Deep Seawater Intake Sohar Port

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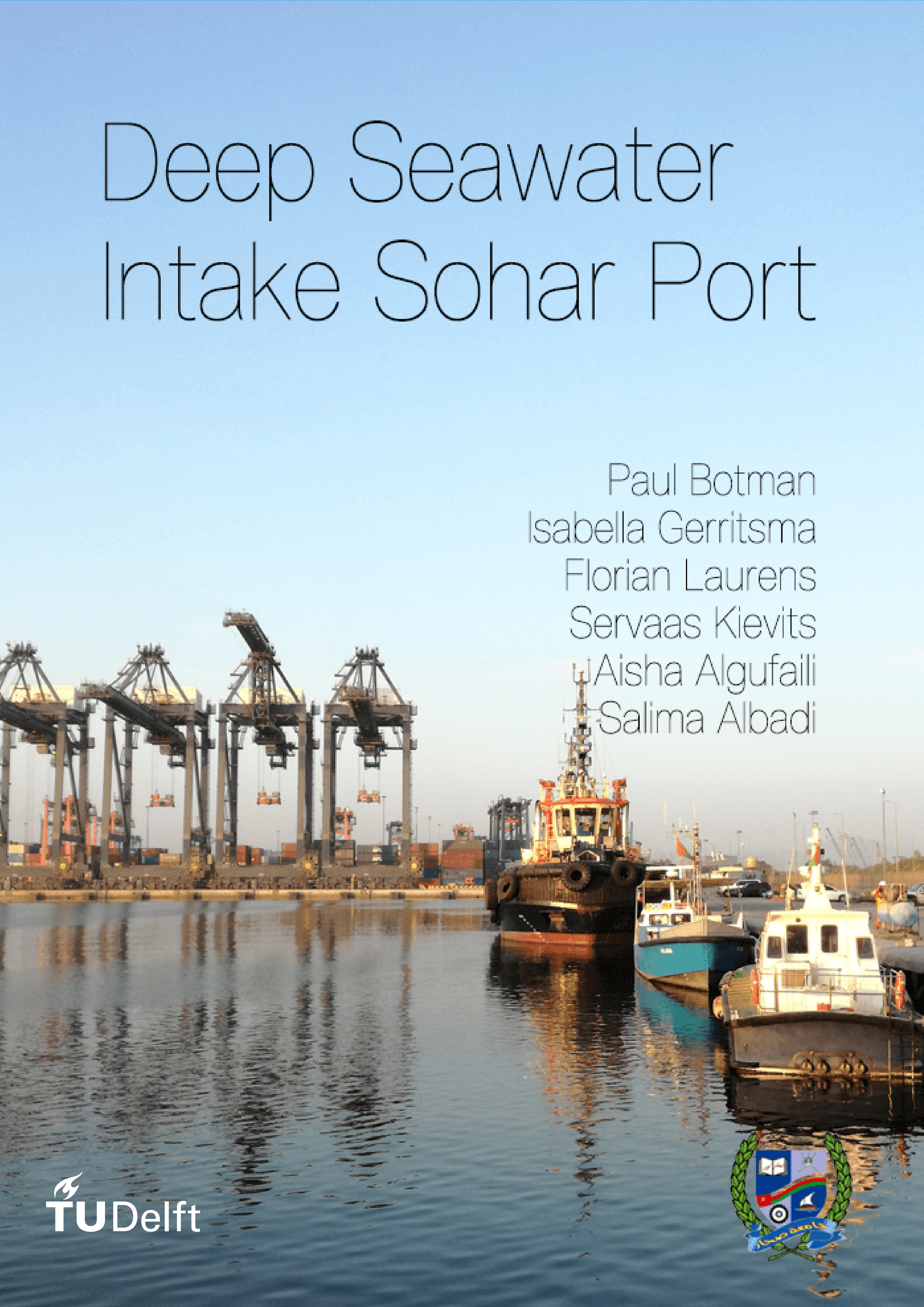

TU Delft

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by

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Abstract

This paper is the result of the first collaboration project between Delft University of Technology and Sohar University. The project team consisted of 6 core-members from both Sohar University and TU Delft along with 5 more students, together appointed to help find an answer for a problem stated by Sohar Industrial Port Company and Majis Industrial Services.

This paper proposes a deep seawater intake for the cooling water system of Sohar Industrial Port, Oman. In the region's summers, surface water temperatures tend to rise to very high levels. Among other things, this results in inefficient cooling of the processes associated with the steel manufacturers, petrochemical plants, refineries and power plants present in the port. The proposed inlet subtracts water 4 km offshore at an average temperature of 24.9 °C. Using this colder water, the demand is expected to go down with approx. 2% in the winter and 16% in the summer, saving system capacity and pumping costs. The 2,148 MW generated power at Sohar port is expected to increase efficiency by 0.72%. Furthermore, the coastal waters are vulnerable to algal blooms. These toxic algae can not be filtered out efficiently and lead to temporary closure of the desalination plants (mainly Reverse Osmosis) causing a threat to the drinking water supply in the entire north of Oman. This paper concludes however that there is not an (economically) feasible inlet location that is unaffected by the algal blooms. Other water characteristics such as turbidity and organic content are also expected not to show significant improvement at the proposed inlet location but more elaborate measurements should validate this.

A technical feasibility study was conducted to find the optimal system design. Multiple alternative materials being metals, alloys, HDPE and concrete have been investigated to serve as water conveyors to transport the water from the inlet to the shore. A possible design for the off-shore water inlet structure was made as well as a recommended design for the connection of the pipelines with the current facilities. Site selection, material selection, friction head loss calculations, pipeline sizing, concrete ballast weights, seabed pipeline stability and planning have been discussed in this report. Finally, a financial feasibility study has been conducted. A model was built and costs have been quantitatively estimated based on the technical design. Benefits have been quantified where possible and if not, were qualitatively described. It is concluded that it is not financially feasible to build a deep seawater intake for the entire port. Building a limited-scale variant, only providing RO and power plants, is a better solution but still unfeasible. Recommendation is done to scrutinise the processes within power plants and RO-plants further as their potential benefits are considerable.

Preface

In front of you is not only a feasibility study but also the result of the very first collaboration project between Sohar Industrial Port Company (SIPC), Majis Industrial Services (Majis), University of Technology Delft and Sohar University. It is with the deepest gratitude that we look back at the opportunity we have been given by Majis and SIPC and it feels as if it is only a week ago that we started working here in the Port of Sohar.

At least as important as the project itself was the valuable collaboration between Omani and Dutch students. By working together with different cultures much more was learned than just the factual knowledge of a project. Different cultural perspectives lead to new creative solutions in ways that could not have been achieved if this multicultural collaboration had not taken place at all. With this project as a successful start of the relationship between SIPC and Sohar University, it can only be hoped that the mutual benefits will continue and will help establish a firm ground for students to start their professional career on.

To express our gratitude we would like to thank first of all Mark Geilenkirchen for welcoming us so warmly into the SIPC office and offering us the great opportunity to work on such an interesting project in the Port of Sohar.

From Majis, we thank Abdullah Al-Sadi who has helped us every day and every week with advice, data, feedback and his enthusiasm, supported by Younis Al-Kiyumi and Zamzam Al Balushi who were very helpful with gathering and providing all necessary data. Besides Majis, a huge contribution was made by the Ministry of Agriculture and Fisheries Wealth (MAFW) and Oman National Hydrographic Office (ONHO) in terms of data provision, covering bathymetry and all the environmental aspects.

Additionally, the work of Dr. Eyad from Sohar University was appreciated to great extent, since he devoted much of his spare time sharing his knowledge with us and created the uttermost useful bathymetry plots.

Special gratitude is extended to all the employees from both SIPC and Majis. You have made us feel welcome since the day we arrived in the port. By coming by for just a brief chat or giving in-depth advice, asking us to come play football, preparing delicious food and juices and by always being friendly we have felt at home since the moment we arrived.

Last but not least, we would like to thank Tom Costa for making this all happen. Working devotedly during the weeks and discovering beautiful Oman in the weekends was all possible thanks to your efforts and patience. Without you this project would not have been the success it is now. It has been a great pleasure to work and enjoy Oman with you.

Sohar, October 2018

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1

Problem statement

1.1. Introduction

SOHAR Port and Freezone is one of the fastest growing port and freezone developments in the world, thereby placing stress on port infrastructure and environment. For environmental and economical reasons it is important that this growth is carried out in a sustainable way. Moreover, SOHAR Port and Freezone sees it as their responsibility to play their part in the development of clean technologies. As (almost) all ongoing industrial processes in the harbour require water in some sort, a substantial part of the port infrastructure is dedicated to this.

Majis Industrial Services (Majis) is responsible for providing (most of) this water to the different industries with a total current design discharge of 380,000 m^3/h and forecasts of up to 760,000 m^3/h for 2025. A new water intake has recently been added to accommodate this increase. Nonetheless, Majis and Sohar Industrial Port company (SIPC) are facing rising challenges in water management that could bring opportunities and synergies on multiple levels.

This chapter elaborates on the background of this research. First of all an overview of the stresses and opportunities relevant for our research within the port is given. This is followed by the definition of the research question. The scope of this project is included afterwards to identify what is, and what is not part of this research. Additionally the methodology discusses the steps that have been taken to answer the research question. Finally the organisational chart aims to map the various parties involved in the project as well as to point out their particular role within the project.

Desalination plants

A part of the seawater is treated in various desalination plants for the production of drinking and process water. The techniques that are used for this are Reverse Osmosis (RO) and Multi-Stage flash (MSF). Especially RO is sensitive to pollutants in the water since it is filter based and the filters get clogged easily. Currently the Majis RO plant, with a design capacity of 20,000 m^3/day, does not produce more than 15,000 m^3/day on average due to the poor water characteristics at the intake, as is given by Majis.

Power plants

In the port area four power plants with a total installed capacity of 4.2 GW are located that all make use of the services provided by Majis. 3 out of the 4 power plants at Sohar port (representing 2.5 GW) use a once through cooling system that is sensitive to water temperature. The Combined Cycle Power Plants show an increase in efficiency if colder cooling water is used [Kim and Jeong, 2013].

Cooling capacity

Most of the water provided to the port is used as cooling water. Especially in the summer this gives rise to stresses because large amounts of (warm) water need to be pumped in. This can be explained by the fact that the heat dissipation capacity of the cooling water depends on the temperature difference between seawater and process effluent, which is lower in the summer [Kim and Jeong, 2013]. Furthermore, environmental regulations pose restrictions on the maximum allowed outflow temperature of the water. If colder ocean water is taken in, it means that more heat can be dissipated by the same amount of water, thereby reducing the required discharge and saving massively on pumping costs.

Environmental issues

The seawater outfall is currently located very close to the intake. This results in a part of the water that is being recirculated into the system. A consequence is that the already heated discharged water from the outfall flows back into the intake and the system to be heated even more. Also pollutants (e.g. heavy metals) flow back into the intakes. This potentially poses a threat to the drinking water producers in the port. Majis is therefore investigating measures to change the location of the seawater outfall.

Secondly, since the coastal zone is the most zoologically active area, many fish and sometimes sea turtles get stuck in the seawater inlets. According to Dr. Eyad from Sohar University zoological activity is less, further offshore. Finally, currently the water is currently supposed to cool down in the outlet channel but this does not happen sufficiently leading to exceedance of local temperature discharge regulations and a large thermal plume around the port.

Harmful algal blooms

The coastal waters of Oman suffer from algal blooms causing e.g. severe damage to the membranes of the RO-processes. As a result Majis is forced to lower/stop production of their desalination plants, having costly impacts as well as a reduced life time of the filters. Other industries have mentioned that the algae negatively impact their installations and processes as well. Continuation of processes despite of the algae is only possible by adding excessive amounts of chemicals to the water. These large quantities of chemicals are bad for assets and environment.

Future growth

The port of Sohar is still growing rapidly, so that new opportunities for land reclamation are always in high demand. The current location of the seawater intake is close to a current land reclamation. SIPC would be very interested if the area of the current intake basin would come available so that the land reclamation could be extended.

Furthermore, the currently existing water facilities accommodate to a maximum of around 760,000 m^3/h. After that, the facilities will need expansion. This situation could already occur as early as 2025 according to Majis. To conclude, the ability to provide higher quality and/or cooler water might also open the door for new business opportunities that require such characteristics.

1.2. Research question

The main challenge and conclusion that can be drawn from the above situations is that the current point of water extraction is not ideal for both the temperature and the quality of the water. In a water analysis study conducted for the Gulf region [Bidokhti and Ezam, 2009] it is shown that water further offshore is supposedly both colder and cleaner. If this water could be transported to the shore in a way, the potential benefits would be immense.

With colder water the ΔT will become larger which means a higher heat dissipation capacity per m^3 of water, leading to a smaller demand. Another advantage of deeper seawater is that the water presumably contains less algae as those are assumed to be related to the dissolved oxygen level in the water. Moreover, the colder water will increase the production of the power plants [Kim and Jeong, 2013]. To do a feasibility study for this project the research question has been formulated as follows:

What is the optimal, technically and economically feasible design for a deep seawater intake, providing colder and cleaner water for the port of Sohar?

1.3. Scope

This section presents the scope which defines what is and, more importantly, what is not part of the project. The full system of water provision in Sohar port is very large and consists of many different parties and elements. Although the team has a strong opinion that the optimal design should follow from a close collaboration between stakeholders, the system is considered too extensive to have the formation of such a collaboration performed within two months. This leads to the necessity of a well-defined scope.

