (Appendix E), but water use will be reduced as well. Tree testing is recommended, since tree species and sub species can react variable on soil and climate conditions.

Boron may be a limiting factor for tree growth, although most Eucalyptus species that are salt tolerant can also tolerate high boron concentrations. Boron removal at the present time is not an economic feasible option, although technically possible (Trambitas et al, 2003; Thorsen, 2003)

Eucalyptus trees have been restricted in Oman, due to the perception that these trees are high water users. However, an exception for a Eucalyptus forest can be made in the Nimr area, since the plantation would not use water from readily available water sources (pers. comm. Ministry of Municipalities, department of Environment).

During construction of the reed beds, soil composition is important. In the trial version, soil was transported from up to 15 km away to provide the correct soil type. To minimize effect of soil pits and major soil transport, it would be logical to develop the reed beds were the soil is, and transport the water to the soil, as opposed to transporting soil to the water.

Due to a shallow depth of the soil profile, and the risk of salinization, it is highly recommended to develop a drainage system (most likely subsurface drainage, similar to the drainage system used in the reed beds). A drainage system will have the main goal to remove applied salts from the soil to maintain favorable soil salinity conditions. Drainage effluent must be collected in evaporation ponds where water can be separated from the salts. As long as the salts are contained during and after the project, environmental permits will be given for the project (pers. comm. Ministry of Municipalities, department of Environment).

Based on water availability data, 1200 ha of trees would be required for a reliable and fairly constant water demand (Appendix F and G).

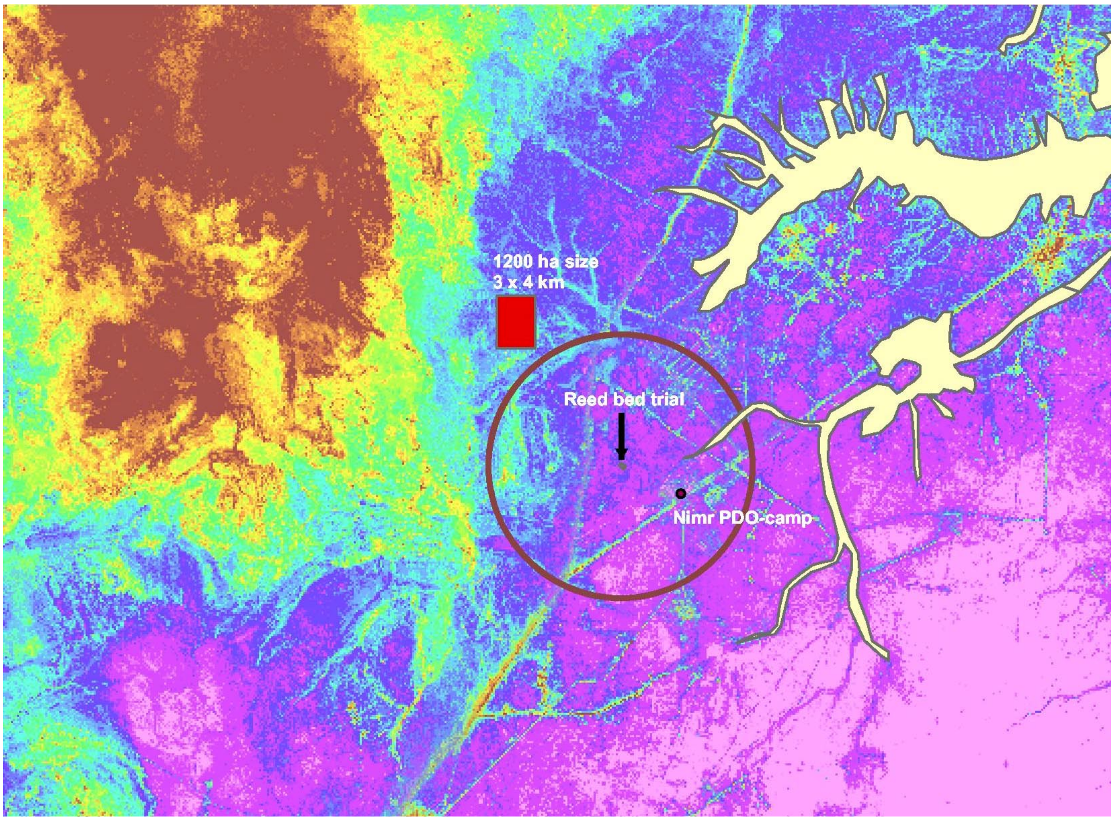


Figure 3 Landsat5 TM false color image of reed bed location in Nimr. Circle with reed bed location at the center indicates 10 km radius area. Nimr PDO camp is indicated within the circle. Soil type 7 (semi-suitable for irrigated agriculture) is approximated on the right using yellow areas. An area of 1200 ha is shown in red for size comparison.

Forestry reliability

Similar to the reed bed system, the forestry system must be reliable in water demand. However, the forestry system is more flexible in water application than the reed bed. Since the trees cover a large area, a buffer of water storage is available in the root zone (Appendix H). Trees do not necessarily have to be irrigated to full water use potential. Certain levels of water stress will be acceptable when the objective is to use water (as opposed to using water for optimal biomass production).

Over-design of the forest area will increase the reliability that water will be used (evapotranspiration). Over-design will imply that certain parts of wood production will likely not be profitable (tree production is then not maximized, and economic inefficiencies will occur).

Forestry safety
Fire danger is a major safety risk in a forest operation, especially in a desert climate. To reduce risk of forest fire, it is advised to design the area such that fire safety strips exist in between smaller units of forest.

Windy conditions, combined with a shallow root zone for the trees may result in tree toppling. Good management of the tree growth is needed to minimize the risk of tree toppling.

One of the requirements by PDO of a reed bed/forestry operation is that products will not be taken up in the food chain. For this reason, it is important to make local population aware of the potential dangers of using products from the forest operation. Also, grazing of camels in areas irrigated with produced water must be prevented through fencing. It is unlikely that there will be immediate health concerns, but at the present time, there is uncertainty related to food safety and long term effects on health, thus making prevention of product uptake in the food chain an important issue.

Drainage system and root intrusion
The forestry system will need artificial drainage to move salts through the system and collect them in evaporation ponds. Artificial drains in a shallow soil are technically feasible, but care should be taken that root intrusion does not occur. A generic rule is that the root system does not extend beyond the leaf canopy of the tree, thus drainage lines should be installed at sufficient distance away from the trees. It is also recommended to design the drains that outflow can be managed, thus allowing to keep drains permanently filled with water, thus reducing the chance that roots will develop in the drains.

3.3 Upscaled system considerations

Overall system distribution
For the forestry system, the soil depth available at Nimr may be a limiting factor. An option exists to create spatially distributed smaller forests on suitable soils, as opposed to creating one large continuous tree plantation. For each forest area, a set of reed beds may be constructed near the forest plots, reducing the potential risk of monoculture (large scale reed beds/forest may be more susceptible to diseases or insects than a distributed system, however, the trial versions never experienced major pests or diseases). This distributed system will need a more complicated water distribution system, but technology and knowledge on water (and oil) piping is locally available.

To prevent salinizing existing non-saline soils, it may also be an option to develop forest plots on already salinized soils. These soils will likely be found in depressions (e.g. wadi's), which may bring a serious risk of flooding of the forestry operation if a rainstorm occurs. On the other hand, salts in a depression which includes drainage could be leached by a rainstorm event. Another complication is that wadi's provide a very valuable – and virtually the only – resource (providing fodder) for the Bedouins. It is likely that the Bedouins will claim customary rights on the land.

A decentralized type of operation (for example 4 REC units, operating almost independently on 1/4th of the available water) would reduce some of the reliability risks, but would also reduce the economic advantages of a large scale operation.

Waste management after project termination
After termination of a project using a REC system, an area of more than 1200 ha would be abandoned. This would have a similar environmental impact as the development of 1200+ ha reed bed and eucalyptus forest. An environment (insects, birds, wildlife) will have developed around a REC system that, without water, will likely not survive. It is suggested to develop starting at the early stages of the project, a compensating forest/wetland area at the same time as making the REC system as unattractive as possible to wildlife (it will be impossible to limit insects, thus birds and wildlife will be attracted regardless to the forestry production). This compensating forest/wetland area should be maintained even after project termination. Note that this should be a **negotiation point** between PDO and contractor, but also between PDO and the Omani government.

At the end of the project, all useable wood will likely be harvested to obtain maximum profit. When water is not available for regrowth, only few trees will likely survive (on rain water, stored soil water), but tree development will be severely limited.

Reed beds will, after termination, likely die off. Soil in the reed beds must be collected in a contained waste pit, or reed bed soil will have to be washed with a Chelate solution (light acid) to remove any accumulated heavy metals, similar to the proposed maintenance of the reed beds (pers. comm. Dr. Hasbini). Soil in the reed beds is in itself contained through the use of liners. It is likely, however, that liners need to be removed after termination of the project, to allow return to the "natural state" of the area.

A major impact that the project will have is the accumulation of salts from deep aquifers to the soil surface. When water and salts during the project duration were well managed, most salts will have been collected in the evaporation ponds. The ministry of Municipalities (Department of the Environment) has indicated that as long as salts are contained at the end of the project, that permits will likely be issued. Their viewpoint is that without water, there is no waste after 20 years, but there has been no (local, ecological, economic, etc) development in the area either.

Monitoring of the deposited salts for possible accumulation of naturally occurring radioactive material (NORM) is recommended.

Ecological aspects of water use

Compensation forest/wetland cannot be developed using produced water, since this is water that, per PDO's request, should be kept out of the food chain. Shallow groundwater is a more likely water source. Shallow water disposal of produced water was terminated to prevent oil and boron contamination of the shallow groundwater. However, boron increases measured in the shallow groundwater are limited, and the water quality appears sufficient to be used for compensating forest. The salinity of this water (6,000 ppm) is high, but native salt tolerant species of trees have been tested (pers. comm.. Min of Municipalities) and could be grown. Suggestions were made that this compensating forest can also be used as compensating area for local development. Honey trees could be grown, and other trees that could provide grazing material for camels and goats could be provided as well. The size of this compensating forest can be determined based on negotiations between PDO, local population, government and contractor. Shallow groundwater consumption, requirements from local population and requirements from ecological development should be taken into account.

Environmental monitoring

Monitoring of a REC system would be of major importance for both management and reliability of the system, as to provide enough insight in environmental management and the prevention of problems.

Water volumes and water quality will have to be monitored at different stages in the water chain for system evaluation and management purposes. The monitoring system needs to have an alarm function, such that when certain reed beds do not function as designed, adjustments can be made.

Some heavy metal accumulation is expected to occur in the reed bed soil system. Note that heavy metals are present in trace amounts, and that the quantities are not considered problematic. Monitoring of water effluent as well as the soil chemistry composition can provide a better insight on the required timing for reed bed maintenance.

Soil salinity monitoring is needed mainly in the forest system, both to prevent soil salinization that could affect tree production, as well as monitoring of the effectiveness of the drainage system to prevent the creation of a salt-wasteland at the end of the project.

Shallow groundwater monitoring will be required for environmental purposes. Both the quality and the water levels will need to be monitored, since shallow groundwater exploitation may be part of this project.

Some of the monitoring requirements could be combined with research topics for interested institutions and universities. It may be in the interest of the contractor and PDO to develop a research program on the long-term effects of using produced water on the bioaccumulation of heavy metals, both out of scientific interest, as well as to provide an alarm function in case that accumulation proves to be problematic for human or animal health. At the current time this is not expected to occur.

Labor and local community

Labor requirements for an agricultural system are variable over time. For the reed beds, maintenance of reeds, irrigation system, and drainage system are more or less continuous tasks. Peak labor demand will be needed during planting or seeding of the reed beds, but this is a one-time labor requirement. Operating the irrigation system of the reed beds will mainly be automated, thus monitoring of the irrigation system, and monitoring of influent and effluent water quantities and quality is an important additional task. For an area of 66 hectare, 2 full time skilled people should be able to manage the reed bed system (compare to an irrigator in California who manages 250 ha of crop production).

The forestry operation (1200 ha) requires some more labor intensive irrigation, although depending on the layout of the irrigation system, this can be partially automated as well. Planting trees is a one time peak labor demand. Harvesting is a more continuous labor demand (600 ha do not necessarily need to be harvested all in one week), but will only require labor six years after initial planting, and is highly mechanized. Land preparation will be done using tractors, thus operators will be needed, but this will be done only at the establishment of the forest system. Weed control, and soil management (prevention of crusting, soil aeration, furrow maintenance etc) is all mechanized. In a continuous forest production, timing is more flexible than in annual row crops, thus farming operations in a forestry system can be spread out more over time. This reduces the need for peak labor.