The goal to provide water with an alternative intake should clearly start at the point of extraction. From here the water will flow through pipelines until it is delivered in the current facilities. At this location the water is pumped up by all clients and used for their processes. Establishing contact with all different clients and mapping their internal systems is expected to be time-consuming. This is therefore excluded from the scope.

Following this reasoning, the scope of this project extends from the offshore seawater extraction point up until the point where the clients take out the water.

Guaranteeing future research that will result from recommendations, finally a model is made that contains all findings and is easily modifiable if new parameters appear. This is also included in the scope.

1.4. Methodology

In order to answer the research question and decide on the feasibility of the project, the subject is divided into sub-research questions. A clear methodology is described in this chapter, following a structured approach to find answers to the sub-research questions. By concluding on those, an answer to the research question can be formulated. The sub-research questions are stated as follows:

- What requirements and limitations are posed to the current system?
- What is the ideal location for the seawater intake?
- What are the potential benefits for colder and qualitatively better water?
- What are the technical possibilities to construct such a system?

First, an analysis is made of the current situation, mapping the opportunities and design requirements for the project. A site investigation is conducted including an analysis of the current water system in order to provide boundary conditions and circumstantial data for the new intake.

Furthermore, the various processes in the port are analysed to see where possible benefits or possibilities occur. Besides, a quantification and a comparison of these opportunities are made, leading to multiple scenarios for future implementation.

Afterwards, based on these analyses, the recommended design for a new deep seawater intake is made. Combining the analyses and the design, consequently the technical and financial feasibility are discussed.

The research concludes with an assessment of the risks where uncertainties that play a role in the success of this project are discussed.

Following this framework will lead to answers on all sub-research questions and, therewith, to a sound answer on the research question.

1.5. Organisational chart

The division of responsibilities of team members but also of stakeholders within the project is described in this section. This research project is the first of many projects that follow from the new collaboration between SIPC and Sohar University. Moreover, for this project specific, SIPC has found a good partner in Majis, that has had a major contribution to this project.

Both SIPC and Majis have facilitated the team by offering work space during the span of the project. Moreover, both Abdullah Al Sadi from Majis and Tom Costa from SIPC have been busy with the daily guidance and questions of the team. Both gentlemen are supported by departments that have provided the team with plenty of data. These departments also participated in weekly meetings where Abdullah, Tom and Dr. Eyad from Sohar University always took place and gave their input on the made progress.

Moreover, Sohar University has contributed on the scientific site of the project. They have opened their laboratories for experimenting and will also execute the future research that follows from this project. This future research is carried out by three graduation students from Sohar University that fall under the direct supervision of Dr. Eyad.

The core team existed of six students with different backgrounds. Two of them are students from Sohar University and the other four are from Delft University of Technology. Moreover, two interns from Majis have performed a side project to study the effects of the current intake and outfall on the marine life, thereby highlighting the relevance for this project.

The responsibilities of every team member have been given in an organisational structure that can be found in Appendix A.1.

2

Site investigation

Summary The design of a new deep seawater intake is heavily dependent on local conditions and circumstances, making this analysis a crucial starting point for the feasibility study.

The Sohar Industrial Port Area (SIPA) is managed by SIPC. SIPC is focused on creating and retaining ideal circumstances for industries situated in SIPA, in a sustainable way. SIPC is, together with Majis, the main stakeholder in this project.

Majis provides a maximum of 380,000 m^3/h to the in SIPA situated industries divided over cooling water, process water and potable water. In most cases, the water is extracted from the intake basins by the industries but Majis also delivers water to the doorstep of industries. Pre-treatment is enough for the cooling water production but further treatment is necessary to produce process and potable water.

(Petro)chemical, steel, iron, aluminium and plastic industries have been characterised as main water users and four power plants are present in the port, claiming a major part of the cooling water. Benefits regarding colder cooling water will be mostly in those industries.

A proposed shore normal trajectory of pipelines with a length of 4 km, reaching $CD-20\ m$, results from a bathymetry and water temperature analysis. With a rather flat bathymetry and the thermocline ending at a depth of around $CD-17\ m$, reaching for larger water depths is considered to be uneconomical. Shipping areas are avoided, but the planned land reclamation calls for a partly trenched pipeline. The soil has been characterised with a 5 - 7 m layer of silty sand, making a trench easy to construct. For the construction and stability of the pipeline and intake head the wave and flow conditions have been analysed. They can be considered as mild.

Four water quality parameters have been scrutinised. Of those, dissolved oxygen concentration and salinity decrease at a larger water depth, increasing the efficiency of the RO-plants. Unfortunately, chlorophyll-a concentration and turbidity levels, indicating suspended (organic) particles in the water, are higher at larger depth compared to the surface water. The chlorophyll-a concentration can also be used as a Harmful Algal Bloom (HAB) indicator. Though, measurements should validate this during a HAB as well as for longer time spans. Concluding this, more research on the water quality parameters and HABs is strongly recommended to estimate the possible benefits better.

2.1. Introduction

As the SIPA exhibits lots of different industries and the project concerns several stakeholders, it is important to enumerate and explain those. This is done in Section 2.2, where the stakeholders are mentioned and summarised in a graph with interest and power on the x and y axis, respectively. Given this, Section 2.3 explains the situation regarding the seawater distribution corresponding to the stakeholders thoroughly. It elaborates on the services provided by Majis and corresponding costumers and costs. In the third section (Section 2.4) an analysis of the environmental aspects regarding the deep seawater intake is enclosed and consists of the pipeline routing criteria, construction and stability criteria and the water quality.

2.2. Stakeholder analysis

Two major stakeholders in this project are SIPC and Majis. Other stakeholders are the government of Oman and the other industries in the port, where the power plants and desalination plants share a larger interest in this project. Fishermen do benefit from a better water quality, appointing them as concluding stakeholders. Figure 2.1 shows the stakeholders sorted by their interest and power to this project. Section B.1 elaborates on the specific reasons for their interest and power.

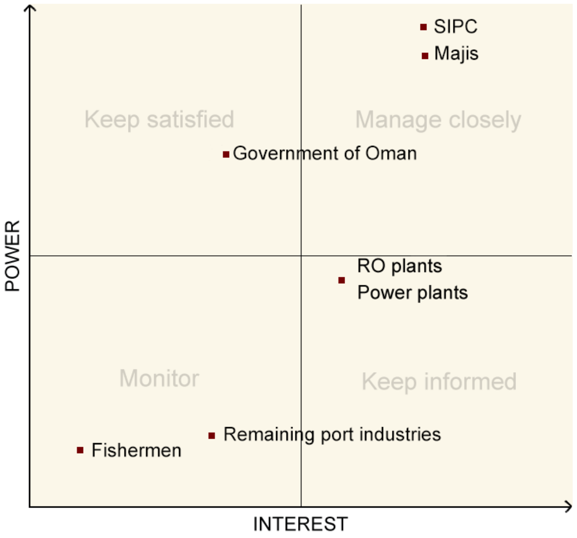


Figure 2.1: Stakeholders for the project.

2.3. Intake analysis

As follows from information provided by Majis, their intake supplies most water required for operations in the Sohar Port. Their services, organisation and the division of customers are therefore observed more closely.

2.3.1. Services

Majis provides the industries with three different types of water. Currently the combined maximum extraction of $380,000\ m^3/h$ comprises: cooling water (1) which is used by the companies to cool their installations to an acceptable temperature ($378,600\ m^3/h$), process water (2) used in steam turbines and chemical processes ($8,000\ m^3/day$) and potable water (3) used both as drinking water and to supply fire hydrants within the Sohar Port ($12,000\ m^3/day$). Furthermore, excessive potable water is used as process water after additional treatment. Both potable and process water are produced in a Reverse Osmosis (RO)-plant owned by Majis, adding up to the total production capacity of the RO-plant of $20,000\ m^3/day$. In addition to the RO-plant, Majis has agreements with other organisations for the provision on their behalf of potable and process water, all within the design discharge. Moreover, the Independent Water Plant (IWP) extracts water to produce potable water by its own RO-plant. Besides that, potable water is produced by Sohar Power Company by the Multi-Stage Flash method, as is described below.

There are two different ways for Majis to provide services; one is to extract the seawater to a basin where companies themselves can pump the required water from, using their own pump facilities. This represents a design discharge of $320,000\ m^3/h$. The other option is that Majis delivers the water to the doorstep of the company. This option comprises the remaining $60,000\ m^3/h$ and includes among other things, water meant for the RO-plant.

All water obtained by Majis is extracted at the seawater intake stations located in an enclosed bay protected by breakwaters, as can be seen in Figure 2.3. The 800-meter long breakwaters' main purpose is to provide calm, laminar flow conditions with low turbulence and turbidity. The most near shore part of the intake channel is an open basin with a depth of $CD - 4\ m$ from where the water flows into the pre-treatment system. Here several steps are taken to clean the water, so that the filters in the RO-plant and the pipe network will not clog or get damaged. The RO-process requires a first step of disinfection by means of a shock dosage

	Reverse Osmosis (m^3/day)	MSF (m^3/day)
Majis	20,000	-
BOO Company	6,000	-
Sohar Aluminium	1,000 - 4,000	-
CERTP	4,100	-
Sohar Power Company	-	145,000
Independent Water Plant	250,000	-
Total true capacity	284,100	145,000

Figure 2.2: Division of desalinated water sources

of chlorine to the water 4 $hrs/week$ whereas the industries demanding cooling water prefer a first step of continuously dosed chlorine in the water. Since both processes prefer different ways of dosing, the water for RO is already diverted in this stage. Further steps are the passing through a bar screen with gaps of 30 mm and a rotating band screen with a mesh width of 3 mm to remove larger particles from the water. The above information was provided by Majis.

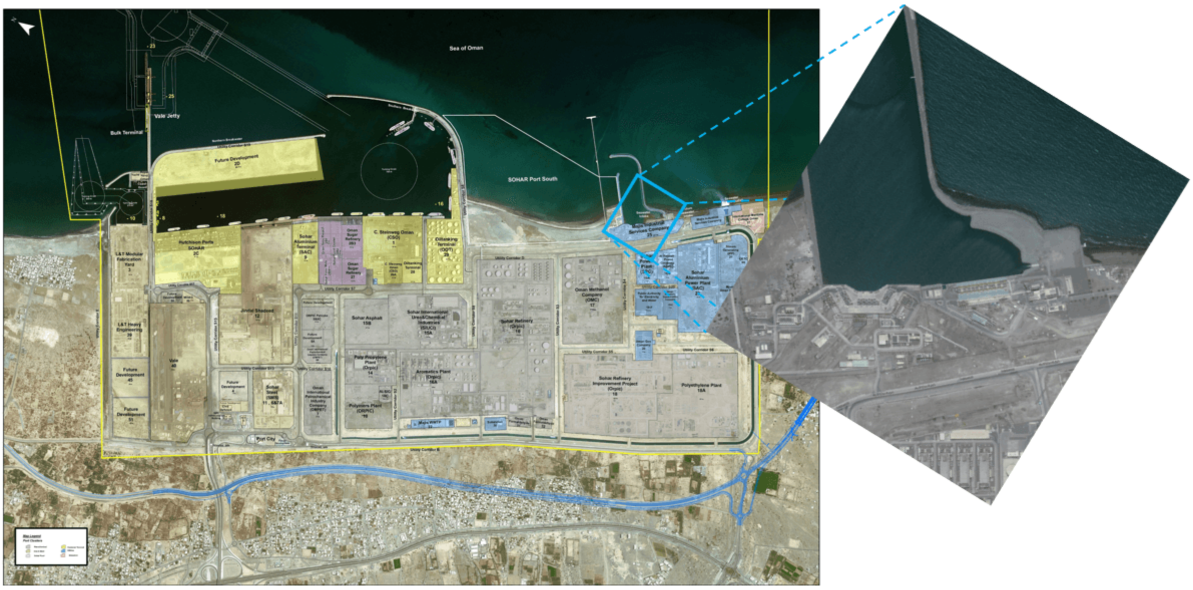


Figure 2.3: Location of the pumping stations in the port

After these pre-treatment steps the major part of the water flows directly to the pump facilities of the industries where it is used as cooling water and a minor part flows to the RO-plant to undergo further treatment. The process in the RO-plant will be further observed in Section B.

2.3.2. Organisation

Majis owns two pumping stations, of which Sea Water Intake Pumping Station (SWIPS) I is the first and SWIPS II recently has been built and is not fully operational yet. At SWIPS I, 48 pumps (including redundant and reserved chambers) extract water after it has passed through one of the 10 bar and band screen facilities. Meeting the current demand, these screen facilities are assumed to also meet future demand as the station is satisfied with customers and will not take in more water. The design demand for SWIPS I is $340,000\ m^3/h$.

At SWIPS II, in the current situation 11 pumps extract water from a basin after the same pre-treatment steps discussed earlier, but there is still space for new customers to place their pumps on the SWIPS 2 station. The pumps in SWIPS II currently get their water from 6 bar screen and band screen facilities. A total occupation of 25 pumps following 10 pre-treatment facilities is planned for the future. The design demand for SWIPS II is $420,000\ m^3/h$.

The majority of the industries currently connected to the pumping stations extract water with their own pump facilities. Only CCWS at SWIPS I is facility owned and operated by Majis. In Figure B.2 and B.3, Appendix B, the division of all tenants over SWIPS I and II is shown.