It is estimated that, similar to labor development at the Rahab farm, local laborers can be trained “on-the-job” when interest exists.

Other upscaling considerations

For large scale farming/forestry, agricultural equipment will have to be purchased. This includes tractors, sprayers, land preparation equipment, and later during the project, tree harvesting equipment, and transport trucks. On-farm transportation could be done through “gators”, which are more manageable than pick-up trucks. It may be advisable to maintain a bulldozer and transport truck as part of fire fighting equipment, that can also be used during construction and emergency maintenance. Purchasing cost can likely be written off against savings compared to local contractor prices for soil movement.

Fertilizer can be added when necessary, using standard application methods; either through mixing tanks at the irrigation inlet, or through dry application followed by irrigation.

Field roads in a forestry system do not need to follow PDO-road construction regulations. Field roads are not heavily traveled, and will only be used either for

heavy equipment (tractors, harvesting equipment, transport trucks) or light equipment (gators). Grading will be sufficient for maintenance roads.
Fencing of the area will be needed to keep wildlife and camels out. For an area of 1200 ha (3 x 4 km), approximately 14 km fence will be needed.

4 Involving the local population

4.1 Two worlds

Oil and gas exploration and production is a highly specialized business of which the dynamics are dictated by the global economy. Camel and goat rearing are activities that do not require much formal education and of which the dynamics are local or regional. In fact the two activities could co-exist next to each other yet be completely separated. At Nimr they are only marginally interrelated:

- a limited number of local people work at the PDO facilities as service people
- construction contracts for low-technical services are offered to local community contractors (LCCs)
- in case of a new oil-related project compensation is paid to the nearest local community or communities; this assumes the form of all kind of hardware, including pumps, schools and health clinics; projects with a budget of over $ 100,000 carry a budget line for social investments of 0.5-1.0% of the project budget
- complaints about damage often result in compensation

The former two relations are controlled by contracts, which stipulate clear standards and norms regarding what is allowed and what can be expected. In case of the fore last and last relation a contract does not appear to exist (a service level agreement of some sort stipulating what can be agreed does not exist apparently). In the absence of any norm setting institution demands for compensation are not restricted. It is believed that PDO feels uneasy with this relation at times.

4.2 Direct involvement in decision making by local population

The question is raised whether a farm producing trees on a commercial basis can be a similar isolated activity. The nature of the project motivates the study team to believe that it cannot and it should not. The crucial factor is water, by far the scarcest resource in the area, and a resource that the local people will be very eager to improve their access to. With more of it, their standards of living can improve. All types of products can be generated that could be marketed at the local and regional market. Of course it is true that the treated water is of a quality that limits its usage as an input to many production processes, or needs highly sophisticated technologies to make it available at acceptable quality, but this is not as the local people see it, at least until now. To illustrate this, the following is an excerpt from the study team's day-to-day report describing the expectations voiced by one of the local informants:

"<He> suggested that perhaps coconut palm or date palms were possible. He strongly suggested grazing grounds, or at least fodder. Or the water should be given to the local people who then would put it to some effective use. He further suggested

– expressed feelings of local communities – that the attractive opportunities would not be contracted out to an (international) firm. The local people would not benefit".

The usual way for PDO to discuss new projects with the local population is by organizing an Initial Impact Evaluation, which is basically a procedure to scope present conditions and possible negative or positive spillover effects of a new project, followed by more in-depth studies within the framework of an Environmental Impact Assessment. Such studies are in the field of social society, health, and the environment. Stakeholder engagements complete the process. The engagements are meant to inform the people about the project and how it would affect their lifestyles. In the process base line data are collected that describe the population and the conditions of their lives prior to the start of the project (to be compared with later or ex-ante data, should this be needed). Ultimately agreements can be made about the level of compensation that the local population will receive (see above). It is important to note that the project itself is not subject of discussion. Only when exactly and where exactly the project will be implemented may be negotiable (latter statement needs verification).

These procedures can also be applied in case of the REC project, but are not sufficient. The important difference is that in case of the REC project, the local population or their representatives should be invited to participate in the actual design of the project. Direct involvement in decision making by the local people is needed in order:

- to ensure their longer term approval of the project, which is also in the interest of PDO
- to improve the standard of living of the local people
- to prevent them from being marginalised in the socio-economic sense in case the rural development process, that potentially is started with the first REC, followed by more of such projects, really takes off

Offering the kind of compensation that is usually provided does not structurally change the access that the local population has to the resources on which they depend, hence, their chances to improve their standards of living. Offering them access to (clean) water does. What exactly needs to be done cannot be decided by PDO or any other outsider, but is decided by the local people themselves in consultation with PDO. Thus far PDO's plans have incorporated the interests of PDO itself and of the contractor that will win the tender and set up the REC; the plans should be elaborated to integrate the interests of the local people.

4.3 (High level) decision making

Present relations between PDO and the people living in the immediate surroundings of the oil extraction facilities are maintained at basically three platforms:

- at the office of the Community Relations Officer, at Marmul or at the Nimr base camp; these are day-to-day contacts,

- at the three-monthly meetings between senior PDO staff and high level representatives of the local people, Sheikhs and Walis
- occasional meetings at ministry level; these are ad hoc meetings that take place to discuss problems that cannot be sorted out at the other platforms

To this could be added the not-regular meetings to prepare projects discussed earlier. The meetings of the Social Investment Committee are of a different nature. Participants of this committee are representatives of the Government of Oman and PDO, not local people. On the agenda of these high level meetings are coordination between Government and PDO plans, formal agreement of (large) projects, five year development plans, etc.

The detailed technical design of the REC project should be on the agenda of the three-monthly meeting between PDO and high level local representatives. Not for approval, but for discussion, with the possibility to change (even reject) the plan. The basic question should not be whether the project can receive a green light and the kind of compensation that would be appropriate, but how the interests of the local population can be catered for in the project. It is important to realize that this is a fundamentally different question.

4.4 Timing and other operational issues

The dialogue with representatives of the local population and also the stakeholder engagements can start immediately after PDO has given the green light for the up scaled REC. The study team discussed the Tender Plan for Reed Bed Commercialization (C31/0631, version 5 May 2004), by PDO. Two critical moments in time on this tender plan are:
- 30 June 2004, at which date the Major Tender Board approves the project, and
- 23 October 2004, the date on which the tender package must be ready

After this date changes should not be made to the plans. This leaves the period between 1 July and 23 of October, or almost four months, for the dialogue with local representatives on the detailed plans. This is considered sufficient. The tender plan itself does not need to be changed. The dialogue with local people can proceed parallel to the PDO tender process.

Not included in the plans yet, but relevant because of several reasons is the need for a monitoring plan. The aim of the monitoring system is to gather information on the changes that are occurring. In case of unwanted changes adjustments can be made. The base line survey that is standard procedure in the stakeholder engagement procedure can be used as a starting point.

It was already mentioned that the standard PDO HRM (HSE) procedures can also be applied in this case, but need modification:
- (high level) local people need to be invited and assisted to help taking major decisions as to what the project will actually do and how

- these consulations – dialogue - need to start immediately after PDO has taken the decision to implement the project, and continue throughout the project (see also section 6.2)

The question presents itself whether PDO has the ways and means to mobilise the local represenatives for this purpose and for their role in the decision making process, hence to make the dialogue a success. The HRM department does have the required expertise. A problem is, however, that the standard practice does not recognise the two above mentioned, crucial points. In fact, in case of this water (development) project the orientation of the approach towards the local people needs to be different from how PDO works usually. It is believed that this change in orientation is most effectively achieved with assistance from outside (consultant, contractor).

4.5 Some relevant sociological factors

There are five tribes with a possible interest in the Reed Bed Farm, because of their proximity to the farm: Al Jazar (mainly cattle rairers, fishermen, employees), Shleem (some grazing and fishery), Heima (employees, few farms, some cattle rairers), Thimrit (employees, civil servants and army people, some farms), and Mukshin (cattle, employees, near the 'empty quarter', where water is really scarce). Depending on the exact details of the project and its exact location one or perhaps two of these tribes have a more direct interest in the project. It is noted that near to the PDO camp people of the Harsoosi tribe were met.

One can anticipate a request by the local people for growing fodder, as this is one of the resources that they depend on. It can also be anticipated that PDO's plan to establish a REC will not be challenged. Given the quality of the treated water, it should not be used for growing fodder. It may be possible, however, to use ground water to grow fodder as a parallel activity next to using treated water for tree production. The management of the REC project could also assume responsibility for growing fodder, or a shared management board is created in which also local people participate, or responsibility for growing fodder is given to a local firm. The latter options are preferred for a rural development perspective. The management question is another issue to be tackled during the meetings with the local representatives.

The assessment by the study team made clear that Sheiks and other Wali can be trusted to organize opinion forming in the local communities and that they are the ones that can effectively negotiate on behalf of the local communities. The accepted PDO practice to organize stakeholder engagements can be considered to be supplementary. The two procedures together should provide sufficient guarantee that the opinion of the different interests of the local population are accommodated for.

Finally, when planning the exact location of the REC – reed bed and tree estate – one should take into account the use that local people make of the land, even of land that looks unsuitable for any purpose. People have customary rights to that land, even though it is PDO concession land. The wadis in particular are important to the local people, as they are used as grazing land.

5 Financial

This chapter will provide insight into the costs of using oil-contaminated water – treated by means of reed beds- to grow Eucalyptus trees in relation to generated benefits. The cost-benefit analysis of the reed bed Eucalyptus combination (REC) is just an example of such an economic feasibility study for alternative use of oil-contaminated water. The data used and assumptions made in previous economic analysis -which indicated that REC was economically not feasible- are reviewed in this study.

The costs of the delivery system depend on the distance of the Deep Well Disposal (DWD) injection well from the Nimr production station (NRPS). The longer the distance the higher the operating costs of the booster pump and the costs of the CS-PE (Carbon Steel PolyEthylene lined) pipeline. For a comparative analysis costs are calculated from the tap point onwards for DWD as well as for the REC (the costs of the CS-PE pipeline are therefore not taken into account). The total present value of the DWD pump operating cost is 0.11 $/m3; this is the sum of the present value of the capital costs involved (0.028 $/m3: design, wells, pumps, pipes and construction) and the present value of the costs for operation (0.075 $/m3: power cost). All costs are calculated over a 20 year period (PDO, 2003a). The operating costs are based on constant energy costs of 31.5 $/MWhr for the year 2001, not considering possible changes.

In Section 5.1 the various costs and benefits of REC will be presented for the header system, reed bed system, crop production (Eucalyptus) and other costs and benefits. In Section 5.2 three scenarios of reed bed eucalyptus combinations (REC) are evaluated. The sensitivity of the results to the assumptions made is tested in Section 5.3.

5.1 Costs and benefits

A breakdown of costs and benefits for A) mechanical pretreatment by means of Dissolved Air Flotation (DAF); B1) 15 ha reed bed versus B2) 65 ha reed bed; C1) 900 ha Eucalyptus versus C2) 1200 ha Eucalyptus; and D) other costs like costs of Rhodes grass for local people and wildlife forest is shown in Table 5.1. A distinction is made between capital and operating costs. The underlying assumptions are described in detail in Appendix K.

The flow of costs and benefits over a 20 year period are converted to a present value using a 8 % discount rate (as a discount rate of 8% was used as well to calculate the costs of DWD). The total cumulative present values of the cash flows are presented in Table 5.1 as well as the contract price of water, i.e. minimal payment required for receiving water in order to break-even.

It becomes clear that the costs of mechanical pretreatment by means of DAF exceed the benefits of oil recovery, due to the high costs of chemicals used in DAF ($290,000 per year). A price of water of 0.015 $/m3 is needed to cover costs of mechanical pretreatment.

Table 5.1 Cost and benefit of pretreatment, reed bed, Eucalyptus and other cost

	Costs	Remarks	Total Cumulative Present Value over 20 yr ($)	Contract price to break-even ($/m3)
Capital costs Dissolved Air Flotation (DAF)	-$1,500,000	Initial investment		
	-$1,500,000	Replacement in year 10	-$2,194,790	0.014
Operating costs DAF	-$350,000	Annual Cash flow	-$3,436,352	0.021
Benefits Oil recovery	$330,000	Annual Cash flow	$3,239,989	-0.020
A) Mechanical pre-treatment			**-$2,391,153**	**0.015**
Capital costs reed bed	-$4,000,000	Initial investment	-$4,000,000	0.025
Operating costs reed bed[1]	-$30,000	Annual Cash flow		
	-$5,000	Cash in yr 9, 10, 11	-$301,506	0.002
			-$4,301,506	**0.027**
Capital costs reed bed	-$8,000,000	Initial investment	-$8,000,000	0.050
Operating costs reed bed	-$30,000	Annual Cash flow		
	-$5,000	Cash in yr 9, 10, 11	-$301,506	0.002
			-$8,301,506	**0.052**
Capital costs water reservoir	-$50,000	Initial investment	-$50,000	0.000
Capital costs Eucalyptus[2] incl. evaporation pond and seed	-$1,480,000	Initial investment	-$1,480,000	0.009
Operating costs Eucalyptus[3]	-$36,000	Annual Cash flow	-$353,453	0.002
Benefits Eucalyptus[4]	$1,350,000	Cash in yr 6, 9, 12, 15, 18	$2,825,581	-0.018
C1) 900 ha of Eucalyptus			**$942,128**	**-0.006**
Capital costs Eucalyptus[2] incl. evaporation pond and seed	-$1,930,000	Initial investment	-$1,930,000	0.012
Operating costs Eucalyptus[3]	-$36,000	Annual Cash flow	-$353,453	0.002
Benefits Eucalyptus[4]	$1,800,000	Cash in yr 6, 9, 12, 15, 18	$3,767,442	-0.023
C2) 1200 ha of Eucalyptus			**$1,483,989**	**-0.009**
Miscellaneous capital costs	-$500,000	Initial investment	-$500,000	0.003
Other operating costs	-$70,000	Annual Cash flow	-$687,270	0.004
D) Other costs			**-$1,187,270**	**0.007**

[1] Consists of $21,600 labour (1.5 units of 14,400 $/yr/unit) plus $8,400 other costs.
One-third of the reed beds will be remediated with light acid in year 9, 10 and 11 at a cost of $5,000.
2 Consists of $1,500/ha plus $120,000 for an evaporation pond and $10,000 for seed.
3 Consists of $36,000 labour (2.5 units of 14,400 $/yr/unit).
4 Consists of 5 harvests of half the area in 20 yr of 100 tonnes/ha/harvest at a price of $30/tonne.

The capital costs of creating reed beds are relatively high compared to the operating costs. It is the highest cost component in the analysis. A contract price of water of 0.027 $/m3 is needed to cover costs of 15 ha of reed bed and a contract price of 0.052 $/m3 is needed to cover costs of 65 ha of reed bed.

Benefits of Eucalyptus production exceed the costs when the price of Eucalyptus is $30/tonne, although it takes 12 years before cumulative benefits of Eucalyptus production exceed cumulative costs, as the initial investment costs are high. It reduces the contract price of water with 0.006 $/m3 in the case of 900 ha Eucalyptus and 0.009 $/m3 in the case of 1200 ha Eucalyptus Benefits of 1200 ha equal costs when the price of Eucalyptus is $18.5/tonne.

We assumed annual operating costs of $ 36,000 for labour. When an expatriate will be involved, costs can be even $150,000 for labour and a price of 0.009 $/m3 (instead of 0.002 $/m3) will be needed to cover labour costs. The contract price for 900 ha Eucalyptus will be 0 $/m3 and -0.002 $/m3 for 1200 ha Eucalyptus in that case.

We assumed $120,000 for an evaporation pond. When costs are $1,200,000 the required contract price will increase 0.006 $/m3.

A price of water of 0.007 $/m3 is needed to cover all other costs, when we assume miscellaneous capital costs of $500,000 and annual net operating costs of $70,000 for Rhodes grass and wildlife forest. Miscellaneous costs includes costs of tractors, vehicles, machinery to plant and harvest, farming equipment, cabins, housing, road, forest fence of 14 km ($100,000), sampling, environmental monitoring, waste management after the project terminates etc. When miscellaneous capital costs are $1,000,000, a price of 0.010 $/m3 is needed to cover all other costs (as a price of 0.006 instead of 0.003 $/m3 is needed to cover the miscellaneous capital costs).

5.2 Scenarios

Three scenarios of REC have been evaluated, respectively REC1, REC2 and REC 3 (see Table 5.2). REC1 combines 65 ha of reed bed with 1200 ha of Eucalyptus. The area planted under Eucalyptus is over designed to avoid the necessity of large water storage (to offset the variable water demand by trees and fairly constant supply of water). In REC2 there is mechanical pretreatment by means of Dissolved Air Flotation (DAF), which reduces the required size of the reed beds to treat the water to 15 ha. REC3 combines 65 ha of reed bed with 900 ha of Eucalyptus. A water reservoir is created between the reed bed and farming system to offset the difference in timing between water delivery and water requirement. The contract prices of Table 5.1 are used to calculate the contract price of each REC in Table 5.2.

The contract price of water for each of the three scenarios are shown in Table 5.2 as well. The contract price of water is 0.050 $/m3 for REC1 and 0.053 $/m3 for REC3. The contract price of water is lowest (0.040 $/m3) in the case of mechanical pretreatment (REC2). This is mainly the result of the smaller capital costs for creating 15 ha instead of 65 ha of reed bed. (If the capital costs of creating 15 ha of reed bed would have been $ 5.5 million, the contract price of water would also be equivalent to 0.050 $/m3).The benefits of Eucalyptus production are more or less equal to other costs involved, which means that treatment is the main cost component.

Table 5.2. Scenarios evaluated and contract price of water for each of the scenarios $/m3

	REC1		REC2		REC3	
Mechanical pre-treatment			DAF	0.015		
Reed bed treatment	65 ha	0.052	15 ha	0.027	65 ha	0.052
Buffer capacity					Reservoir	0.000
Eucalyptus	1200 ha	-0.009	1200 ha	-0.009	900 ha	-0.006
Other costs		0.007		0.007		0.007
Contract price of water		0.050		0.040		0.053

It takes time before initial investment costs of 10.43 M $ are recovered. Figure 5.1 shows that it takes for instance 15 years before benefits equal costs in the case of a 20% profit margin on the break-even price. In case of a 40% profit-margin on the break-even price, it takes 12 years before costs are recovered. Every 10% increase in the profit-margin generates an additional 0.8 M$ at the end of the 20 year time period.

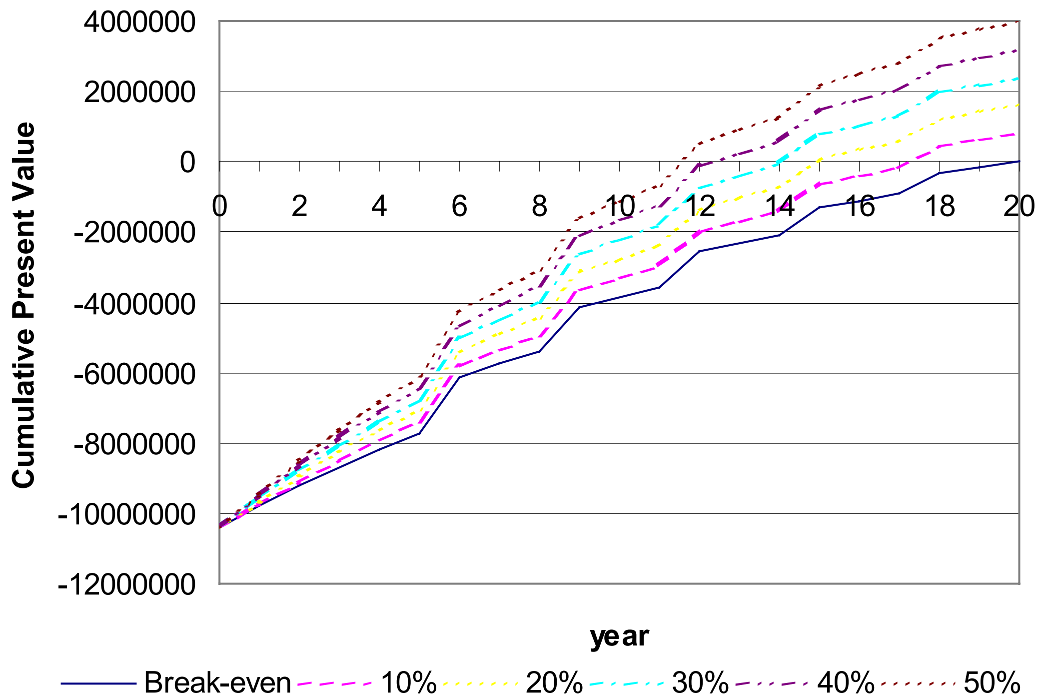


Figure 5.1 Cumulative present value of REC 1 for the break-even price plus a profit-margin of respectively 10%, 20%, 30%, 40% and 50% on the break-even price.

5.3 Sensitivity analysis

There is uncertainty about some of the value estimates. The impact of different values on the results of REC1 is studied in this section. The capital cost of the reed bed (-$8,000,000) may vary as well as the price of Eucalyptus ($30/tonne) and the costs of land preparation ($1,500/ha). The impact of 20% lower values as well as 20% higher values on the contract price of water are shown in figure 5.2. It is interesting to note that the impact of a change in the price of Eucalyptus is comparable to the impact of a change in the yield of Eucalyptus.

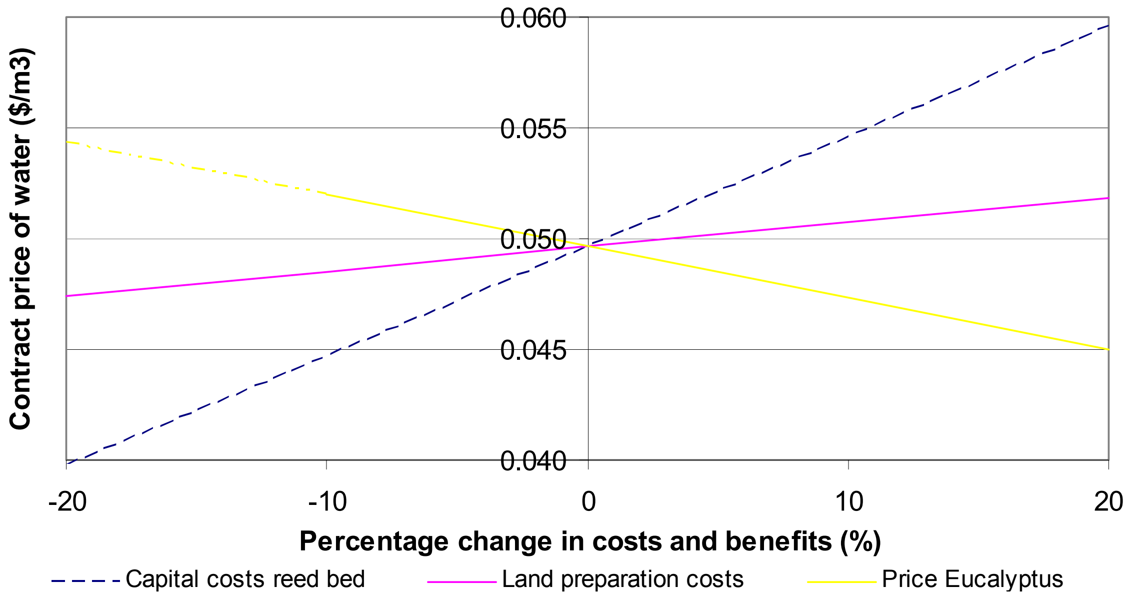


Figure 5.2 Sensitivity of the contract price of water

The steeper the line the more sensitive (responsive) the contract price of water to higher/lower values. Figure 5.2. shows that the contract price of water is most sensitive to a change in the capital costs of reed beds and least sensitive to the costs of land preparation.

5.4 Extreme cases

It is important to note in this respect that most assumed values are based on worst case estimates. The assumed capital costs of constructing reed bed are based on contractor rates for PDO. These seem to be rather high, as contractors use higher rates for PDO as rates are linked to oil field operational standards. When rates are linked to non-oilfield operational standards (e.g. water handling) then costs can be reduced considerably. Suppose for instance that the enterprise can do the job for half the costs ($ 4 million instead of $8 million) -which is not a very unrealistic assumption; agricultural systems designs can usually be more flexible than oil production system designs-, the contract price of water will be 0.025 $/m3 for REC1 and 0.028 $/m3 for REC3.

When the oil price is 30$ per barrel (instead of 16$), oil recovery benefits are $ 620,000/yr (instead of $330,000/yr). The contract price of water will consequently be 0.022 $/m3 for REC2.

We assumed capital cost of DAF of $1.5 million assuming a life span of 10 yr. The contract price of water is 0.040 $/m3 in that case (REC 2). Higher capital costs of DAF of for instance $4.5 million will increase the contract price considerably (0.067 $/m3) and mechanical pretreatment is not competitive compared to the other scenarios. When the capital costs are $3.0 million the contract price of REC2 is equal to the contract price of REC3 (0.053 $/m3).