2.3.3. Customers

The industries that mainly use water can be characterised as (petro)chemical, steel, iron, aluminium and plastics industries. Moreover, four power plants are present in the port. From those four, the Sohar Power Plant not only produces power but also produces drinking water with the Multi Stage Flash (MSF) method. In this method seawater is led through heat exchangers where simultaneously with cooling of the process water, desalinated water is created by flashing the seawater into steam [Sidem and Veolia]. Moreover, all four plants operate as combined cycle gas turbines (CCGT). The Sohar Power Plant, the Al Batinah and the Sohar Aluminium Power Plant use seawater to cool their condensers via a once through seawater system [Al Batinah Power, Sohar Aluminium, Sohar Power Plant] whereas the Shinas Generating Power Plant, which is not operating yet, has its own cooling tower [shi, 2017], with which cooling happens more efficiently and relatively less water is needed, compared to the other power plants.

Power plants	Production (MW)	Water usage (m^3/h)	Type of cooling
Sohar Power Plant	558	28,444	One time through
Al Batinah Power Company	744	37,925	One time through
Sohar Aluminium Power Plant	1,000	50,975	One time through
Shinas Generating	1,700	14,000	Cooling tower

Table 2.1: Power plants in the port

All industries discharge heated cooling water in a discharge channel with a temperature that can be a maximum of 10 °C higher on average than the surface water of the sea, as regulations by the government pose. This sets an important design criterion for this project.

2.3.4. Costs

Little is known about the costs of each industry related to cooling water as f.e. pumping costs and costs for construction and maintenance of the internal cooling system. The only numbers provided are from Majis and concern both the capital and the operating costs of the pumping stations and the RO-plant. The current costs to provide a cubic meter cooling water and potable or process water are 0.002 OMR and 0.4 OMR, respectively. Considering this, the total production costs per year are:

	Costs ($\times 10^6$ OMR/yr)	Costs ($\times 10^6$ USD)	
Cooling water	2.78	7.22	
Potable water	1.31	3.40	
Process water	0.88	2.29	+
Total current costs	4.97	12.91	

Figure 2.4: Current yearly costs for Majis' water production

2.4. Environmental analysis

Construction, design and location estimation of both the pipeline and inlet requires insight in certain site specifications. For example the bathymetry determines to great extent the length and depth of the pipeline coupled to a particular water temperature at that depth. However, hydraulic parameters such as waves and currents, determine the more structural design aspects.

For a decision on the trajectory of the pipeline the site specifications bathymetry, water temperature and navigation are elaborated in Section 2.4.1. Following this, the soil composition, hydraulic conditions and marine life and water quality are discussed in Section 2.4.2 to formulate the other design conditions for the pipeline and inlet structure.

2.4.1. Routing conditions

Bathymetry

Implemented in Figure 2.5, is the data provided by the Oman National Hydrographic Office (ONHO). The figure shows the detailed bathymetry around Sohar Port. A rather gentle and constant slope can be recognised, resulting in a slowly increasing water depth in offshore direction. Those conditions are assumed to be the case for the entire project area as the bathymetry is more or less uniformly distributed alongshore [Deltares, 2014], also further offshore. To reach deeper parts quickly, a trajectory normal to the shoreline is advised.

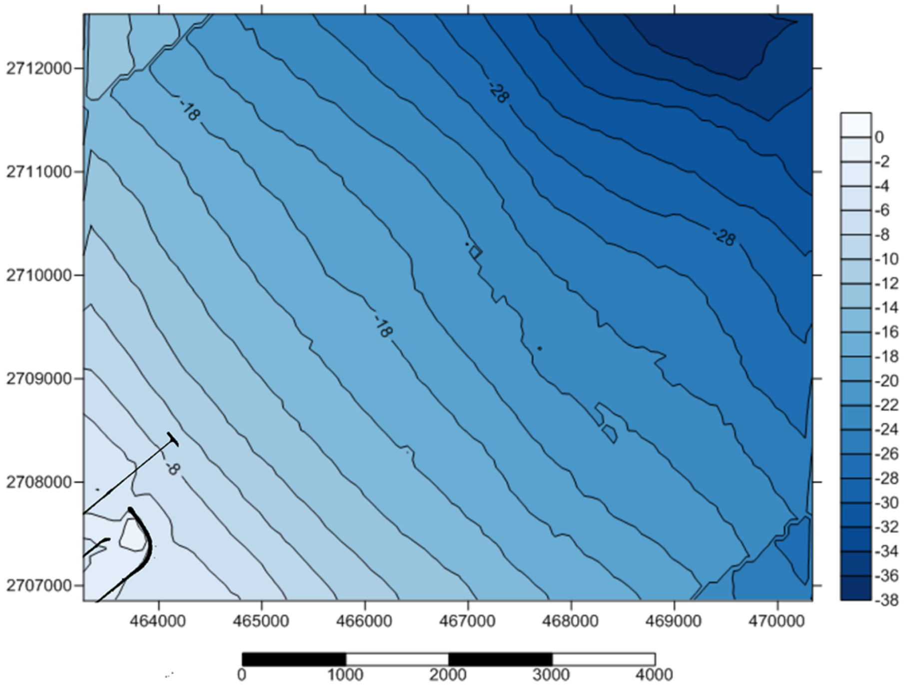


Figure 2.5: Bathymetry around Sohar Port. (ONHO)

The (very) gentle increase in water depth is illustrated in a more detailed way in Figure 2.6 where a cross-sectional cut of the project location is depicted. To reach for larger water depths for significant cooler seawater, the pipeline must be relatively long. Considering a water depth of, for example, only 30 meters would already lead to a required minimum pipeline length of 7 km.

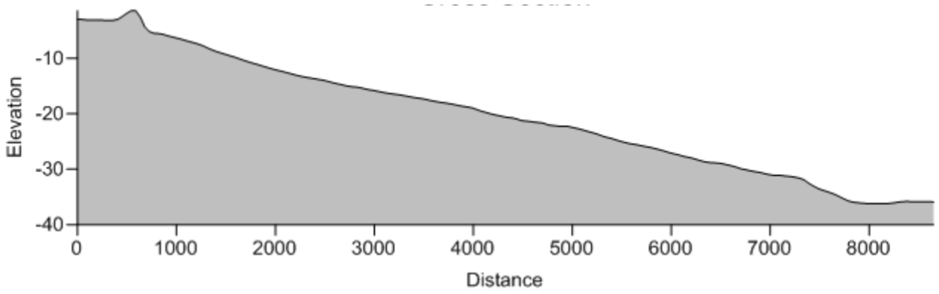


Figure 2.6: Cross-shore section. (ONHO)

Water temperature

More than enough data of the surface water temperature at locations close to the current seawater intake and the outfall location is at hand. Though, water temperature data for different depths at more offshore locations is needed to make an estimation for deep seawater intake temperatures. For this there are two sources of deep seawater temperature data.

Firstly, Bidokhti and Ezam [2009] gives an overview of the outflow from the Persian Gulf through the Strait of Hormuz into the Gulf of Oman. For the presentation of this outflow, measurements on the water temperature at increasing water depths were carried out along lines in the Persian Gulf and in the Gulf of Oman. The water temperature gradient along depth for line F and F' is representative for the region around Sohar and is given in Figure B.4. Unfortunately, as the temperatures for the given depth are extracted from measurements at a much courser scale, the numbers are interpolated and are expected to be rather uncertain. However, the roughly assumed water temperatures for up to 50 meters water depth in winter and summer are summarised in Table 2.2 to show the clearly lower rate of temperature decrease below 30 meters. Together with the flat bathymetry, it can be concluded that the pipeline should not be extended any farther than 30 meters.

	Temperature (°C)	
Water depth (*m*)	Winter	Summer
20	21.7	24.0
30	21.7	22.5
40	21.7	22.0
50	21.7	21.5

Table 2.2: Water temperature (°C) at specific depths. [Bidokhti and Ezam, 2009].

More accurate data can estimate the exact preferred water depth and was made available by the Ministry of Agriculture and Fisheries Wealth (MAFW). This data includes temperature measurements at water depths up to 23 meters (relative to CD) for two locations, 4 km and 7 km offshore respectively, around 15 km south of Sohar Port. Data was gathered for several months in 2014, 2015, 2016 and 2018. In Figure B.5a, B.5b, B.5c and B.5d, the measurements for every season are included. As the measurements only reach up to 23 meters deep the lowest measured temperatures never drop below 23 °C. The spring and summer months show (as expected) most significant temperature differences, whereas autumn and winter do the least.

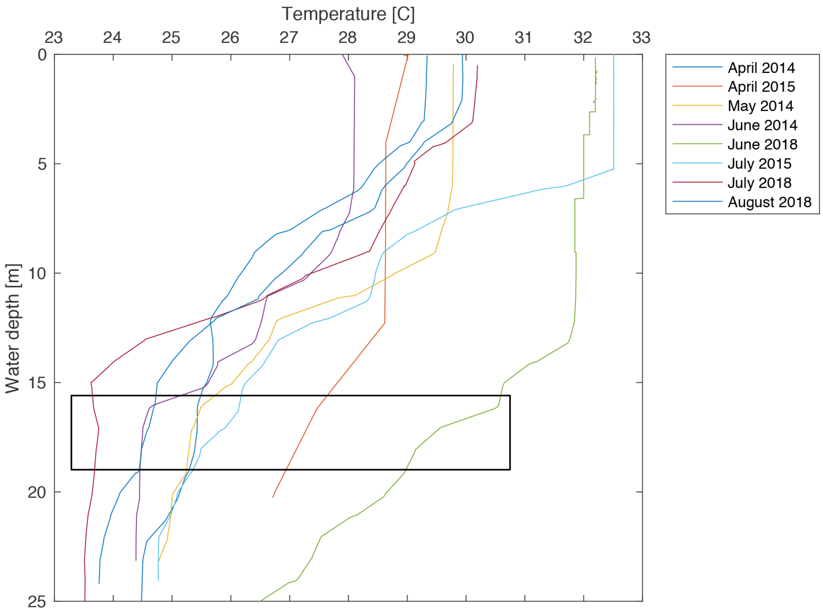


Figure 2.7: Water temperature T [°C] along depth. The black box represents the range of depth of the elbow point.

In Figure 2.7 the water temperature T (°C) along depth is given for the spring and summer months. Clearly visible is the largest average decrease in temperature between 5 and 19 meters water depth relative to MSL (CD -3 up to -17 *m*). After this depth the temperature decrease tends to stagnate leading to relatively more pipeline length for every °C temperature drop. The average temperatures per season for the lower boundary water depth (CD -17 *m*) are given in Table 2.3, together with the difference to the average surface water temperature in the Majis basin.

Water temperature T (°C)	Summer	Autumn	Winter	Spring	Year
Surface	33.3	30.0	25.1	32.7	30.3
Deep (CD -17 *m*)	24.5	25.4	23.4	26.2	24.9
Difference	8.8	4.6	1.7	6.5	5.4

Table 2.3: Average water temperature T [°C]

Shipping

Ships moor and anchor in and around the port, resulting in a significant risk for damage of the pipeline. This can be the case if large ships become uncontrollable and hover over the pipeline or they try to anchor to avoid complete loss of control. The Valemax, the biggest vessel served in the port, has for example a 23 meter draft, if loaded. A thorough understanding of the shipping in and around the port is therefore crucial. Currently, Majis is outside the range of mooring and anchoring of ships and there is no navigation channel in front of Majis. Though, proposals are on the table for expansion of the harbour.

Firstly, there are already three existing anchor areas (A, B and C) for vessels and two new areas (D and E) will be acclaimed to enlarge the total anchor space. A schematisation of these five anchor areas is included in Figure 2.8 with the approach directions of the vessels as well. The red line in Figure 2.8 represents the boundary of the concession area of Sohar Port, with two dotted lined areas to indicate the planned expansions (Phase 1 and Phase 2).

Secondly, land reclamation is planned for the area next to Majis, with possible future mooring and anchor areas there. Majis is situated south-east of the reclamation area with the land reclamation area shown in Figure 2.8 by the orange filled area. The pipeline should be protected from the ships approaching and leaving this newly acclaimed land, or rather should not be routed in front of it.

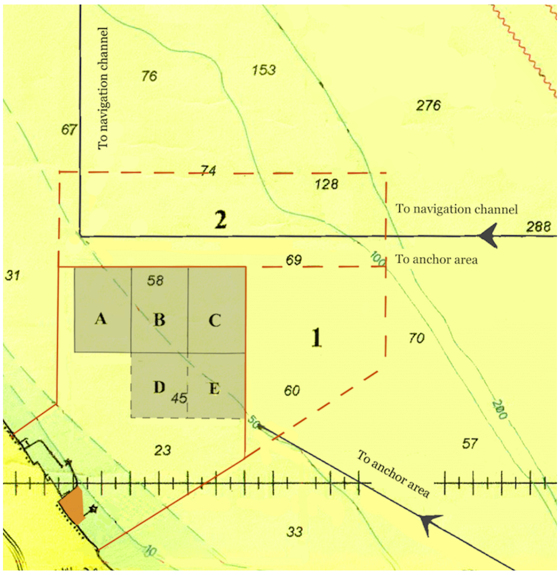


Figure 2.8: Navigation routes and appointed areas.

Conclusion

Resulting from the bathymetry the pipeline was advised to be routed just about normal to the shoreline. In addition, due to the relatively flat bathymetry, for significant lower water temperatures a (very) long pipeline needs to be installed. With pipeline length (direct costs) also friction and corresponding extra pumping costs arrive, all undermining the feasibility of the project. Therefore, the 'elbow' point in the temperature curve, CD -17 m, is chosen as the desired intake depth. Keeping in mind that the inlet structure will be approximately 3 m high, the pipeline should end at a water depth of CD -20 m, corresponding to a pipeline length of 4 km (Figure 2.6). This would not coincide with existing and future anchor and mooring areas as long as the pipeline is not routed in front of the soon to be reclaimed land.