As the potential market for Eucalyptus wood is not studied here, it is not clear whether there will be benefits from Eucalyptus. One of the suggested markets was an existing charcoal factory in Oman. When the wood can not be sold or transaction costs exceed the benefits the price of Eucalyptus will be 0 $/tonne, the contract price of water will consequently be 0.073 $/m3 for REC1, 0.063 $/m3 for REC2 and 0.071 $/m3 for REC3.

The flow of costs and benefits over a 20 year period are converted to a present value using a 8 % discount rate, which is rather high. When a discount rate of 4% is used, the contract price of water will be 0.03 $/m3 for REC 1 (and 0.04 $/m3 at a discount rate of 6% for REC 1)

When water is used for REC, there will be less DWD. PDO needs less carbon credits as a result of avoided emissions of eliminating DWD (say 26,000 tonne of carbon per year), which is $260.000 at a current price of $ 10 per tonne of carbon. The cumulative present value of such a cash flow over a period of 20 year is approximately 2.55 M $, which is equivalent to a saving of 0.016 $/m3.The price of carbon is expected to increase sharply as Kyoto targets are tightened and low-cost abatement strategies for initial emission reductions are exhausted. The price of carbon permits could be in the order of $102 per tonne of carbon by 2010 (Bueren and Vincent, 2004). Carbon credits generated by tree cropping is not taken into account here as it seems to be small (as Eucalyptus is only capable of sequestering 3.5 tonne of carbon per hectare a year). Besides Eucalyptus will only be a carbon sink when there is no CO_2 emission during usage of the wood.

6 Tendering and Monitoring

6.1 Tendering and contract issues

Also for this project an accurate and transparant tendering process is required. Basically the standard PDO tendering procedure can be followed. This implies that companies that have shown an interest in the project are screened on the basis of the information that they have provided with regard to their experience in similar projects, track record, solvability, etc. In this way a long list of projects is reduced to a short list. Companies on the short list are requested to produce a technical proposal, and separately a financial proposal. The technical proposals are evaluated first. Critical evaluation issues include:

- the soundness of the proposed approach from a technical perspective: will the reed bed design be adequate, will the estate be designed in such a way that the PDO objective to process the treated water is achieved, will the salts be managed appropriately, etc.
- the measures proposed to accommodate the interests of the local population
  the measures proposed to manage the positive and negative spill-over effects that impact on the environment

A system of points can be developed that attach weights to the different evaluation criteria. About ten evaluation criteria would provide sufficient insight in the soundness of the technical proposals.

One to three companies are selected on the basis of the technical proposals. The financial proposals of these companies are subsequently considered applying the standard PDO procedure.

One issue that needs careful attention (contract issue) is malfunctioning by the contractor with strong negative impact on PDO. More concretely the situation that the contractor cannot process the flow of water that PDO provides because of reasons that he is to blame for. The contract between PDO and the contractor should carry an article that allows PDO in such a case to take appropriate action to protect its interests. This should include the option to take over the operation, while ensuring appropriate reimbursement of capital investment.

Also in the contract should be mentioned that the contractor will guarantee continuous operation.

6.2 Monitoring

The REC project is innovate in the sense that waste water is processed in an unconventional way. The technical and social implications make it a complex project. Financially the project looks attractive. PDO has some experience with processing waste water in this way, but not on the scale as planned. And PDO plans to transfer responsibility and implementation of the reed beds and estate to a third party. The study team believes that a special effort needs to be made to help the project to become a success.

PDO is advised to set up an Advisory Board with the task to monitor the progress of the project and to suggest actions to direct the project, should this be required. Members of the Advisory Board should be recruited from those parties that have a direct interest in the success of the project; minimally PDO and representatives of the local population should be on the board. If required technical advisors could be asked to strengthen the board. Costs for the Advisory Board are not included in the financial analysis.

References

Almeida, A.C., J.J. Landsberg and P.J. Sands. 2004. Parameterisation of 3-PG model for fast-growing Eucalyptus grandis plantations. Forest Ecology and Management. In Press.

Anwar, T, 2004. Quote for construction of reed beds and irrigation system. Lalbuksh Voltas Engineering Services and trading LLC.

Bosklopper, Th.G.J., P.H.J. Verbeek, A.A.M.F.R. Smit, R. Hopman, 1999. "Greening the desert – feasibility study of produced water clean-up for irrigation". KIWA, Nieuwegein, The Netherlands.

Dillon, J., F. Memon and D. Butler, 2003. Report for Shell on 'Treatment Technology Review and Assessment for Petroleum Process Waters'. Imperial College London.

Farnworth, J., J. Youngman and P Cookson, 2003. "A review of the desert agricultural project Rahab Farm". 7-11 June 2003.

ICBA, 2002. "Evaluation of Reed Beds. A comprehensive analysis of the Nimr Reed-beds". December 2002 (Revised). International Center for Biosaline Agriculture, Dubai, UAE.

Landsberg, J.J. and R.H. Waring, 1997. A generalised model of forest productivity using simplified concenpts of radiation-use efficieny, carbon balance and partitioning. Forest Ecology Management Vol 95. pp 209-228

PDO, 2001. "Nimr reed-bed trial interim evaluation report". Report No. ONM/017/01. April 2001, ONE/13.

PDO, 2003a. "Water Management Framework 2002 – From opportunity to realization". Petroleum Development Oman LLC - Water Management Team. Report No: OSE/5-01-11-2002

PDO, 2003b. "Evaluation greening the desert technology". PDO Water Management Team. Report No. OSE/5-03-11.

Ritzema, H.P., 2004. Handbook Subsurface Drainage Practices. In Press

Sands, P. 2003. 3PGPJS - A User-Friendly Interface to 3-PG, The Landsberg and Waring model of forest productivity. Cooperative Research Centre for sustainable production forestry and CSIRO Forestry and Forestry products. Technical Report No 29, Edition 2.3

Tanji, K.K. and N.C. Kielen, 2002. “Agricultural drainage water management in arid and semi-arid areas”. FAO Irrigation and Drainage Paper #61, Rome.

Thorsen, G., 2003. “Boron removal from water sources in oil fields phase 1”. Norwegian University of Science and Technology. Report to Shell International Exploration and Production. Contract # 4600000941.

Trambitas, D, M. Seckler and G.J. Witkamp, 2003. “Literature survey on boron removal from water”. TU-Delft. Laboratory for process equipment.

Van Bueren, M. and D. Vincent, 2003. Eucalyptus biomass fuels: price competitive or way off the money?. 47th annual conference of the Australian Agricultural and Resource Economics Society, Perth, 12th-14th February, 2003.

Itinerary

Tuesday 4 May	departure Schiphol airport, Amsterdam
Wednesday 5 May	arrival Seeb airport, Muscat
	meeting with Tan Ging Taung (Head of Corporate
	meeting with Tan Ging Taung (Head of Corporate Environmental Affairs PDO), Anton Sluijterman (Head of the Water Team), Yasmeen Lawatiya (former Reed Bed project engineer PDO, Amir Ajmi (Head of the Sustainable Development Team PDO), Raja Hammadi (Social Performance Advisor PDO), Ahmed Mohd Al-Sabahi (Corporate Environmental Advisor PDO)
	technical meetings with Anton Sluijterman, Raja Hammadi
Thursday 6 May	meeting with Bassam A. Hasbini, irrigation management engineer at ICBA
	travel and visit to Rahab farm
	meeting with Salem Al Riyami (Head Construction Nimr) and Ahmed Kazzaz (manager Nimr Reed Bed facilities)
	visit at Nimr
Friday 7 May	presentation on Reed Bed Farm by Bassam A. Hasbani, followed by discussion
	meeting with Ahmed Saat, Community Relations Officer at Nimr
	meeting with Ahmed Kazzaz and Bassam A. Hasbani
Saturday 8 May	visit to families belonging to the Harsoosi tribe
	travel to Muscat
	meeting with T. Anwar (Lalbuksh Voltas Engineering Services & Trading L.L.C)
Sunday 9 May	meeting with Tan Ging Taung
	meeting with Salim Ali Al-Mamary (Assistant Director General Agriculture, Ministry of Agriculture and Fisheries
	meeting at Sultan Qaboos Universtity , Department of Soil and Water Sciences: Mushtaque Ahmed (Head of Department, hydrologist)), Malik M. Al-Wardy (soil scientist), Abdullah Al-Mahruki (PhD student Reed Beds), Sim Zekri (economist)
	meeting with S. Ramesh Sivathanu (Punj Lloyd LTD)
Monday 10 May	data and information processing
	meetings with Amir Ajmi (head Sustainable Development Team, PDO), mrs Shaza Zeinelabdin (environmental consultant)
	meeting with Ali Amer Al Kiymi, D.G. Ministry of Regional Municipalities, department of nature

	conservation, and Paul Sharples, Ministry of Regional Municipalities, department of environmental impact
Tuesday 11 May	data and information processing second meeting at SQU with Mushtaque Ahmed, S.A. Prathapar, Abdullah Al-Mahruki and Heiko Patzelt
Wednesday 12 May	data and information processing meeting with MacIntosch (PDO), wrap up meeting with PDO team to discuss provisional conclusions
Thursday 13 May	travel Muscat-Dubai visit and introduction to ICBA, Dubai. Meeting with Dr. Bassam Hasbini, Irrigation management scientist and Dr. Shoaib Ismail, Agronomist
Friday 14 May	team discussions
Saturday 15 May	arrival Schiphol airport

Appendix A Comparison of deep well disposal and reed bed treatment

In many places in the world, wastewater has to be used since there is no other alternative. Often, compared to fresh water use, using wastewater is more problematic, due to environmental concerns as well as sustainability of the system and waste production (e.g. salts). In the case of PDO – oil produced wastewater, there is an alternative to agricultural use, namely pumping it back where it came from (Deep Well Disposal; DWD). There are advantages and disadvantages to this alternative:

<u>* Advantages of DWD</u>
- Water is pumped back from where it came (similar depth and same reservoir).
- Possible contamination of oil, salts, boron and heavy metals to surface environment is minimized.
- Mechanical pumping is reliable and/or quickly repaired.
- No competitive claims are put on water use.
- Risk of visible environmental impact (positive or negative) will be lower than using water on the soil surface.

<u>* Disadvantages of DWD</u>
- Water (in a desert environment) is not productively used. In Nimr area produced water is brackish and found re-usable in reed bed and bio-saline pilots.
- Water is pumped back at another location than where originally produced as a waste and not supporting oil production.
- Rock fracturing could be changing aquifer characteristics or even jeopardize the reservoir cap-rock. It is uncertain whether the practice of ongoing and increasing water injection under fraccing conditions is sustainable for a long period (envisaged over 20 years)
- Costs of DWD are relatively high and will increase (PDO, 2003a), particularly when fuel gas is charged at commercial rate.
- Power generation for driving injection pumps contribute significantly to carbon-dioxide emission.

<u>* Advantages of biomass production</u>
- Solar energy is the main driver behind a biological system, thus replacing organic fuel sources.
- Biomass products could be made available to the interior market.
- Biomass production in the inland of Oman would fit in the policy of shifting agricultural production away from the water-scarce northern coast.

<u>* Disadvantages of biomass production</u>
- Biological treatment followed by biomass production is a complicated process.
- Biological treatment and water use for biomass production decrease reliability of safe water disposal.
- Competitive claims will likely be put on the water
- Visible risk of environmental impact large (could also be positive, however)

Appendix B Redesigned reed bed capacity (A1)

Based on chemical analysis for a 6 month period (Nov 2002 – April 2003), **assuming that during this period the reed bed was operated at a flow of 250 m^3/day**, a capacity of oil treatment was calculated using standard hydrology methods as follows (based on ICBA, 2002):

1) Since inflow and outflow measurement are taken at the same moment in time, while the inflow and outflow at that moment are not necessarily related (due to lag time, residence time), a probability curve was developed for inflow oil volume and outflow oil concentration.

2) The probability that OIW content of the outlet water of the reed bed is less than 5 ppm was 0.71. The concentration of oil in water entering the reed bed with a probability of 0.71 corresponds to approximately 240 ppm (ml oil per m^3 water).

3) Assuming a constant flow of 250 m^3/day (no actual measurements were available), a volume of 60.0 liter oil was treated in one day, on a reed bed area of 3500 m^2.

4) Treatment capacity of reed bed is 17.1 ml oil per m^2 of reed bed per day.

The total area needed for treatment of 45,000 m^3/day, with an average OIW content of 250 ppm, can be calculated based on the total volume of oil delivered per day (11,250 liter oil), divided by the reed bed capacity. This results in an area of 66 ha.

Note that the capacity of reed bed A1 is higher than previously calculated from the design of reed bed B1. Design changes made include:

- Coarser soil texture
- Decreased soil depth (from 1.25 m to 0.8 m depth)
- Different drainage layout and filter material (no membrane, fewer drains)
- Different irrigation layout (fewer irrigation lines)
- Provision for aeration (venturi air injector)

(ICBA, 2002)

<u>Note</u>: Compared with the efficiency of reed bed B1, at an outflow requirement of 5 ppm, a treatment capacity of 2.9 ml oil per m^2 reed bed was calculated. Reed bed A1 appears to function 6 times more efficient.

<u>Note</u>: If the inflow rate during the 6 month period of measurements was 100 m^3/day, the treatment capacity of the reed beds would have been 6.8 ml oil per m^2 reed bed, and the reed bed area needed to treat 45,000 m^3/day with 250 ppm would be 165 ha. However, based on personal communications, it is likely that the reed bed was operated at a flow rate of 250 m^3/day.

SAMPLE POINT	SAMPLE DATE		CHLORIDE	OIL IN WATER	TOTAL DISS. SOLIDS
			kg/m3	ppm (v/v)	kg/m3
NIMR REED BED A1 OUTLET	02-NOV-2002 15:00	2-Nov-2002	3.984	7	8.02
NIMR REED BED A1 OUTLET	09-NOV-2002 15:00	9-Nov-2002	3.481	4	7.26
NIMR REED BED A1 OUTLET	17-NOV-2002 10:00	17-Nov-2002	3.11	7	6.99
NIMR REED BED A1 OUTLET	23-NOV-2002 16:00	23-Nov-2002	3.481	5	7.25
NIMR REED BED A1 OUTLET	01-DEC-2002 10:00	1-Dec-2002	3.7	3	7.55
NIMR REED BED A1 OUTLET	21-DEC-2002 10:00	21-Dec-2002	4.047	0	8.26
NIMR REED BED A1 OUTLET	30-DEC-2002 16:00	30-Dec-2002	4.945	2	7.6
NIMR REED BED A1 OUTLET	04-JAN-2003 10:00	4-Jan-2003	5.863	1	8
NIMR REED BED A1 OUTLET	11-JAN-2003 16:00	11-Jan-2003	5.122	7	7.87
NIMR REED BED A1 OUTLET	18-JAN-2003 16:00	18-Jan-2003	4.968	3.4	7.8
NIMR REED BED A1 OUTLET	25-JAN-2003 16:00	25-Jan-2003	5.031	3	7.7
NIMR REED BED A1 OUTLET	01-FEB-2003 10:00	1-Feb-2003	6.209	3	7.67
NIMR REED BED A1 OUTLET	09-FEB-2003 16:00	9-Feb-2003	5.033	5	7.72
NIMR REED BED A1 OUTLET	16-FEB-2003 15:00	16-Feb-2003	5.012	5	7.41
NIMR REED BED A1 INLET	23-FEB-2003 17:00	23-Feb-2003	4.41	5	7.71
NIMR REED BED A1 OUTLET	02-MAR-2003 16:00	2-Mar-2003	4.56	7	7.88
NIMR REED BED A1 OUTLET	10-MAR-2003 16:00	10-Mar-2003	5.282	10	7.96
NIMR REED BED A1 OUTLET	16-MAR-2003 16:00	16-Mar-2003	4.966	2	7.92
NIMR REED BED A1 OUTLET	23-MAR-2003 10:00	23-Mar-2003	6.004	6	8.21
NIMR REED BED A1 OUTLET	29-MAR-2003 16:00	30-Mar-2003	5.106	0	8.68
NIMR REED BED A1 OUTLET	06-APR-2003 10:00	6-Apr-2003	6.17	14	8.93
NIMR REED BED A1 OUTLET	13-APR-2003 10:00	13-Apr-2003	5.78	3	8.82
NIMR REED BED A1 OUTLET	20-APR-2003 10:00	20-Apr-2003	5.78	3	8.91
NIMR REED BED A1 OUTLET	26-APR-2003 10:00	26-Apr-2003	6.399	0	9.45

NIMR REED BED B1 INLET	02-NOV-2002 15:00	2-Nov-2002	3.116	189	5.06
NIMR REED BED B1 INLET	09-NOV-2002 15:00	9-Nov-2002	2.619	238	5.63
NIMR REED BED B1 INLET	17-NOV-2002 10:00	17-Nov-2002	2.641	335	5.75
NIMR REED BED B1 INLET	23-NOV-2002 16:00	23-Nov-2002	2.113	206	5.8
NIMR REED BED B1 INLET	01-DEC-2002 10:00	1-Dec-2002	2.813	220	5.74
NIMR REED BED B1 INLET	21-DEC-2002 10:00	21-Dec-2002	2.881	125	5.88
NIMR REED BED B1 INLET	30-DEC-2002 16:00	30-Dec-2002	3.974	204	5.95
NIMR REED BED B1 INLET	04-JAN-2003 10:00	4-Jan-2003	4.545	376	8.2
NIMR REED BED B1 INLET	11-JAN-2003 16:00	11-Jan-2003	3.805	251	5.64
NIMR REED BED B1 INLET	18-JAN-2003 16:00	18-Jan-2003	3.914	314	5.61
NIMR REED BED B1 INLET	25-JAN-2003 16:00	25-Jan-2003	3.912	376	5.94
NIMR REED BED B1 INLET	01-FEB-2003 10:00	1-Feb-2003	9.922	51	5.95
NIMR REED BED B1 INLET	09-FEB-2003 16:00	9-Feb-2003	3.903	244	5.9
NIMR REED BED B1 INLET	16-FEB-2003 15:00	16-Feb-2003	3.931	79	5.82
NIMR REED BED B1 INLET	23-FEB-2003 10:00	23-Feb-2003	5.422	78	4.05
NIMR REED BED B1 INLET	23-FEB-2003 17:00	23-Feb-2003	3.19	46	5.74
NIMR REED BED B1 INLET	02-MAR-2003 16:00	2-Mar-2003	3.29	245	5.97
NIMR REED BED B1 INLET	10-MAR-2003 16:00	10-Mar-2003	4.24	379	5.91
NIMR REED BED B1 INLET	16-MAR-2003 16:00	16-Mar-2003	4.042	102	5.84
NIMR REED BED B1 INLET	23-MAR-2003 10:00	23-Mar-2003	4.806	44	5.32
NIMR REED BED B1 INLET	29-MAR-2003 16:00	29-Mar-2003	4.031	191	6.45
NIMR REED BED B1 INLET	06-APR-2003 10:00	6-Apr-2003	3.676	245	5.88
NIMR REED BED B1 INLET	13-APR-2003 10:00	13-Apr-2003	3.69	266	5.74
NIMR REED BED B1 INLET	20-APR-2003 10:00	20-Apr-2003	3.77	313	5.76
NIMR REED BED B1 INLET	26-APR-2003 10:00	26-Apr-2003	3.544	349	5.56
NIMR REED BED B1 INLET	26-APR-2003 10:00	26-Apr-2003	3.474	181	5.66

Appendix C Reed bed design

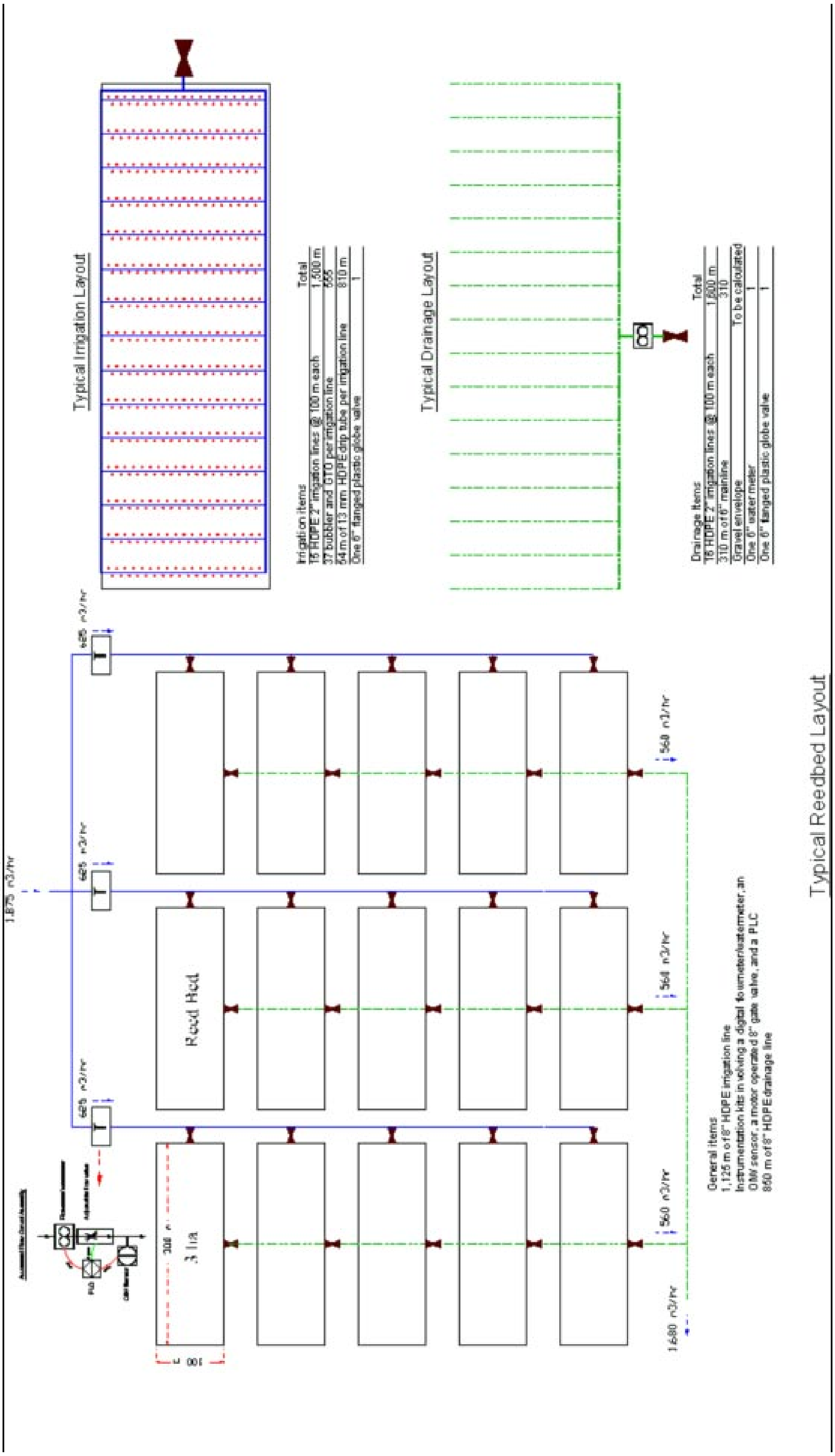
Each reed bed has several treatment cells. Each cell is defined by a single irrigation line in the center, and each cell is bordered by a drainage line. The length-width ratio for a cell is assumed to be allowed up to 0.2 (the smaller the ratio, the more expensive the system will be). An assumption of 100 m length per cell was made as being sufficiently length for good irrigation control. One cell will therefore be 20 m wide. The assumption is made that 15 cells per reed bed can be well managed, therefore each reed bed has a width of 300 m, and a length of 100 m (surface area 3 ha). For 66 ha, a total of 22 of these beds are needed.

To divide a flow of 45,000 m3/day over 22 reed beds results in a flow per reed bed of 2050 m^3/day (24 L/s; 68 mm/day), or approx 140 m^3/day per cell. This is slightly lower per m2 reed bed than the flow rate used in the trial, thus no infiltration problems are expected to occur with this design. Irrigation would be continuous.

Note: Current A1 layout has 3 cells, each cell has a width of 17 m and a length of 70 meter, thus a width:length ratio of 0.24. It has been operated with a flow rate of 250 m^3/day (71 mm/day), thus each cell handled 83 m3/day. A1 was designed for a flow rate of 450 m^3/day. Irrigation is continuous, 24/7.

Soil type and structure are important for the reed bed construction. The soil should be sufficiently porous that water flow and infiltration will not be limited, and the depth of the soil should be sufficiently deep that a maximum volume of reed roots can be developed. A depth of 80 cm was suggested as being optimal. The volume of the reed bed root zone and the porosity of the soil are also related to the residency time. The longer the residency time of oil contaminated water, the more effective the treatment will be.

A soil volume of 80 cm in one upscaled reed bed, a surface area of 3 ha, and a pore space of 50% would provide a water storage volume of less than 12,000 m^3 (completely saturated conditions must be prevented due to preferred aerobic conditions), for a flow of 2050 m^3/day would result in an average residency time of 5.8 days.