2.4.2. Design conditions

The soil composition and hydraulic conditions are site specifications required to properly design the pipeline and its inlet, regarding its stability or the way of embedding the pipeline and/or structure. For the inlet structure also the marine life surrounding the inlet is important.

Soil composition

Different Standard Penetration tests (SPTs), Cone Penetration tests (CPTs) and rock and soil samples were executed and collected by Fugro and LLC [2017] to provide information about the varying layers of soil and the corresponding density and strength characteristics. A number of 28 drillings were done with depths varying from -0.37 m to -18.30 m. See Figure B.6, for the specific test locations. Although the pipeline will extent far more seaward, the same soil characteristics are assumed for the future location of the pipeline.

According to Fugro and LLC [2017] the results of the CPTs show that the area consists of surficial marine deposits of very loose to very dense silty sand with shell fragments. Under this layer other layers with varying thickness of extremely weak to weak sandstones, conglomerates and locally siltstones were identified.

With the SPTs it is shown that (cohesionless) surficial soil can be characterised as very loose whereas with increasing depth the results show an increase in density up to very dense soil 5-7 meters below the seabed.

In Table B.7 the locations of the loose soil is included. Figure 2.9 shows the estimated soil composition.

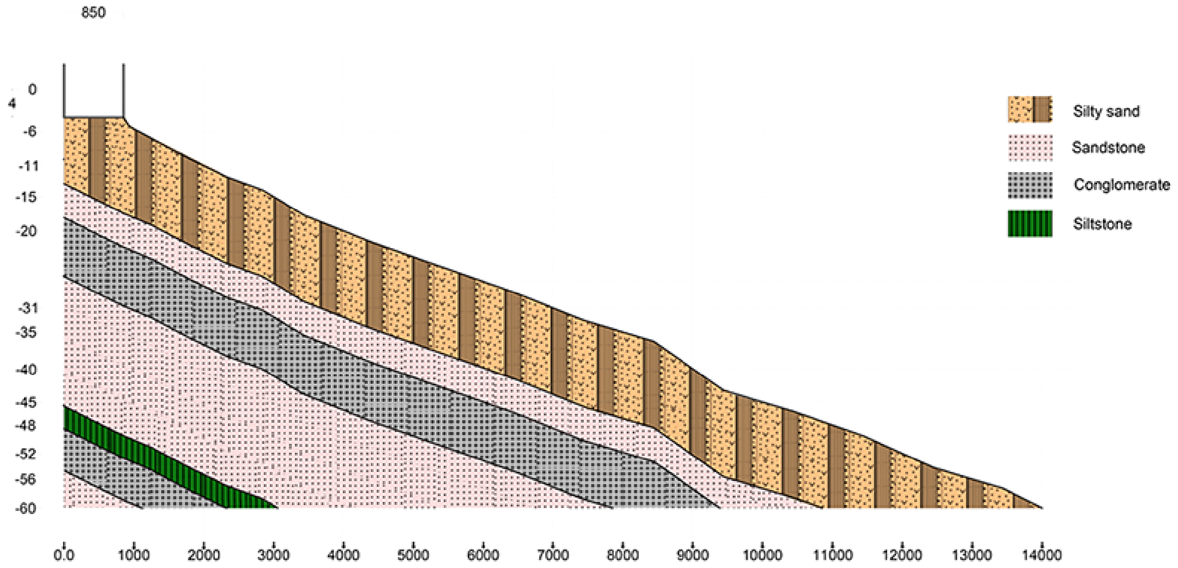


Figure 2.9: Cross section showing the soil composition around Sohar Port.

Hydraulic conditions

Fully exposed to the dynamic environment of the sea, weight collars will need to serve as stability for the pipeline. To calculate the mass of the weight collars, data of wave conditions and currents are required representing the forces on the weights and pipeline. Especially cyclones or storms can be critical events in terms of possible pipeline damage. Also for the stability of the inlet structure the similar wave and current conditions are needed.

Deltares [2018] recently completed a study on the wave and water level conditions around and more offshore of Sohar Port. The study includes normal and extreme wave conditions based on numerical models. Though, for more information about the currents around Sohar Port another (older) study by Deltares [2008] is used. The data used in this research paper is from 1995, but Deltares [2018] states that the older data is still valuable, and does correspond fairly well with the newest obtained results.

Wave conditions In general, the wave climate around Sohar Port is mild. Similar to the bathymetry, the wave conditions show approximately uniform behaviour in the project area. They are composed of the normal wave conditions and the extreme wave conditions, which has been converted from available offshore wave climate data. Appendix B gives an overview of this offshore data in Figure B.8, together with the results of the wave modelling in Figure B.9.

For the normal wave conditions, the modelling results show eastern incoming waves where wave heights of 0.5 m and 1 m are not exceeded, respectively, 75% and 98% of the time, with the highest wave heights occurring from eastern to north-eastern direction. Corresponding to the previous wave heights, wave peak periods from 2.0 to 8.0 seconds are found. From eastern direction the waves with longest wave periods (swell waves) originate. In addition to these averaged conditions, for extreme conditions south-eastern waves correspond to the highest wave heights. With an extreme wave height of 4.00 m in 1/100 year, those waves have the longest wave periods as well.

Currents Estimated maximum depth-averaged current velocities do not exceed 0.5 m/s in the project area and the flow conditions are governed by a composition of wind forcing, air pressure distributions and large oceanic circulations. Tidal flows compared very small in the Sohar region, though, these are much more predictable than the previous, mostly non-deterministic non-tidal flows [Deltares, 2008]. Therefore additional measurements are recommended to determine these non-tidal flows more accurately in the Sohar region.

2.4.3. Water quality

The seawater that is pumped into the cooling water system still contains particles smaller than 3 mm (the band screen pore size) as no further treatment is applied. Fouling and scaling of the cooling water system results. Taking in seawater of better quality (less suspended/dissolved particles in the water) reduces the risk of fouling and scaling. Cleaning or replacing (parts of) the cooling water system less frequently, would be a big advantage for all the industries in Sohar Port.

Secondly, the RO-plants use filters that, currently, need to be cleaned often and actually replaced before the end of their design life. Less clogging and fouling of those filters because of better water quality would result in financial win for the RO-plant owners. Also, avoidance of intake of HABs in the water system is economically utmost interesting, since they cause downtime of the RO-plants when present. HABs are excessive amounts of (toxic) algae in the seawater and prevention of filter/pipe damage forces the RO-plants to shut down temporarily.

Parameters for water quality are firstly discussed, whereupon the occurrence of HABs is covered in the successive section.

Water quality parameters

Turbidity, chlorophyll-a concentration, dissolved oxygen (DO) level and salinity are parameters for water quality in the MAFW data.

Turbidity, chlorophyll-a and DO concentrations are useful both for the cooling water system and the RO-plant efficiency, whereas salinity is important for the RO-plant efficiency only.

In Table 2.4 the four parameters are given for the seawater surface and for a water depth of CD -17 m, as a yearly average. The values at the surface for DO, turbidity and salinity are provided by Majis and concerns measurements at their intake. In Figures B.10, B.11, B.12 and B.13 seasonal graphs are given for the four parameters, constructed by the MAFW data. The data is just for a few specific moments in time, making it rather inaccurate. A more extensive evaluation is actually needed.

In the following paragraphs the parameters are explained separately.

	Turbidity (NTU)	Chlorophyll-a ($\mu g/L$)	Dissolved oxygen (ppm)	Salinity (psu)
Surface	2.69	1.70	7.11	37.47
Deep (CD -17 m)	16.19	2.00	5.68	36.83
Difference	+13.50	+0.30	-1.43	-0.64
	+502 %	+18 %	-20 %	-2 %

Table 2.4: Water quality parameters.

Turbidity Cloudiness or haziness of the water is denoted by turbidity. Removing all the suspended particles (also organic particles) causing this cloudiness, is necessary for the process and potable water so a high turbidity is associated with a lower RO plant efficiency.

Section 2.3.1 already described the purpose of the breakwaters around the intake of Majis. By exposing the water less to waves and currents, leaving particles time to settle, the turbidity of the water is decreased to an average yearly value of 2.69 NTU, see Table 2.4. The measurements of the MAFW indicate a turbidity of 16.19 at a 17 m depth (offshore locations), indicating a relatively much higher turbidity. Dependent on the storage method, the turbidity will be around 16 NTU but can be made lower when particles have time to settle.

Chlorophyll-a Chlorophyll is a direct indication for the amount of algae cells and thus organic material that can clog and foul the filters. [UNESCO, 2017]. In most algae it is the main photosynthetic pigment, making it possible to use it as a proxy for photoplankton biomass (algae). With an increase of 0.30 $\mu g/L$, an 18% higher chlorophyll concentration is found at a water depth of CD -17 m, see Table 2.4. So, in terms of chlorophyll-a concentration the water quality is not better at the new inlet location.

Dissolved oxygen Dissolved oxygen (DO) is formed during the process of photosynthesis, in the presence of light and chlorophyll, representing an indirect indicator for organic material concentrations (chlorophyll). Yet, the DO concentration is also dependent on the water temperature, salinity and water pressure, whereas these factors determine the possible maximum amount of dissolved oxygen. Moreover, the DO concentration decreases in the process of organic material decay. Coming back on the previous mentioned chlorophyll concentration, which is a direct indicator for the amount of organic material, the DO concentration just indirectly indicates the presence of organic particles, but not the exact amount. This is constrained by other factors. Besides organic material presence, DO concentration measurements are important for another reason. Because higher DO levels speed up corrosion in water pipes, a low DO concentration is preferable, [APEC, 2018], and is therefore removed in the RO-process. Lower intake concentrations gains in RO efficiency.

The DO concentration shows a reduction of 20% (Table 2.4), so fewer has to be removed in the RO process. It does, though, not indicate the right amount of organic particles considering the increase of chlorophyll-a at depth.

Salinity The salinity denotes the amount of dissolved salt and ions in the seawater, that have to be removed by the RO membranes to obtain process and potable water. Removing less salts, a lower salinity gains in efficiency of the RO plant, because the applied osmotic pressure can be less. In summer, when higher temperatures cause surface water to evaporate faster, the salinity of the surface water increases while in deeper layers it does not. Extracting deeper water can be beneficial, since the salinity of this deeper water will probably not increase as much as it does in the surface water.

Regarding this prediction, Table 2.4 shows a decrease of salinity of 1.72%. This is, unfortunately, very little, because not only the salinity decreases with depth, the temperature decreases as well. Viscosity increase of the water counteracts the lower salinity and there is no efficiency gain by assigning lower osmotic pressure.

Harmful Algal Blooms

HABs are a marine hazard threatening the RO-plants in Sohar Port. In the treated water, neurotoxins produced by the algae can persist along with bad odour and taste and skin-irritating compounds. Moreover, the organic material produced by some algal blooms can hugely reduce the efficiency or even shut down plant operations as the compounds clog intake filters and foul membrane surfaces [UNESCO, 2017]. This study also points out the observed increase in the number of toxins and HABs over the past years. Figure B.14 (from Piontkovski et al. [2012]) shows this increase along the Omani coast from 1988 to 2010. It is therefore a growing concern of Majis, also when recollecting the economic loss due to the notorious HAB in the Gulf of Oman in 2008.

UNESCO [2017] is very clear on the site specific data necessity, as there are more than just one species, all showing varying behaviour. Some species occur only in the upper 0 - 20 meters of the water column whereas other species can be detected in significant concentrations up to 50 to 90 meters. Coherent between the species is the concentration decrease with depth (see Figure B.15), but as stated before, they vary in occurrence depth, and moreover, some migrate from shallower water to deeper water over time. Figure B.16 shows the migration of phytoplankton (algae) during the day and night. The algae use the sunlight for photosynthesis during day and migrate to deeper, more nutrient water during night. This species of algae was also found in the 2008 HAB in the Gulf of Oman. B.17 shows the observed HAB-species in Oman hitherto and B.18 the migration depths of several HABs. Comparing those two figures, it can be concluded that vertically migrating species are common in the Arabian Sea or Sea of Oman. The part of the total HAB occurrences that included vertically migrating HAB species is yet unknown.

In terms of horizontal distribution, a more offshore location neither guarantees HAB-free seawater. Many HABs originate offshore and are subsequently carried by winds and currents to nearshore waters. It may also happen the other way around, when blooms are transported offshore by what are called 'upwelling-favorable' winds.

Although the significance of specific occurrence data of HABs is clear, there is not enough valuable data of this around Sohar. Salinity, temperature, chlorophyll-a and DO concentrations can be used as indicators for HABs and their behaviour, but the data of MAFW is very time specific. It is unknown if the measurements have been carried out during HAB occurrences (though it is likely that they are not). More (detailed) research is necessary.

Conclusion

Turbidity and chlorophyll-a concentration show an increase at CD -17 m, when at the same time DO concentrations show a significant decrease. Salinity levels decrease with depth, but this decrease is considered insignificant to current salinity levels.

In order to prevent downtime of the RO plants, it is recommended to measure HAB-specific parameters in the Gulf of Oman surrounding Sohar Port in case of a HAB occurrence. Information on the species and their migration depth, toxicity are important. Moreover, the measurements need to cover a larger time scale, especially during HAB-prone seasons. For Sohar, November to March are appointed as HAB-prone months.

3

Project opportunities

Summary Building a new seawater intake could benefit the port in multiple ways. It is important for the feasibility to map and analyse the projected advantages. This chapter discusses the expected benefits.

The efficiency of RO-plants is largely dependent on the water quality. The expected RO benefits are (very) uncertain and should follow from additional water quality measurements. The potential range varies from 0 - 3.8 mln OMR/yr in savings, the largest contributors to the total expected savings are the decreased downtime and electricity usage.

The power plants make up approximately 60% of the present water demand. The plants are expected to keep discharging the same amount of water in the future, regardless of the water temperature. Their benefit is in the fact that colder water leads to a higher efficiency of their steam turbines with which they will be able to achieve the same production but use less natural gas. The estimated efficiency gain is between 0.43% and 1.03%. Benefits are between 0.38 mln OMR/yr and 2.6 mln OMR/yr.

A reduction in cooling water demand in the port is expected due to the fact that the colder water will have a higher heat dissipation capacity and hence the amount of water necessary to cool a certain process will reduce. Those cooling water consumers make up 40% of the current total water demand. The water reduction for these consumers will be between 5% in the winter and 39% in the summer, resulting in an expected cost decrease of 0.8 mln OMR/yr now and 3.1 mln OMR/yr for the future.

There are multiple potential environmental benefits. Moreover, reduced downtime due to HABs and better accommodated future growth are opportunities that have been described.

It followed that both the RO-plants and power plants show the largest financial benefits relative to the required amount of water. It is seen as very promising to consider the option of only connecting these industries to the new deep seawater intake. Calculations show that a future design discharge of $219,000\ m^3/h$ is required for this limited-scale option.

As environmental benefits and future growth opportunities decrease for smaller discharges, also a full-scale alternative is considered where all industries are connected to the deep seawater system. It follows from computations that a future design discharge of $694,000\ m^3/h$ is required for this large-scale option.

3.1. Introduction

An offshore seawater intake can be beneficial for the port in multiple ways. This chapter analyses qualitatively and, where possible, quantitatively the project opportunities. This is done in order to get a feeling of the potential benefits and where they can be attained best, elaborated in Section 3.2 and 3.3. The benefits then are categorised and addressed one by one in Section 3.4 to 3.7. In the last section, Section 3.8, an analysis of the achieved results is enclosed whereupon the boundary conditions are achieved for Chapter 4.

3.2. RO-plant

Reverse osmosis is a filter based desalination process that can benefit in multiple ways if water with a better quality is used. The total discharge that goes via SWIPS I & II to the RO-plants in the port is $24{,}000\ m^3/day$. The potential benefits together with their corresponding quantification have been obtained from Abdullah Al Sadi (Business developer, Majis). They are enumerated and explained below:

1. **Increase in capacity** - Currently the production of process and potable water does not meet the design capacity of the Majis RO-plant. The plant was originally built to produce 20,000 m^3/day but on average actual production levels are around 15,000 m^3/day. This production gap largely exists due to the frequent backwashing of the filters, during which they can not be used. The cleaning frequency largely depends on the quality of the water, i.e. contamination level of the water. A potential average production of $18,000$ m^3/day can be reached if deep seawater is used. For the Independent Water Project RO-plant the design capacity is $250,000$ m^3/day [iwp]. The present average production of this plant is estimated at $220,000$ m^3/day .

2. **Decrease in electricity usage** - The electricity usage for producing 1 m^3, is expected to decrease from 4.5 kWh to 3.5 kWh. This energy is required to overcome the osmotic pressure and push the water through membranes to remove salt and other dissolved particles. Presumably, the water at the new intake is cleaner and hence the required amount of electricity will go down to achieve this 1 kWh decrease.

3. **Decrease in chemical usage** - The total costs for chemicals necessary for the RO process, will reduce by half.

4. **Longer filter life cycle** - By a decrease in pollution the life cycle of the filters and assets of the RO-plant will significantly improve. The amount of savings that can be achieved have been estimated at 10% of the current budget.

5. **Decreased HAB-related downtime** - The final saving is related to the reduction of influence of HABs, i.e. the downtime of the RO-plant will be considerably less. Yearly averaged, the production of the plant is currently reduced for 30 days by 33 %, and for an average of 10 days by 53 % up to 100 %.

The benefits are described in more detail in Section E.2. Benefits have been calculated for Majis' power plants but also other RO-plants should be taken into account. Most significant is the IWP so that the benefits for Majis have been extrapolated to the IWP plant to also incorporate their potential benefits. The accompanied profits have been summarised in Table 5.3.

Validation
The above calculated benefits are largely based on assumptions and data provided by Majis. After analysis of the first water quality data that became available through the Ministry of Agriculture and Fisheries Wealth there is reason to doubt those assumptions. The data, collected at a site a few kilometres away from the proposed intake location, does not show the presumed increase in characteristics. The data contradicts especially when it comes to turbidity levels. The currently existing enclosed bay offers long retention times for the water so that turbidity can sink to the bottom. The water at the intake is therefore almost free of turbidity, compared to the water at the proposed deep seawater intake. As the data on this topic is considered insufficient, it is recommended to dive into this for site specific data verification. It was decided to stick with the earlier made assumptions for the calculations since the data received is collected at a distance away from the proposed intake of this project.

Results
Figure E.1 illustrates the model used to calculate the benefits for the RO-plants. The total savings mount up to 3.8 mln OMR (9.87 mln USD) and are the combined benefits of the different RO-plants. In Table 3.1 the extra revenue through increased production and the decrease of production are shown for the Majis and IWP RO-plants.

	Majis RO-plant		**IWP RO-plant**	
	($\times10^6$ OMR)	($\times10^6$ USD)	($\times10^6$ OMR)	($\times10^6$ USD)
Decreased production costs	0-0.36	0-0.95	0-3.1	0-8.1
Increased production capacity	0-0.35	0-0.92		
Total	0-0.72	0-1.86	0-3.1	0-8.1

Table 3.1: Predicted benefits for the RO-plants. A decrease in the production costs and an increase in the production capacity is expected.

3.3. Power plants

In Section 2.3.3 it is explained that only for the steam turbines a lower cooling water temperatures results in significant lower electricity costs. Of the four operating power plants in the port, three (Sohar Power Plant (SPP), Al Batinah Power Company (ABPC) and Sohar Aluminium Power Plant (SAPP)) use gas and steam turbines, all of them potentially benefiting from colder cooling water. Shinas Generating (SG) uses a cooling tower which is essentially different from the once-through cooling systems of the other power plants. Shinas potentially has a (small) benefit but has not been taken into account for this project. In the following paragraphs, the benefits are both qualified and further quantified.

Temperature - Power relation

When the steam produced by the gas turbines is let through the steam turbines, cooling water is added in the steam turbines. When the cooling water temperature is below the saturation temperature of the steam entering, condensation occurs. Colder cooling water gives a lower condensate pressure and correspondingly a higher thermal efficiency. See Figure C.2 for the cycle thermal efficiency related to the condensate pressure. [Kim and Jeong, 2013].

When this cycle thermal efficiency is translated into plant power an inversely proportional relation between sea water temperature and plant power output results, see Figure 3.1. It follows from this graph that for every degree °C of cooling water temperature decrease, the plant power output increases with about 0.40 %.

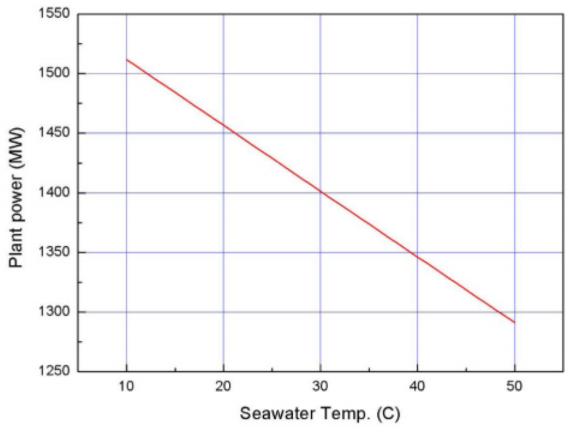


Figure 3.1: Relation between cooling water temperature and the electric power output [Kim and Jeong, 2013]

The number of gas and steam turbines have been collected and summarised in Table 3.2 [Al Batinah Power, Sohar Aluminium, Sohar Power Plant]. The steam turbine of the SPP accounts for one third of its total electricity production [Sohar Power Plant]. Since the other power plants make use of the same technology for power production it is assumed that they also produce one third of their electricity with their steam turbine(s), although this has not been confirmed.

Power plant	Gas turbines	Steam turbines
Sohar Power Plant (SPP)	3	1
Al Batinah Power Company (ABPC)	3	1
Sohar Aluminium Power Plant (SAPP)	6	2

Table 3.2: Number of gas and steam turbines per power plant

In the summer SPP produces at maximum capacity, which is 585 MW, in the winter at around 85%. This is assumed to be the case for all three power plants. In Table 3.3 the power production per plant is shown.

Since one third of the turbines at every power plant is a steam turbine, the total increase of plant power output will only be 0.40 %/3 = 0.13 % for every degree of colder water. Chapter 2 gives the decrease of cooling water temperature per season with the new deep seawater intake. For simplicity, spring and summer are averaged as summer and autumn and winter are averaged as winter, resulting in a water temperature decrease of 7.7 °C in summer and 3.2 °C in winter. According to those temperatures, the increase of the power production becomes 1.03% and 0.43%, for summer and winter respectively. The new production levels are summarised in Table 3.3.

	Summer		**Winter**		
Power plant output	Old (MW)	New (MW)	Old (MW)	New (MW)	
Sohar Power Plant	585	591	497	499	
Al Batinah Power Company	737	745	627	630	
Sohar Aluminium Power Plant	1000	1010	850	854	+
Total	2322	2346 (+1.03%)	1974	1982 (+0.43%)	

Table 3.3: Total produced power increase due to colder cooling water.

Flow quantity

Flow analysis from data of a single day (see Figure C.3) shows that approximately 202,000 m^3/h of the intake flow at SWIPS I & II is designated for the power plants, covering 60% of the total flow. For the yearly average flow, 300,000 m^3/h has been assumed. Above data and average flow assumption have been provided by mr. Satish from OSWS. OSWS (Oman Sustainable Water Services) is the company responsible for operating SWIPS I & II.

CRT vs. gas savings

Profits following from the production increase are calculated using two different methods. Both are explained elaborately in Section E.3.

The first calculation method is based on the Cost Reflective Tariff (CRT) model and uses average electricity prices to translate the production increase into benefits. The cost reduction, using this CRT-model, is 2.6 mln OMR/year as shown in Table 3.2.

The second method calculates the decrease in gas use and translates this into a profit value. This would be the result if the plants keep producing at the same output rate and would merely benefit from a lower gas bill. The expected benefits for the second method can be found in Table 3.3.

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
New revenue through power production	317.6	825.9	
Old Revenue through power production	315.0	819.0	–
Benefits per year	+2.6	+6.9	

Figure 3.2: Increased revenue from higher production according to CRT-model

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
New gas costs per year	52.6	136.8	
Old gas costs per year	53.0	137.8	–
Annual gas costs reduction	+0.4	+1.0	

Figure 3.3: Savings on gas usage.

Conclusion

In reality the worth of the increased production will be somewhere in between the two values indicated above. The CRT-model overestimates the benefits because CRT embodies all costs to produce electricity. On the other hand, only assuming the savings on gas as benefit for the power plants underestimates reality because the worth of produced electricity is higher than its equivalent in gas. The above calculated numbers were used as the lower and upper boundary for future calculations. It can be concluded that savings will be largest in the summer when the temperature compared to the original situation is largest. In the summer the increase in production is 24 MW (+1.03%) and in the winter around 8 MW (+0.43%). The financial benefit is between 0.4 - 2.6 mln OMR/year (1.0 - 6.9 mln USD/year).

3.4. Heat dissipation processes

The heat transport in cooling systems depends on the heat dissipation capacity, which is assumed to be constant in a system. It is determined by the mass flow rate, the specific heat of the cooling water and the difference in water temperature between the inflow and outflow of the system. When a temperature difference is set, a mass flow rate trough the cooling system (and additionally a discharge) can be calculated. With this new discharge, the required pumping power to pump this water to the industries is calculated.

In order to decrease the pumping power, and ultimately, save electricity costs, the discharge has to be reduced. This is done by increasing the ΔT. In (3.1) it is shown that when ΔT increases $\dot{m}$ decreases. Environmental regulations do not allow the water temperature at the outfall to be higher than 10 °C than the surface water temperature ($\Delta T = +10\ °C$). With the surface water temperature set and this limit posed by regulations, the only way to make the ΔT larger, is by taking the water in colder. Extracting water at a larger depth can realise this. Chapter 2.4 concluded $CD - 17\ m$ for the water intake depth.

With a water temperature at a water depth of $CD - 17m$, the discharge needed for the cooling system will be calculated. Firstly, with (3.1) giving the heat dissipation capacity, the mass flow rate is calculated. Then using (3.2), the pump power results directly from this discharge.

$$q_{conv} = \dot{m} \times c_p \times \Delta T \tag{3.1}$$

Where:

q_{conv} = duty of heat transfer (W)
$\dot{m}$ = cooling water flow rate (kg/s)
c_p = specific heat (J/(g°C))
ΔT = temperature difference between inlet and outfall seawater (°C)

$$P_h = \frac{q \times \rho_{sea} \times g \times h}{3.6 \times 10^6} \times \eta \tag{3.2}$$

Where:

P_h = hydraulic power (W)
q = discharge (m^3/h)
ρ = density of seawater (1,025 kg/m^3)
g = gravitational acceleration (9.81 m/s^2)
h = differential head (m)
η = pump efficiency (%)

Water and power usage

Of the cooling water designated for the factories only the total flow that goes through the intake is known. Nothing about the processes in the industries is known since none of that data has been made available during the stretch of this project. Because this was the case calculations were made with (3.1) and (3.2), to make clear assumptions.