1.875 m3/hr
625 m3/hr
625 m3/hr
625 m3/hr
300 m
100 m
3 ha
Reed Bed
560 m3/hr
560 m3/hr
560 m3/hr
1.680 m3/hr
General items
1,125 m of 8" HDPE irrigation line
Instrumentation kits involving a digital flowmeter/watermeter, an
OMV sensor, a motor operated 8" gate valve, and a PLC
850 m of 8" HDPE drainage line
Typical Irrigation Layout
Irrigation items
Total
15 HDPE 2" irrigation lines @ 100 m each
1,500 m
37 bubbler and GTO per irrigation line
555
54 m of 13 mm HDPE drip tube per irrigation line
810 m
One 6" flanged plastic globe valve
1
Typical Drainage Layout
Drainage Items
Total
16 HDPE 2" irrigation lines @ 100 m each
1,600 m
310 m of 6" mainline
310
Gravel envelope
To be calculated
One 6" water meter
1
One 6" flanged plastic globe valve
1
Typical Reedbed Layout

Appendix D Water quality

		Treated water water standard Oman TWWS 1995 (1)	Drinking standard Oman Std8 1978 (1)	Water Quality for produced water in Nimr (1)	Average reed bed inflow water 2000-2002 (2)	Average reed bed effluent 2002 (2)	Average reed bed effluent 2003 - new design A1 (3)	Shallow groundwater Nimr (4)
Parameter	Abbreviation	mg/L	mg/L	mg/L	mg/L	mg/L		mg/L
Biological Oxygen Demand	BOD	15						
Chemical Oxygen Demand	COD	150						
Suspended Solids	TSS	15						
Total Dissolved Solids	TDS	1500	500-1500	5500-10900	6400	9620	7980	6000
Electrical Conductivity	EC(dS/m)	2.3	0.8-2.3	7.9-15.6	10.6	14.6		
Sodium Adsorption Ratio	SAR	10		31.86				
pH	pH	6-9	6.5-9.2	7.1-8.4	7.6	7.5		
Aluminum	Al	5				0.27		
Aromatic Hydrocarbons	BTX			0.21-0.64				
Arsenic	Ar	0.1	0.05			0		
Barium	Ba	1		0.22		0.2		
Beryllium	Be	0.05				0		
Bicarbonate	HCO3			560-636	522	570		
Boron	B	0.5		4.2-6.5	4.4	4.9		2-3
Bromide	Br			25-28				
Cadmium	Cd	0.01	0.01	0.0002-0.034		0.012		
Calcium	Ca		75-200	27-75.2	68	410		
Carbonate	CO3			20	0	0		
Cesium	Cs			0.001-0.002				
Chloride	Cl	650	200-600	2610-5800	3340	4710	4935	
Chromium	Cr	0.05		0.058		0.021		
Cobalt	Co	0.05		0.0006-0.0007		0.013		
Copper	Cu	0.5	0.05-1.5	0.0001-0.036		0		
Cyanide	Cn	0.05	0.05	0.0001				
Fluoride	F	1		0.6-1.9				
Iron	Fe	1	0.1-1.0	0.043-2.1		1.9		
Lead	Pb	0.1	0.1	0.005-0.056		0		
Lithium	Li	0.07				0.2		
Magnesium	Mg	150	150	10-38.4		49.9		
Manganese	Mn	0.1	0.05-0.5	0.063-0.071		0.3		
Mercury	Hg	0.001	0.001	0.0001		0.0002		
Molybdynum	Mo	0.01		0.004		0.02		
Nickel	Ni	0.1		0.0043-0.390		0.03		
Nitrogen	NH4	5		1.9				
Nitrate	NO3	50						
Organic N	N	5						
Oil and Grease		0.5		50-500	12.7	7	4.4	0
Phenols		0.001	0.001	0.15				
Phosphorus	P	30		0.9-7.4		0.2		
Potassium	K					14.4		
Selenium	Se	0.02	0.01			0.03		
Silver	Ag	0.01				0.015		
Sodium	Na	200		1940-2130	2560	3700		
Strontium	Sr			3.9		9.9		
Sulphate	SO4	400	200-400	260-379	350	933		
Sulphide	S	0.1				38.6		
Vanadium	V	0.1				0		
Zinc	Zn	5	5.0-15	0.010-0.014		0.06		

(1) Kiwa, 1999
(2) ICBA, 2002
(3) Data PDO, 2004
(4) pers. comm PDO

Appendix E Salt tolerant tree species

Potential tree species based on Australian experience (pers. comm. Dr. Heuperman) are:

- Eucalyptus occidentalis (firewood)
- Eucalyptus spathula (firewood)
- Eucalyptus camaldulensis
- Acacia ampliceps (Salt wattle) (shallow rooted, good firewood, good biomass)
- Acacia stenophylla (River Cooba)
- Acacia salicina (Cooba)
- Casuarina glauca (Swamp Sheoak; Swamp Oak), used for particle board in Egypt
- Casuarina cristata (Belah)

Note that the Acacia and Casuarina are likely to use less water than the Eucalyptus species.

Other salt tolerant trees are listed in Annex 6 of Report 61 in the FAO Irrigation and Drainage Paper (Tanji and Kielen, 2002).

An online database at http://www.hort.purdue.edu/newcrop/SearchEngine.html provides detailed production and product use descriptions for a variety of trees and crops, including several Eucalyptus species.

An online database at http://www.ffp.csiro.au/tigr/atscmain/searchdb/search.htm contains available seeds for several Australian seed species

Appendix F Water, salt and oil volumes

When 45,000 m^3/day is provided with a TDS concentration of 6,000 ppm (based on measurement shown in appendix B) and an average oil content of 250 ppm, the following volumes are delivered:

270 ton salt per day
11,250 liter oil per day (equivalent to 71 barrels a day)

Unfortunately, this oil cannot be easily extracted at cost efficient volumes. (Oman's daily oil production is quoted as 902,000 barrels a day [http://www.nationmaster.com/country/mu/Energy]).

Salt volumes remaining in the soil and taken up by the reeds will be negligible due to constant leaching and limited storage volume in the biomass of the reeds.

Assuming a reed bed surface area of 66 hectares, and a reference evapotranspiration varying between 4 and 11 mm/day (based on meteorological data of Thumrait), and a fully developed reed bed (assumed crop coefficient 1.2; similar to sugar cane), the outflow volume and salt concentration in the effluent can be calculated. Note that this will be the long-term expected salt concentration and that initially, the salt concentration of the effluent may be higher due to 'washing' of the soil used in reed bed construction.

Month	ETo	Reed bed water use	Volume of water used on 66 ha	Outflow volume	Salt concentration in effluent
	(mm/d)	(mm/day)	(m3/day)	m3/day	ppm
Jan	4.5	5.4	3,564	41,436	6,516
Feb	5.8	6.9	4,578	40,422	6,679
Mar	8.1	9.7	6,423	38,577	6,999
Apr	9.0	10.7	7,088	37,912	7,122
May	9.8	11.7	7,730	37,270	7,244
Jun	10.4	12.4	8,197	36,803	7,336
Jul	8.7	10.5	6,914	38,086	7,089
Aug	9.3	11.2	7,381	37,619	7,177
Sep	8.4	10.1	6,637	38,363	7,038
Oct	7.1	8.5	5,639	39,361	6,860
Nov	5.2	6.2	4,095	40,905	6,601
Dec	4.3	5.1	3,398	41,602	6,490

Appendix G Calculating Eucalypt us area

A generalized growth prediction model was used to obtain an impression of the order of magnitude of biomass production and water use (Sands, 2003). The model was developed in Australia, and specific input parameters were developed for Eucalyptus grandis (Almeida et al, 2004). Note that this is a different species than suggested for use in Oman. However, using this model will give an indication of water use behavior, and reduce some uncertainty of harvest yield.

The model was run with the assumption of a 4 x 4 m tree spacing. This spacing is chosen to allow sufficient lateral root zone in the shallow soil. Since the trees will be irrigated, water will not be the limiting factor for tree production. Soil fertility and the limited soil depth may be limiting factors for tree production.

Figure G-1 shows the predicted stem biomass production. It can be concluded that 6 years after planting, the maximum stem biomass is reached. This would suggest that every 6 years, trees could be harvested. After the first harvest, no replanting is needed, since the cut trees will regrow.

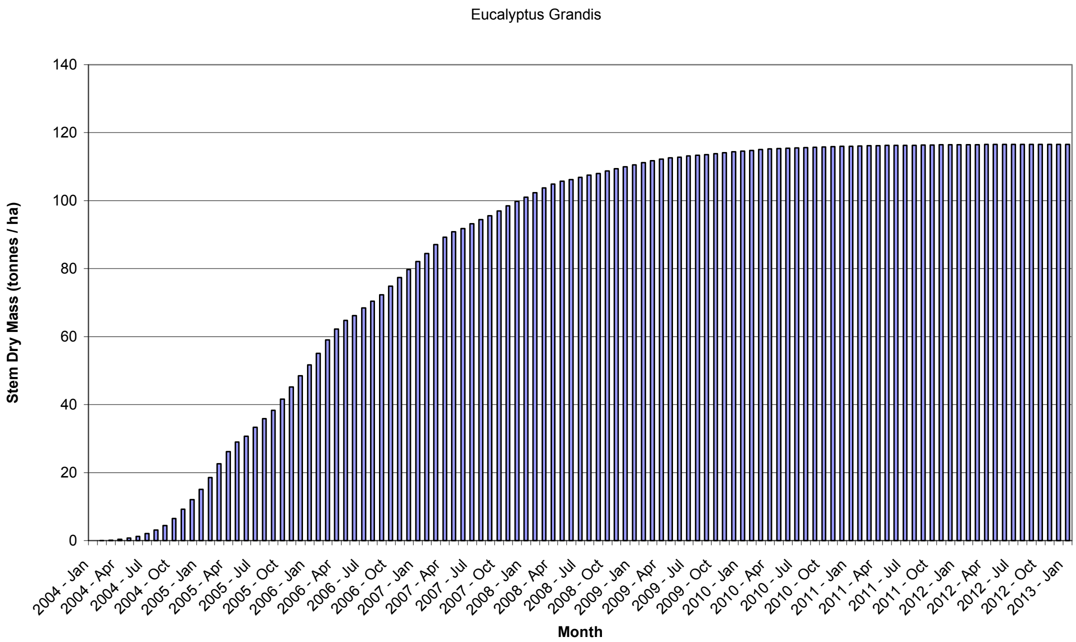


Figure G-1: Stem dry matter from time of planting (seedlings of 100 gram) over a 10 year development period.

Water use per month is shown in Figure G-2. It can be seen that water use is high in the first three years of establishment, but drops of sharply after these three years. Since the forestry system must be designed to optimize water consumptive use, and the supply of water is constant over the year, it is needed to start establishing a new forest area three years after the first phase was planted.

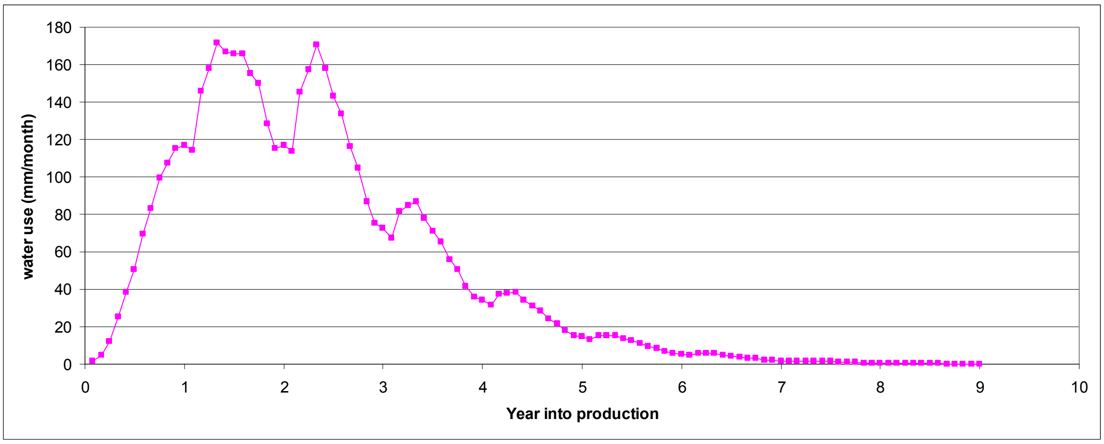


Figure G-2: Estimated water use for transpiration of Eucalyptus trees in Thumrait climate.

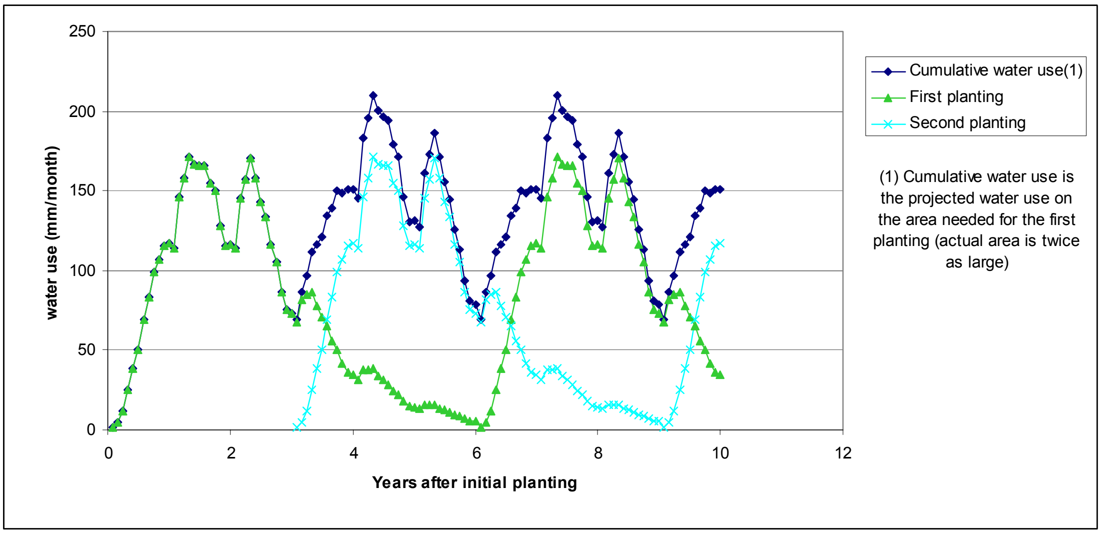


Figure G-3: Estimated water use for 'stacked' forestry development

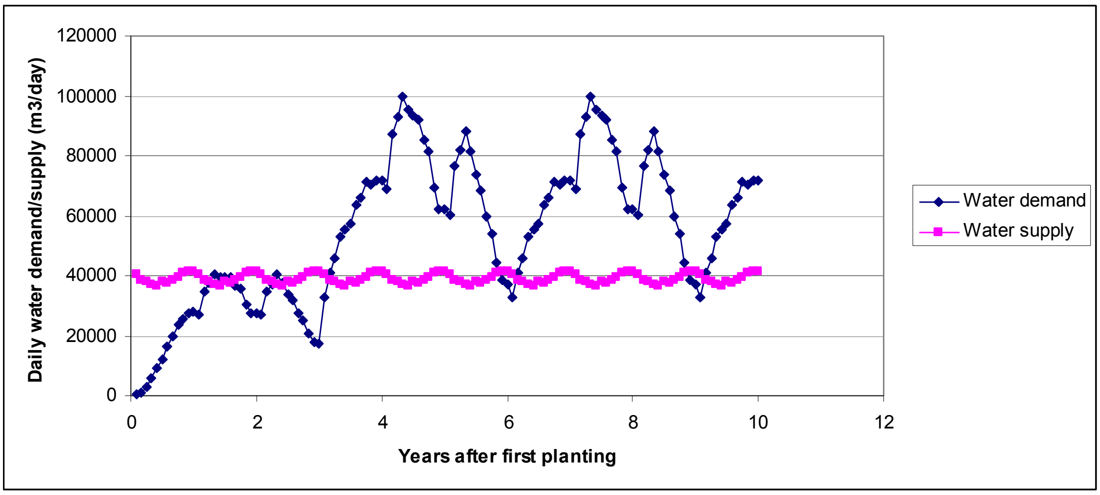


Figure G-4: Water supply and water demand over a 10 year time period

Based on Figure G-3 a monthly water use of 160 mm can be expected. Since an average volume of water of 1,140,000 m^3 of water is available on a monthly basis, it can be calculated that an area for each phase of 710 ha (1420 ha total) should be planted to use most water supplied. However, a water balance calculation, showing water demand and water supply over 10 years, shows that the water demand after year 3 will be higher than the water supply, thus not allowing excess water for leaching (Figure G-4). An adjustment to a total area of 1200 ha (600 ha for each phase) allows for excess water every three years. Leaching of the soil might be needed more frequently, but adjustment of the planting/harvesting scheme allows for management towards a more constant water demand (for example, every year a certain new area can be planted, such that harvesting rotations after 6 years can be annual (albeit from a smaller area). It is also possible to vary the forested area over the 20 year period of the project, depending on water supply availability.

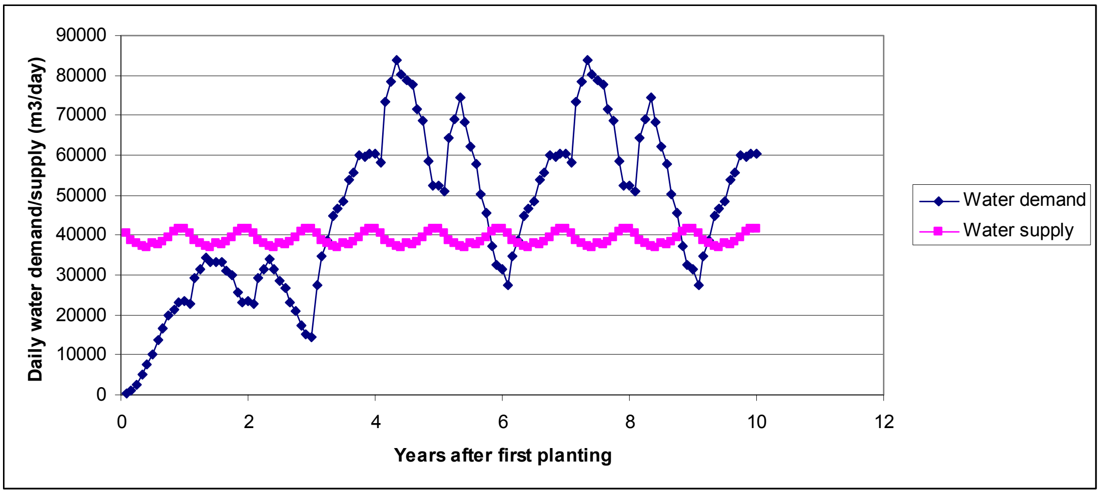


Figure G-5: Absolute water demand and supply for total area of 1200 ha

The low water requirement in the first three years is related to establishment of the first phase (only 600 ha). During this establishment phase it might be needed to negotiate a smaller volume of water off-take by the contractor from PDO than the 45,000 m^3/day.

Phased development of forestry would not only result in a more constant demand of water over time, but would also be interesting from an income point of view. A phased development would require an investment spread out over time, and a phased harvest would result in a more constant income over time.

Appendix H Evaporation pond design

At the design described in appendix 3, an excess amount of water of 1,200,000 m^3 will be collected over a period of 5 months, with a return period of 3 years. An evaporation pond with a depth of 2 m would then have to be 60 ha in size. Better phasing of newly planted areas should make it possible to spread this volume over 3 years, thus reducing the size of an evaporation pond to 20 ha. This would be equivalent to the size of 7 (new design) reed beds.

The forestry system is now designed to optimally manage water disposal, not for optimal tree production. Trees could, during some periods in the year, use less water than available. This will create some water stress, and reduction in growth, but should still allow tree survival.

The first activity under water stress is that stored soil water will be used, and soil moisture storage will be created for periods with excess water. For an area of 1200 ha, with a soil depth of 0.5 m, and an assumed readily available water of 10%, the volume of water storage would be 600,000 m^3. This storage capacity could be used to manage water inflow into the evaporation pond and reduce the required evapotranspiration area.

Appendix I Soil in Nimr area

Soils in the Nimr area are usually shallow, between 40 and 50 cm, and are underlain by a bedrock-like structure. This may restrict deep root growth, and may present problems of tree toppling. Having a windy climate, care should be taken in the development phase of the trees that they are supported.

The Oman Soil Atlas indicates a Type 13 soil in the direct Nimr and current reed bed location. Type 13 is classified as unsuited for large scale irrigated farming, with major limitations being the depth to the rock and rockiness of the soil. However, within 20 kilometers of the current reed bed location is an area classified as soil type 7 (see Figure 3) Soil type 7 is classified as marginally suited, with correctable limitations of excess salt and slope, and recommended corrective measures being leaching and leveling. Permanent limitations are given as excess gypsum, depth to rock, and high gravel content.

Soil chemistry data have not been analyzed, but the soils apparently have a high carbonate level. Irrigating these soils with water with a high sodium chloride concentration may create soil structural changes, limiting infiltration and hydraulic conductivity parameters. More detailed soil testing (both physical parameters as well as chemical parameters) is recommended before the large-scale forestry operation commences. Some analysis has been done at SQU, but data were not available during this feasibility study. A high percentage sand and low clay content, however, may reduce the risk of soil structure collapse.

Appendix J Groundwater resources and quality

Groundwater in the inland of Oman is basically the only reliable water resource. A distinction is made between shallow groundwater (100-200 m depth) and deep groundwater (1000-2000 m depth). In general, natural groundwater flow in Oman is slow (10 m/yr), and moves from the Northern Hajar Mountains towards the south, and from the Dhofar plateau in the south it moves northwards (Figure J-1). An inland terminal point (Umm As Samim) serves as an evaporation pond for rt of the groundwater flow, while another part flows into the Arabian Sea (Al Huqf area).

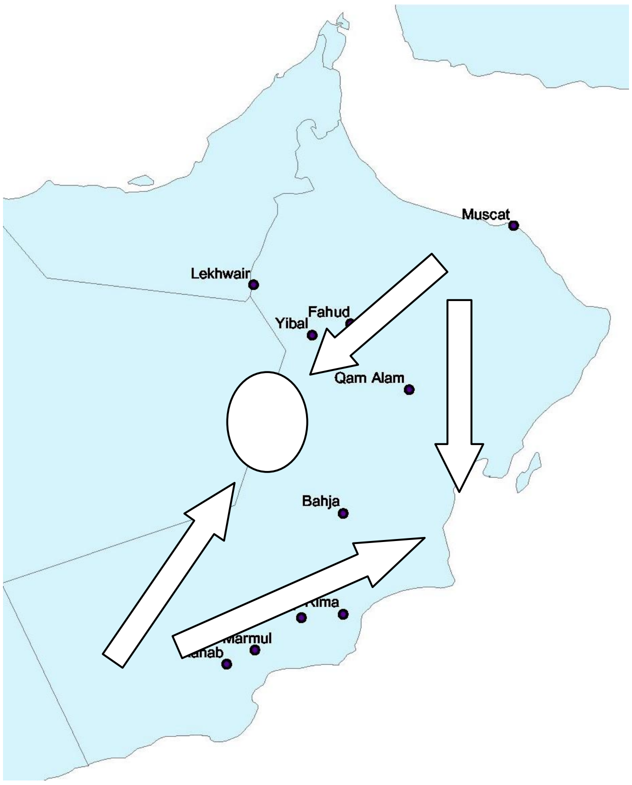


Figure J-1: Simplified groundwater flow in Oman

Groundwater becomes more saline along its flow path. The closer groundwater is used near its source, the better the quality. Figure J-2 shows salinity values (in ppm) for several geographical areas in Oman.

At the Nimr location, the produced water is slightly more saline than the shallow groundwater. Heavy metals are no major constraints for reuse of produced water, while TDS and boron are high, but deemed manageable for biosaline agriculture.