Approximately 40% of the water that is taken in at SWIPS I is classified as water purely used for heat dissipation (not including water designated for power plants). With a current average flow of 300,000 m^3/h this adds up to 120,000 m^3/h. For SWIPS II this number is currently only 20,000 m^3/h. The future users of SWIPS II are unknown however, but for simplicity all remaining slots in SWIPS II have been assumed to use water purely for heat dissipation (i.e. no power plants or RO-plants). The future forecast of SWIPS II hence becomes 95% heat dissipation water (400,000 m^3/h) and the advantages of this water are covered in this section. Adding the heat dissipation water from SWIPS I and II together gives us the design total discharge: 140,000 m^3/h at present and 520,000 m^3/h forecasted for the future.

Table 3.4 shows the water discharge dedicated for heat dissipation in the current situation as well as a situation including the new seawater intake. Results were obtained by using the water temperature data from Section 2.4.1 in combination with (3.2). Similar calculations led to future discharge projections shown in Table 3.5.

		Summer	Autumn	Winter	Spring	Average
Present Discharge	(m^3/h)	140,000	140,000	140,000	140,000	140,000
New Present Discharge	(m^3/h)	85,000	101,000	133,000	104,000	106,000
Difference	(m^3/h)	-55,000	-39,000	-7,000	-36,000	-34,000

Table 3.4: Change in present cooling water discharge

		Summer	Autumn	Winter	Spring	Average
Future Discharge	(m^3/h)	530,000	530,000	530,000	530,000	530,000
New Future Discharge	(m^3/h)	323,000	381,000	505,000	385,000	399,000
Difference	(m^3/h)	-207,000	-149,000	-25,000	-145,000	-131,000

Table 3.5: Change in future cooling water discharge

In Table 3.6 and 3.7 the results can be seen that were found by filling in the new discharge in (3.2). Because the discharges decrease a lot more in the summer than in the winter, the power consumption decreases a lot more in the summer. In those months the prices for electricity are the highest.

		Summer	Autumn	Winter	Spring	Average
Present Power Consumption	(MW)	16	16	16	16	16
New Present Power Consumption	(MW)	9	11	15	12	12
Difference	(MW)	7	5	1	4	4

Table 3.6: Change in present power consumption

		Summer	Autumn	Winter	Spring	Average
Future Power consumption	(MW)	59	59	59	59	59
New Future Power consumption	(MW)	36	42	56	44	45
Difference	(MW)	23	17	3	15	15

Table 3.7: Change in future power consumption

To calculate the decrease in pumping costs the decrease in pumping power has been multiplied by the electricity costs [MEDC Oman, 2018]. The calculations for the cost savings are further elaborated in Appendix E.4. The results regarding cooling water are shown in Table 3.8. The benefits are different for current usage and future projected usage. This is due to the massive difference in discharge now and in the future. Besides this, since little is known from the processes inside the factories, it is assumed that the factories will make full use of the extra ΔT to cool down there processes. This means when the factories do not use the entire ΔT, more discharge and pumping power will be needed.

	Present costs		**Future costs**	
	$(\times 10^6$ OMR)	$(\times 10^6$ USD)	$(\times 10^6$ OMR)	$(\times 10^6$ USD)
Costs without new intake	3.2	10.4	12.0	31.2
Costs with new intake	2.4	8.3	8.9	23.1
Efficiency gain	0.8	2.1	3.1	8.1

Table 3.8: Total costs

Conclusion

A summary of the discharge calculations is shown in Table 3.9. The potential benefit is large in the summer and (very) low in the winter. Taking the current discharges into account the benefits are 0.8 mln OMR (2.1 mln USD) per year with current discharges and 3.1 mln OMR (8.1 mln USD) per year with future discharges.

The benefits are low in the winter because companies are allowed to discharge cooling water back into the ocean at surface temperature +10 °C. The difference between surface water temperature and off-shore intake temperature is very low in the winter, hence the benefit is little.

	No new intake (m^3/h)	New intake (m^3/h)	Δ (m^3/h)	Change (%)
Current situation				
Summer discharge	140,000	85,000	-55,000	-39%
Winter discharge	140,000	133,000	-7,000	-5%
Future situation				
Summer discharge	530,000	323,000	-207,000	-39%
Winter discharge	530,000	505,000	-25,000	-5%

Table 3.9: Water discharge predictions for water defined as 'remaining cooling water'. The current situation uses the discharges as they are right now. The future situation calculates values with SWIPS I & II being used up to their design capacity

3.5. Environmental gains

There are several environmental opportunities that can be achieved through this project. At the moment SIPC is bound to regulations posed by the government regarding environmental impact. Moreover the company itself believes in environmental responsibility which is why it is looking for ways to make the port more sustainable. Three opportunities of this solution that support this cause are:

- Less impact on zoological activity
- Reduction thermal plume

The first advantage is that less marine life is present at the bottom of the sea than in the surface layer, as can be seen in Section 2.4, so that the impact on marine life around the intake will be much lower. The decreased impact on marine life will most likely be beneficial for the fish stocks in Sohar. How large this effect will be and to what extent it might benefit the local fishermen is still to be investigated.

Secondly the thermal plume will decrease because it is assumed that the power plants will not heat their cooling water with a bigger ΔT than they are doing now. In this way a reduction of the thermal plume takes place, that is now present at the outfall. The environment will benefit considerably from this.

3.6. Harmful Algal blooms

More research has to be done on HABs, as is described in Section 2.4. The savings that occur if downtime of the RO-plant can be reduced are therefore mainly hypothetical. The costs are only taken for the Majis RO-plant as it is assumed that the IWP, being a newer and more modern plant, copes better with algal blooms. The days of downtime and reduction give the gain in production that can be achieved. This increased production leads to an increased revenue of $159,507\ OMR/yr$. This gain in revenue was already added to the increase of benefits by the RO-plants. The above is elaborated in Section E.2.

3.7. Future growth

For the future growth of the port the following opportunities are considered:

- Land reclamation
- Increased value assets
- New business opportunities

An important opportunity for SIPC is the possible extension of reclaimed area. Currently a reclamation is planned next to the seawater intake, but as soon as pipelines would transport the water and the superficial inlet is no longer necessary this reclamation can be extended by 23 hectares. This extra reclaimed land can be rented out to attract new industries. This opportunity can however only exist if arrangements can be made between the landlord, the leasing company and the pipeline operator.

The infrastructure of pumping stations, treatment steps and pipelines has been a considerable investment of Majis in the past. Every opportunity to keep using this infrastructure will decrease the necessity of constructing new, thereby postponing or even averting the next capital investment. This is the case for an outfall channel that becomes necessary when the current method of extracting water is maintained. Majis was instructed by the government to relocate this outfall. The reason for this is that the thermal plume from the outfall returns to the intake by the current. This increases the need for more water, higher pumping costs and the strain on the environment but can be prevented with a deep seawater intake. The costs for a new outfall were estimated by Majis at 17 mln OMR.

Furthermore, by efficiently creating space for new clients, the capacity of the pumping stations can be extended, thereby creating additional value for the existing infrastructure. The different industries that have their pumps at the two pumping stations have an opportunity to decrease the costs for occupying the pumping chambers. The clients pay for the chambers that they take up at SWIPS I and II. In case less water is required, assuming that the companies keep using full chambers, they will need less chambers, thereby decreasing their costs and making space for new customers. This would potentially bring an extension of the life cycle of SWIPS I and II. The value that this brings to the project is difficult to estimate precisely as the increase in capacity depends on many factors, and the exact year of re-investment makes such a large difference. A rough estimation is made where a capacity increase of 10% and a postponement of investments of 5 years are assumed. The costs that are saved with this postponement is 4.7 mln OMR.

The possible access to colder and cleaner water might attract different customers than yet present in the port. A data center that could use colder water for cooling purposes is only one example.

3.8. Efficiency analysis

This section analyses the results from the previous sections. The benefits that could be quantified are further assessed in this section. The potential benefits for RO, power plants and remaining cooling water have been summarised in Table 3.10.

	Present benefits		**Future benefits**		
	($\times 10^6$ OMR)	($\times 10^6$ USD)	($\times 10^6$ OMR)	($\times 10^6$ USD)	
RO-plants	0 - 3.5	0 - 9.1	0 - 3.5	0 - 9.1	
Power plants	0.4 - 2.6	1 - 6.8	0.4 - 2.6	1 - 6.8	
Cooling water	0.8	2.1	3.1	8.1	+
Total	1.2 - 6.9	3.1 - 18.0	3.5 - 9.2	9.1 - 24.0	

Table 3.10: Potential cost savings achieved due to a new intake

Consequently, discharge calculations have been plotted against calculated benefits. The results are shown in Figure 3.4 whereas the numbers used for RO and power plants that are averaged over the projected range are shown in Table 3.10. The graph reads that RO and power plants make up a relatively small part of the water discharge but are on the other hand responsible for the major part of the benefits.

3.8.1. Alternatives

Since not all processes benefit in the same way of the proposed deep seawater intake, this section argues that a smaller scale alternative could be more economically more feasible.

An alternative is opted where not the entire port but only the power plants (except Shinas) and the RO-plants will be connected to the new intake system. By doing so, the pipeline system can be much smaller and hence the project costs will go down. Figure 3.5 shows the different design discharges for a small- and full-scale alternative. For the full-scale alternative the design demand is reached in the winter (694,000 m^3/h) when relative cooling benefits are least (small increased ΔT). The limited-scale design discharge (219,000 m^3/h) is reached in the summer when the power plants produce most electricity and need larger amounts of cooling water to do so.

Qualitative comparison

Table 3.11 compares which advantages (discussed in Sections 3.2 through 3.7) are applicable to the full and/or the limited-scale alternative. All earlier mentioned benefits apply to the full-scale alternative. The smaller scale alternative boasts the cost savings for RO and power plants but not the pumping savings achieved by

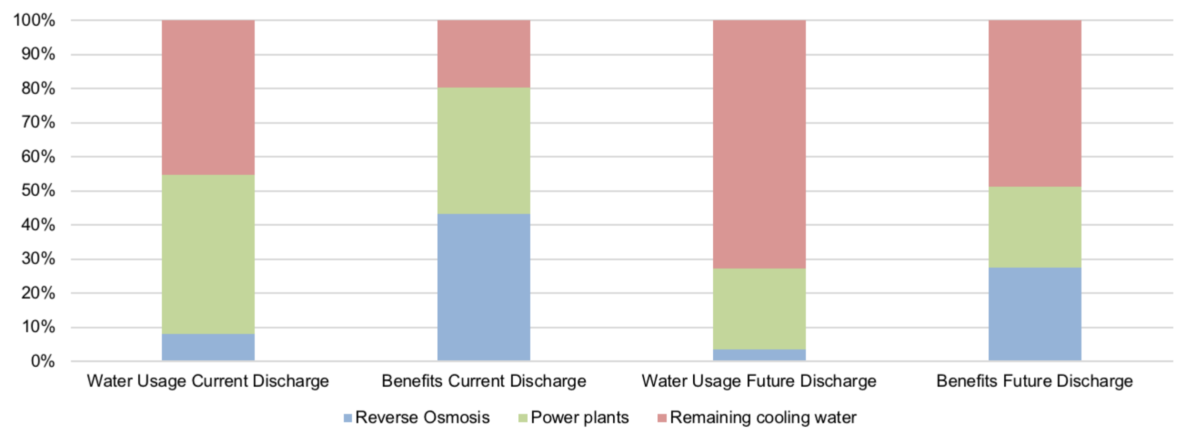


Figure 3.4: Visualisation of water usage and potential benefits.

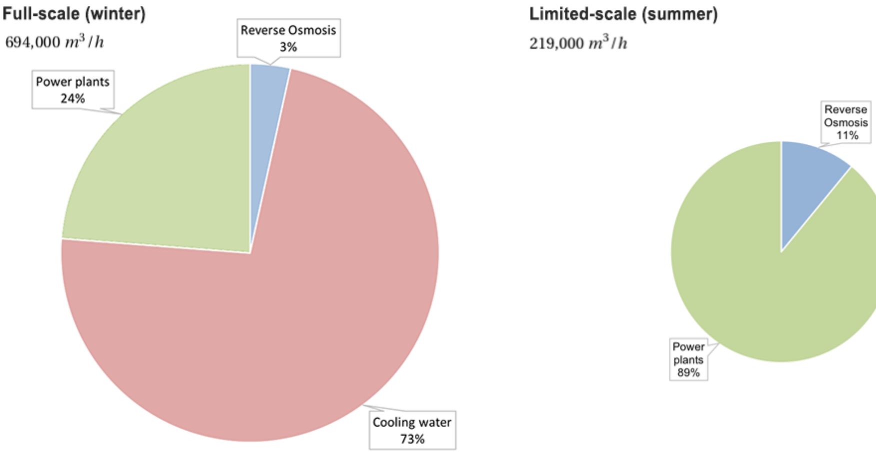


Figure 3.5: Design discharge for the full and limited-scale alternative.

(less) cooler water nor the environmental benefits.

Many of the benefits are present in both the full- and limited-scale scenario. However, for some benefits this is not the case:

- **Decrease in pumping costs** - For the limited-scale alternative the decrease in pumping costs is not applicable since both the power and RO-plants are not expected to change their discharge.
- **Environmental issues** - The reduction in the thermal plume originates from the power plants that will discharge back at a lower temperature, so this advantage is maintained for the small-scale alternative.
- **Future growth** - The biggest differences between the two alternatives are within the future growth. Because a considerable part of the users will keep using the current intake method, the bay in front of SWIPS I & II cannot be used for land reclamation. Additionally, since the quantity of the water is not going to change significantly, the assets by Majis will not have a higher total capacity (see section 3.7). Finally, the limited-scale alternative will not give rise to any business opportunities looking for colder/cleaner water. This is due to the fact that all of the water is already dedicated to the existing RO and power plants, not leaving room for new connections for future users.
- **Increased asset value** - As a result of the limited-scale it would still be necessary to change the location of the outfall.

	Full-scale	RO/Power Plants only
Desalination plants		
Cheaper/higher production	✓	✓
Power plants		
Increased efficiency	✓	✓
Heat dissipation capacity		
Decrease pumping costs	✓	-
Environmental issues		
Reduction thermal plume	✓	✓
Animal entrapment	✓	-
Algal blooms		
Unaffected by algal blooms	Unknown	Unknown
Future growth		
Land reclamation	✓	-
Increase asset capacity	✓	-
No new outfall required	✓	✓
New business opportunities	✓	-
Design discharge	694,000 m^3/h	219,000 m^3/h

Table 3.11: Qualitative comparison of benefits for full-scale and small-scale investment

Side note: RO-alternative

Taking a closer look at Table 3.4 one could argue that an alternative scenario, solely providing the RO-plants with higher quality water, might be most feasible. RO only requires a tiny fraction of the water whilst being responsible for 43% (current) and 28% (future) of the benefits. To further investigate this possibility first of all the water quality and corresponding benefits need to be validated. The current range of benefits is between 0 and 3.5 mln OMR per year. One should note that the ideal 4000 m pipeline length (motivated in Section 2.4.1) might not be the same in a case where only the water quality (and not the temperature) is of importance. As a matter of fact, temperature even has a slightly negative effect on the costs of the RO process. Since investigating this opportunity steps too far off the original research question (providing both colder and cleaner water), the RO alternative has not been further investigated for this research.

4

Offshore seawater intake design

Summary This chapter answers the technical feasibility part of the research question. For an optimal technical design the hydraulic pressure head loss should be kept as low as possible as it will increased construction and pumping costs. HDPE was selected in a comparison for its beneficial characteristics in the proposed project. Pipelines with a 2.5 m outside diameter show the best results in friction loss calculations. Based on the expected future demand, discussed in Chapter 3, a total of 37 pipelines has to be installed when the entire port is to be provided with colder water. For the limited-scale scenario, a total of 12 pipelines has to be installed.

It is stated that the conservation of infrastructure is key factor in the new solution. The operation of the current pumps requires a certain guaranteed water level. The hydraulic pressure head loss over the pipelines would decrease this level, thereby demanding many more pumps to be installed that bring high operational costs. For this reason the decision was made to construct an alternative basin that creates a gravity induced flow. Two different options are explored; a dry well and a wet well. The decision was made for the wet well based on the high operational costs the dry well brings. A design height of 13.4 m was found for the new basin, reaching until $CD-9.5\ m$. It was found that the proposed new basin should ideally be constructed in between SWIPS I II to minimise costs and disturbance during construction. Large screw pumps will pump the water to manifolds from where the water is diverted to the existing basin of the destined pumping station. In the limited-scale scenario a minor extension of SWIPS I is proposed to comply with the number of pipelines. Preliminary calculations support that this is much more cost effective than constructing more pipelines to achieve small head losses.

In order to prevent larger aquatic animals from entering the pipelines, installation of coarse (bar) screens is required. At the offshore end, every pipeline is finalised with a $4 \times 5\ m$ cylinder of reinforced concrete, containing a 30 mm pore size screen.

It is advised that continuous chlorination takes place for all industries except for the desalination plants. Furthermore pigging measures should be installed to clean the pipes from biofouling over the years. An overview of the design of the proposed solution is shown in Figure 4.1.

4.1. Introduction

This chapter investigates the technical possibilities to construct a deep seawater intake. It aims to find the optimum design to achieve the goal of this project, providing colder and cleaner water for the Sohar port.

In the Section 4.2 the design for the pipelines, necessary to transport the colder water from the offshore intake point to the coast, is discussed. First of all the objective and some general design requirements are mapped out. Based on the analysis in Chapter 2, the preferred routing and length are then discussed in Section 4.2.3. Different pipeline materials and sizes are compared in Sections 4.2.4 and 4.2.5. Additionally the pipeline ballast weights, construction method and mechanical calculations are discussed in Sections 4.2.6 through 4.2.8.

Based on the full- and limited-scale scenario posed in Section 3.8 the recommended connection of the pipelines with the existing intake facilities is given in Sections 4.3. After that a design is made for the intake head structure of the pipelines as well as an analysis of the maintenance and operation requirements that

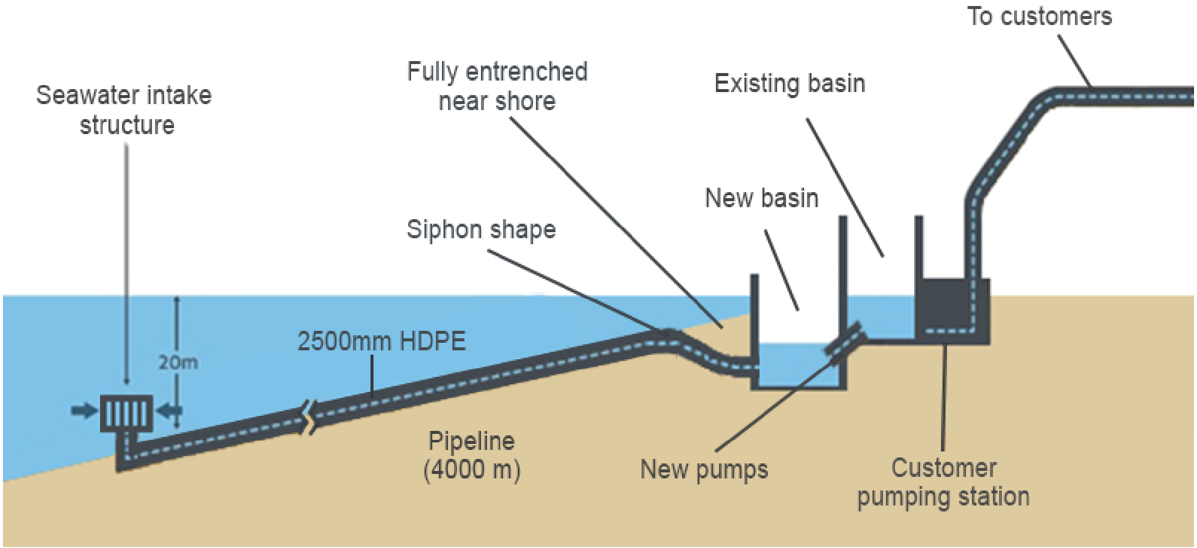


Figure 4.1: Sideview proposed intake system

should be taken into account for further development of this project. To conclude this chapter a rough cost estimation has been made for the project.

4.2. Pipeline

This section maps the considerations leading to the recommended design for the pipeline. Pipeline material, trajectory, size and mechanical design are discussed.

4.2.1. Objective

The main objective for the intake system is to guarantee a flow of cool, clean water demanded by the Sohar Industrial Port and Freezone to be used as cooling water or to produce process and/or potable water. This water will enter in an offshore intake head, move through a 4000 m long (from Section 2.4.1) pipe/conveyor and should be connected in some way with the current facilities. In Section 3.8 it was concluded that providing the entire port in the future requires a design capacity of 694,000 m^3/h. Additionally, providing only the power plants and RO-plants would sum up to a total of (only) 219,000 m^3/h.

4.2.2. Design requirements

Hydraulic pressure head loss

For economical reasons the total accumulated Hydraulic pressure head loss over the pipeline should be as little as possible. This Hydraulic pressure head loss is the loss of energy of the seawater while passing through the seawater intake structure and can be translated into a difference in water height in the ocean compared to at the intake station. It consists of the friction of the pipe-wall, inflow losses, outflow losses and losses due to (sharp) bends in the pipe trajectory. The pressure head loss is further elaborated on in Appendix D.1 and is illustrated in Figure 4.6. This loss should be limited for two reasons:

- The economic feasibility of this project is partially based on a decrease in pumping costs following from an increase in the heat dissipating capacity of the water (see Chapter 5). If the pressure head loss is large, required extra pumping power goes up and this will only increase costs. A costs comparison with a Dutch pumping house [GWW, 2004] was made to estimate those extra costs. With Omani average electricity prices at 0.0166 OMR/kWh [MEDC Oman, 2018], the extra costs result in OMR 354,000 per year for every meter extra pumping height with a discharge of 350,000 m^3/h.
- The proposed project preferably makes use of the currently existing intake assets of Majis since those are brand new. If the friction losses are small enough, a direct connection can be made with the existing intake facilities. The bottom of the existing seawater intake facilities is at $CD-4\ m$. This potentially leaves 4 m head loss but this is not true however since the pumps and filter screens require some water

height to operate properly. We were unable to define the exact minimum operational water level. From a logical point of view, it would have been an unnecessary expense to make the basins of SWIPS I & II deeper than absolutely necessary leading to the assumption that there probably is not a large window $(< 2m)$. This is to be be validated by Majis.

To keep the head losses below the desired maximum, a multitude of measures is available. The Coastal Engineering Manual (EM 1110-2- 3001, 1995) by the U.S. Army Corps of Engineers provides some design guidelines for the design of intake structures:

- Head losses are influenced by inlet design, pipeline material, length, diameter, flow velocity and streamlining of the pipeline.
- Abrupt changes in pipe diameter should be avoided. Rectangular intake openings need to have a transition flow section with at least the length of (a multitude of) the pipe diameter.
- For minimum head losses it is recommended to have multiple inlets per pipeline that create a gradual increase in velocity of the flow towards the shore.

The first two point are incorporated in the design as much as possible. The latter one was not incorporated for economic reasons.

4.2.3. Routing

The recommended trajectory of the pipelines is illustrated in Figure 4.2. A range is given here where the length of the pipelines is $4\ km$ ending up at a water depth of approximately $CD - 20\ m$. The proposed trajectory is a safe distance away from ship traffic areas while at the same time as short (economical) as possible.

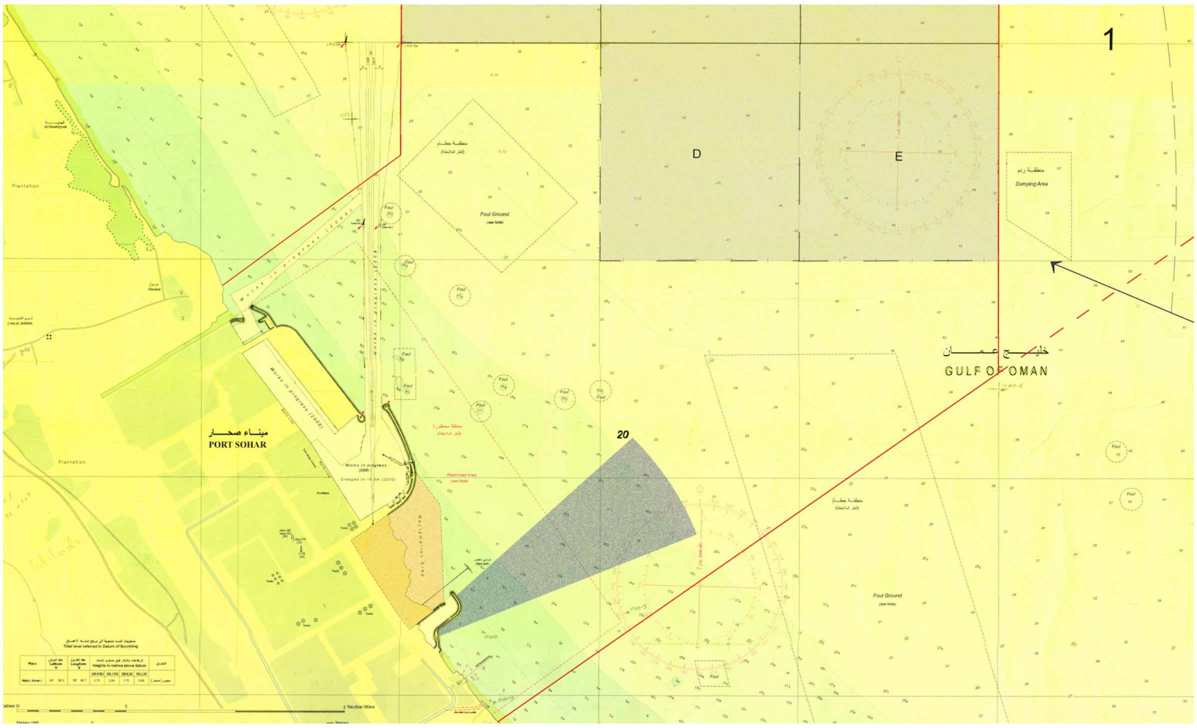


Figure 4.2: Final trajectory of the pipeline.

Near the shore it is recommended that the pipes are buried in the upper sand layer to provide protection against waves and morphological changes. Outside the surf zone the pipeline can be either placed right on top of the sea bed or in a trench. The decision between the options is based on acting forces on the pipes, soil strength and risk of failure and costs. Based on a preliminary analysis, horizontal or vertical pipe instability due to waves, currents or air formation is not expected to happen (see Section D.6). However, because of the relatively weak soil and high financial risks in case of failure it could be recommended to lay the pipelines in a trench anyhow, this decision should be made based on future investigation/research.