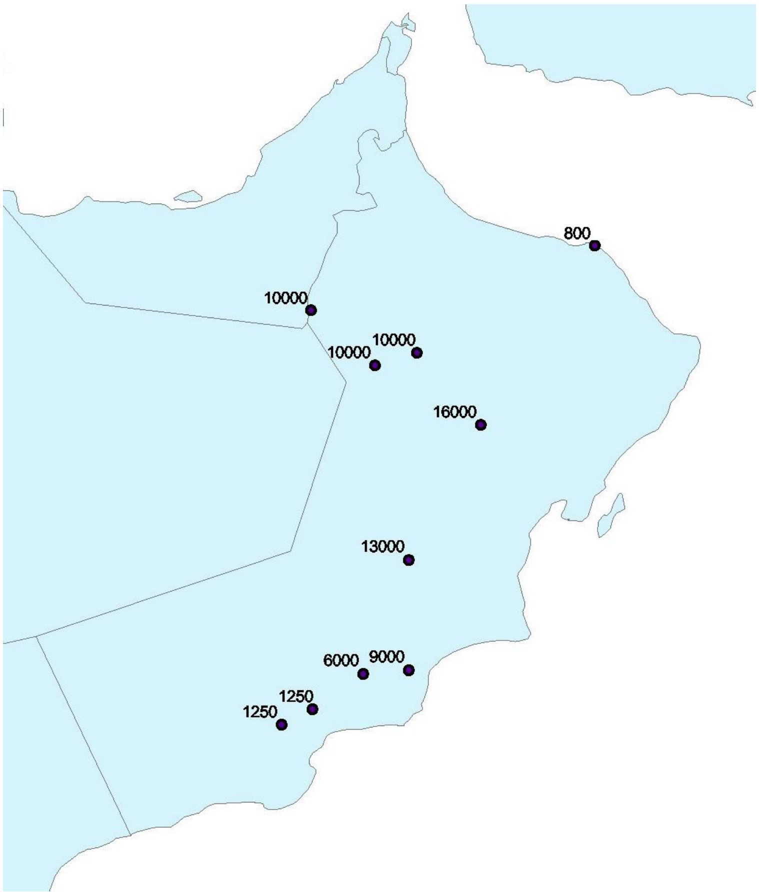


Figure J-2: Measured (shallow) groundwater salinity (TDS, in ppm)

Appendix K Financial

K1. Header system

Dissolved Air Flotation (DAF) can be used to reduce the oil and grease levels by gravity separation. It is one of the most commonly used technologies to treat oily water containing high levels of oil and grease. This method works by injecting air into a tank by a number of diffusers. The air bubbles created attract the dispersed oil and float the oil up to the surface. A surface skimmer subsequently removes this oil. A coagulant chemical is often added to aid in the process.

Costs of DAF consists of Capital costs (0.009 $\$/m^3$) and Operating costs (0.021 $\$/m^3$). The capital costs of DAF are $1.52 million for a flow rate of 42,480 m^3/day (Dillon et al, 2003). We assumed $1.5 million for a flow rate of 45,000 m^3/day. Assuming that the life span of DAF is 10 yr. The capital costs are about 0.009 $\$/m^3$.

Operating costs consist of maintenance costs, chemical costs, labour costs and pumping costs. Maintenance cost is assumed to be 2% of the capital costs, which is $3,000 per year (0.0002 $/m3).The chemical used in DAF is usually either a coagulant like Alum, Ferric Sulphate or Polyelectrolyte. The costs are based on a dosage of 40 mg/l (g/m^3) –which is 0.04 kg/m^3- for Ferric Sulphate which is a standard dosage. At a cost of 0.44 $/kg the cost is 0.0176 $\$/m^3$. DAF is able to operate without little operator input. Only one labour unit is needed at a price of 28,000$/year (900 Rial per month). The costs are 0.0017 $\$/m^3$. Pumping costs are 0.0018 $\$/m^3$ for a headloss of 4.5 metre (4.5 m x 0.06 $/kWh x 0.0068 kWh/$m^3$)

Table K1. Costs of Dissolved Air Flotation $/m3 (excluding disposal costs)

Capital	Maintenance	Chemical	Labour	Pumping	Total
0.009	0.0002	0.0176	0.0017	0.0018	0.03

There is a lack of insight into the size of the disposal costs of DAF, Hydrocyclones and Microfiltration. We assumed total operating costs of $ 350,000 per year.

Oil recovery (0.012 $\$/m^3$)

As the input oil concentration is 250 ppm and the pretreatment outflow concentration is 50 ppm, the recovered oil is 200 ppm. Assuming that there is 159 liter of oil per barrel and that the barrel oil price is 16$ per barrel[1], and oil recovery in the pre-treatment does not create any losses of usable material. Recovery Benefits (RB) are 0.02 $/m3 or $ 330,000 per year.

$$RB = \frac{(ppm_{in} - ppm_{out})}{1000000} * \frac{Barrel\,\mathrm{Pr}\,ice}{BarrelVolume} \qquad (1)$$

where ppm_in = (m^3 oil/m^3 water), ppm_out = (m^3 oil/m^3 water), ppm_in – ppm_out = oil recovery; Barrelprice = $; BarrelVolume = m^3 oil.

[1] The current price is 30$ per barrel

K2. Reed bed system

The capital costs depend on the kind of reed bed. A life span of 20 yr is assumed. Total costs of constructing 45 ha of reed bed are $ 8.1 million (Anwar, 2004). These costs are based on contractor rates for PDO. These seem to be rather high (as contractors use higher rates for PDO). Expansion of the reed bed area does not seem to have a big impact on the total costs, as fixed costs are rather high. We therefore work with $ 8 million for 65 ha and $ 4 million for 15 ha.

Table K2 Construction of New Reed Bed (300 x 100 Mtr. –15) at Nimr

	Earth Work	$
1	Construction of Bund Wall with Excavated Soil from Side (7570 x 5.3)	213200
2	Leveling and compaction of the excavated bed bottom incl. maintaining slope. (300 x 100)	468000
3	Supply and filling of the Soil type - B incl. the slope on top of HDPE Liner. 800 mm thick*	2983500
4	Excavation of trench in final level below irrigation line to install gravel (400 x 400 mm.)	81900
5	Filling the above trench with 16-32 mm gravel with round arrangement as per Drawing	87750
	Drainage Work	
1	Supply and Installation of HDPE Liner 1 mm thick as per the dimensions in the Drawing.	
a)	HDPE Liner 1 mm. Thick - 308 x 108	2784600
b)	Water proofing to the Pipe outlet inside the HDPE liner	9750
2	Supply and Installation of Drainage System.	
a)	Supply & Installation of 200 mm. HDPE Ring Main	162500
b)	Supply & Installation of 150 mm. HDPE Mainline	145080
c)	Supply & Installation of 2" HDPE Perporated Pipe	187200
d)	Installation of Inspection point.	3900
e)	Cover the Drainage line with 6 - 8 mm. Gravel as per Drawing	93600
f)	Supply and installation of 150mm. Dia. flanged Plastic valve.	9750
g)	Supply and installation of 150mm. Water meter.	23400
h)	200 mm HDPE Tee	9620
j)	150 mm HDPE Tee	37128
k)	150 mm HDPE Elbow	3744
l)	160mm HDPE Flange	9360
	Irrigation Work	
1	Supply and Installation of Irrigation System :	
a)	250mm HDPE Ring Main	64480
b)	200mm HDPE Ring Main	89700
c)	Supply & Installation of 200mm Motor Operated Isolation Valve	15600
d)	Supply & Installlation of 200mm Digital Flow Meter with OIW Sensor PLC etc.	11700
e)	200mm dia. Flanged plastic gate Valve	14625
f)	150mm.dia. HDPE Mainline	327600
g)	2" dia HDPE Irrigation Latteral	146250
h)	Adjustable bubbler 1340 Lt. / Hr. + Stakes + R/Clip	25974
j)	13mm Drip tube	23595

k)	13mm GTO	11905
2 a)	250 mm HDPE Elbow	1248
b)	200mm HDPE Tee	7215
c)	200 mm HDPE Elbow	1560
d)	150mm HDPE Tee	79560
e)	150 mm HDPE Elbow	7488
f)	160mm HDPE Flange	4680
	TOTAL	8,147,162

*) Suitable soil is transported to the reed beds (instead of reed beds to the soil).

The operating costs are about $ 30,000 per year and consists mainly of 1.5 units of labour of $1,200 per month each, which is $ 21,600 plus some other variable costs like pesticides. The reed beds have to be remediated with light acid after about 10 year. We assumed that one-third will be treated in year 9, 10 and 11 at a cost of $5,000 for each treatment.

K3. Crop production

A fairly constant supply of water will be obtained from the reed bed outflow. However, due to seasonal variations in temperature, water demand by trees would be variable. There are several strategies to work with the offset between water delivery and water requirement. One strategy would be to create reservoirs between the reed bed and the farming system. The costs of storing 500,000 m3 of water is assumed to be $50,000 (0.10 $/m3). Another strategy is to over design the area under Eucalyptus.

Eucalyptus capital costs

Tree seeds are available from the Australian Tree Seed Center; a databank for Eucalyptus seed suppliers. Prices are about 35 AU$ per 10 gram (equivalent to $ 25 per 10 gram). Number of expected seedlings per 10 gram seed is assumed to be 2,000. For a tree density of 625 trees per hectare, and an operational area of 1200 hectare, approximately 800,000 trees are needed. This would result in a total of 400 times 10 gram, which gives seed costs of approximately $ 10,000. Although it is likely that seed in mass-quantities will be less expensive and seed needed for the nursery can be produced on-site, we assumed seed costs to be $ 10,000.

To grow Eucalyptus some earth work is required and irrigation equipment has to be installed. A drainage system is needed to remove applied salts from the soil to maintain favorable soil salinity conditions. The costs of installing subsurface drainage in Haryana, India, are 770 euro per ha at 2000 prices (Ritsema, forthcoming). As only subsurface drainage is required in Nimr and no advanced main system, drainage costs or 500 $/ha are assumed. Irrigation costs are assumed to be 500 $/ha and land preparation costs also 500 $/ha. This is equivalent to 1,500 $/ha in the initial year. Costs of land preparation including drainage and irrigation equipment are independent on the number of trees planted.

Drainage effluent must be collected in evaporation ponds where water can be separated from the salts. The capital costs of evaporation ponds for drainage water are assumed to be $ 120,000.

Eucalyptus operating costs
To plant, maintain and harvest the Eucalyptus 2.5 units of labour of $1,200 per month each is needed, which is $ 36,000 operating costs per year.

Table K3. Costs of Eucalyptus system

Seed costs	Evaporation pond	Land preparation	Labour costs	Benefits
$ 10,000	$ 120,000	1,500 $/ha	36,000 $/year	1.8 M $/harvest

Eucalyptus benefits
We assume that the only benefits per ha are obtained from stem-wood dry mass. If the predictions of the tree growth model are used as an indication (Landsberg and Waring, 1997), a stem dry mass production of 100 tonnes/ha/harvest can be obtained when 625 trees per hectare are planted (a tree planting spacing of 4 x 4 m). At a per tonne price of $30, and 5 harvests of half the total Eucalyptus (600 ha) area in a period of 20 year, this provides an income of 1.8 million $ per harvest, or 9 million $ in total. Prices seem to be higher than 30 $/tonne, but due to a lack of accurate insight into harvesting, transport and marketing costs a relatively low net price is assumed. Wood transportation costs to Salalah seem to be $10/tonne.

K4 Other costs and benefits
Benefits of salt harvesting
A simple water and salt balance shows that over a 20 year period, a volume of 328,500,000 m3 of water will be delivered. Assuming a salinity level of 6000 ppm (6000 mg/L = 9.4 dS/m), a total of 1,971,000,000 kg of salts will be delivered with the irrigation water. This salt will be spread out over 1200 ha, resulting in a salt load of 164 kg/m2. Assuming that this salt remains equally distributed over a 2 m soil profile, it will result in a 8,213 mg/cm3. Assuming that the soil is sandy, with a saturation percentage of 30% (0.3 cm3 water per cm3 soil), a saturation extract concentration of 8,213 mg in 30 ml water is 274 mg salt/ml water (274,000 ppm = 428 dS/m). These are unacceptable values for salinity (if not impossible; the salts will be deposited in solid form, and not all dissolved in soil water), and additional discharge and collection of salts is needed to prevent complete salting up of the soil. Suppose 2,000,000 tonnes of salt can be harvested at a price of Sodium chloride (NaCl) of 38.5 $/ton for food processing, the benefits would be 77 million $ over a period of 20 years. Technologies to clean the salts are, however, currently too expensive and benefits of salt harvesting are therefore not considered in the analysis here.

Rhodes grass for local people and wildlife forest
The local population has an interest in the products that can be generated with water, and a dialogue is advised between PDO and local representatives (see chapter 4). For the financial analyses it is assumed that the outcome of the dialogue is to grow some Rhodes grass. Further, income can also be expected from wildlife forest. The treated

water is, however, of a quality that limits its usage as an input to many products, but the local people are not aware of that. We assumed 50 hectare of Rhodes grass by using groundwater and to have wildlife forest. The crop budget of Rhodes grass shows a net return of 3,600 $/ha (excluding salary, machinery and electricity costs). This will be $ 180,000 for 50 ha of Rhodes grass. We propose to reserve annually $ 250,000 for both activities, which means net costs of $ 70,000. Instead of developing Rhoades grass production at the Nimr location, a link to the existing Rahab farm could be made.

Miscellaneous costs
We assume $ 500,000 for miscellaneous capital costs, like tractors, vehicles, machinery to plant and harvest, farming equipment, cabins, housing, roads, forest fence of 14 km ($100,000; Dept of Environment, pers. comm.),sampling, environmental monitoring, waste management after the project terminates etc. This also includes the costs for stakeholder engagement to complete the process. The engagements are meant to involve the people in the project and to allow them access to part of the project benefits.