Redundancy

The discharge capacity of the seawater intake system should not only be higher than the expected maximum demand of the customers, but also have certain redundancy for maintenance and/or accidents. An educated guess based on reference project analysis in Le Roux [2010] has led to a required redundancy for this project of around 20%. This number should be further specified with a more concise risk, operation and maintenance analysis. The design discharge capacity of the pipelines is hence calculated as 694,000 + 20% = 833,000 m^3/h and 219,000 + 20 % = 263,000 m^3/h for the large and limited scale alternatives respectively.

4.2.4. Material selection

A good pipeline material is cheap, durable, low in maintenance and easy to install. To guarantee a long lifespan of the pipes, it is first of all necessary to choose a material that can withstand the harsh saline conditions at the ocean floor. The materials investigated were divided into different groups: metals, alloys, plastics and concrete.

Metals

A 2009 study investigated 143 projects in the US that involved transportation of saline water. For (coated) steel pipes the average overall failure rate was 4.4 times higher compared to FRP/GRP/HDPE pipes [Renoud et al., 2009]. Additionally, metal pipes lack the flexibility for fast, safe deployment at sea and are expensive compared to non-metals. Based on this (pure) metals were no further investigated as a possible pipeline material.

Alloys

Alloys are made of a mixture of metals and other elements. Alloys are strong and (very) corrosion resistant depending on the added elements. Stainless steel for example has good material strength characteristics as well as corrosion resistance. For that reason it is very commonly used for subsea oil pipelines. However, alloys are the most expensive of the investigated materials and difficult (expensive) to install. Alloy is commonly used for subsea oil transportation because leaks are not likely to happen and the unit price of oil is high. Because the unit value of colder/cleaner water is relatively low, constructing alloy pipes would be an unnecessarily high expense.

HDPE/GRP

The third material group investigated was plastics, corrosion resistant and relatively cheap. There is a whole range of plastics and some of those show good opportunity for application in this project. After some initial research, possibilities were narrowed down to two materials: Glass Reinforced Plastic (GRP) and High Density Polyethylene (HDPE). In a reference study, nine of the worlds largest desalination intake projects in the world are compared. Three of the plants make use of GRP pipelines, three of HDPE, one of concrete and the last two use a different type of inlet system that does not require pipes [Le Roux, 2010].

Concrete

The last material investigated was concrete. Concrete is not a common construction material for the application it is intended for in this project. The reason that concrete has been considered is the unprecedented scale of this project could lead to unprecedented solutions. HDPE and GRP pipelines are limited by a relatively small maximum diameter in contrast with concrete that can be adjusted to practically any size required. Having one or a few large submerged concrete conveyors could potentially be much cheaper than 20-30 parallel placed large size HDPE lines (see Figure 4.3). From some consultation with experts it was concluded that this possibility will be more expensive and probably less reliable than HDPE, a more detailed explanation can be found in Appendix D.7. The technical feasibility is recommended to be investigated by the Sohar University Students.

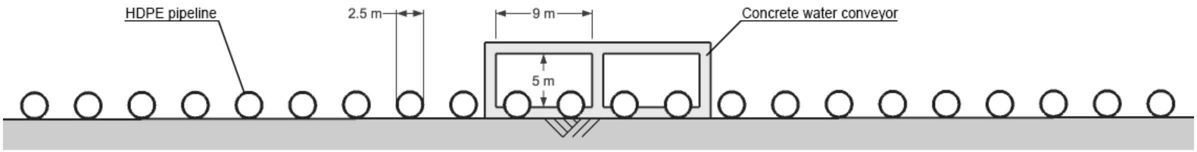


Figure 4.3: 22 × 2500OD HDPE pipes or two 9 × 5 m concrete tunnels, both can transport the same amount of water.

Comparison

The different materials have been compared in Table 4.1. GRP and HDPE show the best characteristics and were therefore mutually assessed. Both show equal quality when it comes to corrosion resistance and life cycle. However, HDPE is more flexible and can be produced in longer lengths resulting in shorter installation time and costs. Furthermore HDPE is cheaper than GRP and has better insulation characteristics because the HDPE walls are thicker. Insulation is necessary to prevent too much heat exchange between the colder water inside and the warmer water outside the pipeline. GRP is on the other hand stronger than HDPE and is also available in larger diameter sizes (scalability).

	Metals	Alloys	HDPE	GRP	Concrete
Strength	++	++	+−	+	++
Corrosion resistance	−	+	++	++	+−
Life cycle	−−	++	++	++	−
Material costs	−	−−	+−	−	−−
Installation time	+−	+−	++	+	−−
Installation costs	−	−	++	+−	−−
Scalability	+−	+−	−	+	++
Insulation	−−	−−	++	+	++
Overal rating	−−	−	+	+−	−

Table 4.1: Comparison of characteristics of promising pipeline materials. Very poor (−−), poor (−), acceptable (+−), good (+), very good (++)

Conclusion

Taking into account the above considerations has led to the decision to choose HDPE as the preferred material. This decision was mainly based on the costs and the insulation of the material since both those characteristics are of vital importance for the project. Material properties for PE100 grade HDPE are summarised in Table 4.2.

Specific weight (kg/m^3)	ρ	960
Design stress (kPa)		6300 (safety factor 1.6, 50 years) 9400 (safety factor 1.6, short period)
Young's modulus (kPa)	E	1.05×10^6 (t_0)
	E	2.00×10^5 (t_{50y})
Poisson ratio		0.45
Average roughness (mm)	ϵ	2

Table 4.2: Mechanical properties of PE100 grade HDPE

4.2.5. Diameter and quantity

To define the preferred size and quantity of the pipelines, first of all two diameters have been compared: 2000 mm and 2500 mm OD (outside diameter). The latter is the largest commercially available diameter at PipeLife Norway, the company consulted for a cost inquiry and also pipe supplier for many similar projects in reference studies.

Initially, some flow scenarios have been modelled to see up to what extend the friction in the different pipelines is dependent on the diameter. In Table 4.3, the results for a flow velocity of 1.5 m/s are depicted. The most eye-catching results are the significant difference in pressure head loss (h_f) and the discharge per pipe (Q). The amount of water that can be transported through a single pipeline is >1.5 times higher for 2500 OD compared to 2000 OD. Combining the initial pipeline costs with the extra pumping costs due to head loss (as explained in Section 4.2.2 and D.1) has resulted in an optimal flow velocity of 1.5 m/s. This value is comparable with flow velocities at reference projects around the world [Ameglio et al., 2011, Le Roux, 2010].

In Table 4.4 the amount of required pipelines necessary to transport either the large-scale or limited-scale scenario has been calculated for the two different pipelines. The results are based on an (economical) design

Pipe size (mm)	t_f (mm)	d (m)	v (m/s)	Re $(-)$	f $(-)$	h_f (m)	Q (m^3/s)
OD 2000	76.4	1.747	1.5	2,638,857	0.025	6.32	4.02
OD 2500	95.5	2.309	1.5	3,298,571	0.024	4.76	6.28

Table 4.3: Pipeline size comparison. With: t_f = flange thickness, d = inside diameter, v = flow velocity, Re = Reynolds number, f = Darcy friction factor, h_f = friction head loss for 4000 m pipe length, Q = discharge per pipe, and hydraulic roughness coefficient $\epsilon = 5$ mm

flow velocity of 1.5 m/s and material prices as provided by PipeLife Norway. The total material costs are quite similar but this table does not take into account the much higher pressure head loss of the OD 2000 pipe. The 2500 mm pipeline is to be preferred because of its considerable lower friction and higher discharge per pipe. However, a larger diameter also has some downsides such as an increased uncertainty in redundancy. This is because risks can be better predicted for larger numbers and vice versa a smaller amount of pipelines leads to increased uncertainty.

	Pipeline costs $\times 10^6$ OMR/pipe	A_c (m^2)	Full-scale # of pipes	Material costs $\times 10^6$ OMR	Limited-scale # of pipes	Material costs $\times 10^6$ OMR
OD2000	2.98	2.68	58	172	18	54
OD2500	4.61	4.19	37	169	12	53

Table 4.4: Comparison of OD2000 and OD2500 pipelines. A_c is the water conveying area of the pipeline. Additionally the required amount of pipelines to transport either the full-scale or limited-scale discharge scenario is shown with the associated costs (1 OMR = 2.60 USD)

Side note: Direct connection pipeline with existing facilities

During the project progress meetings it was opted many times that it is preferred to have the pipelines connected directly to the existing facilities without installing new pumps. To do so the maximum pressure head loss is not allowed to be more than 2 m (as is motivated in Section 4.2.2). With this maximum pressure head loss as a starting point, the required amount of OD2500 mm pipelines was calculated. For the large-scale alternative 58 pipes (267 mln OMR material cost) are necessary. For the limited-scale alternative 20 pipelines (92 mln OMR material cost) are necessary. The advantage of direct connection is that after construction no further pump operational costs are present. A disadvantage is the considerably higher material costs. It is important to state that the 2 m allowed head loss is based on some (weak) assumptions and that a more concise value will have substantial influence on the required amount of pipes (i.e. material costs).

4.2.6. Concrete ballast weights

Since HDPE is lighter than water, pipelines tends to float even when completely filled with water. To overcome this problem concrete weights need to be attached to the pipeline to weigh it down (see Figure 4.4). It is recommended to use circular weights with a diameter of 3.65 m with 5 m intervals along the pipe. The design process for the ballast weights is treated in Section D.2. The concrete ballast weights consist of two parts, held together by hot dipped galvanised steel bolts (see Figure 4.4). Prior to connection of the weights with the pipeline, EPDM rubber padding needs to be applied at the contact surface. This rubber is to prevent the ballast weights from sliding along the pipeline during installation. A visualisation of a section of proposed pipeline, including ballast weights, is shown in Figure 4.4.

4.2.7. Mechanical design

To check whether the proposed pipeline is safe from a mechanical point of view, some calculations have been made. Buckling strength in both lateral and longitudinal direction was calculated. Additionally temperature stresses and stability of the pipeline on the sea bed have been calculated.

Lateral buckling is most likely to occur when outside pressure is much larger than inside pressure. External pressure forces are discussed in Section D.3. As shown in this section, the total pressure difference between inside and outside the pipe must not be larger than 70 kPa or lateral buckling risks arise. The radius of curvature during (and after) installation must be smaller than 140 m or else longitudinal buckling can occur (see Section D.5). Finally, expected temperature variation and the correlated pressure/tensile forces will not give rise to any structural problems (see Section D.4).

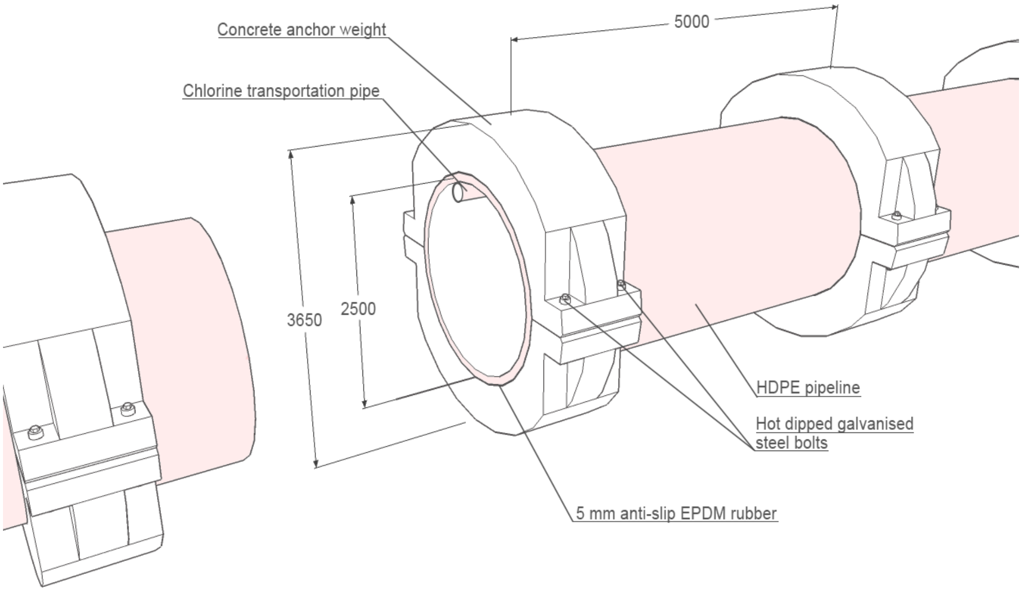


Figure 4.4: 3D visualisation of HDPE pipeline

4.2.8. Construction method

The top layer of the soil consists mainly of a silt/sand mixture. This silt layer is approximately 4 meters thick and a further soil analysis is necessary to decide (if and) up to what extend this layer should be dredged.

If dredging is chosen, the pipes will be entrenched and over time ocean currents will cover the pipelines. This leads to a stable and (ship) collision protected pipeline. Dredging can be done before, simultaneously or after pipe installation with various methods. Project costs would drop substantially if dredging of the entire trajectory turns out to be unnecessary.

The common installation method for a shallow water project is the S-lay method [PipeLife, 2002]. Concrete ballast weights are attached to the pipelines on a laying barge where also interconnection between pipe segments takes place. After this process is finished the pipe is slowly lowered in an S-shape to the ocean bed while the laying barge moves offshore (see Figure 4.5). Lowering takes place with help of water and air valves that control the amount of water in the pipe and either make the pipe more, or less buoyant. To prevent buckling of the pipe, bending stresses in the pipe can not become too large. Hence, the radius of curvature of the pipe should not be smaller than 140 m, this is elaborated in Section D.5.

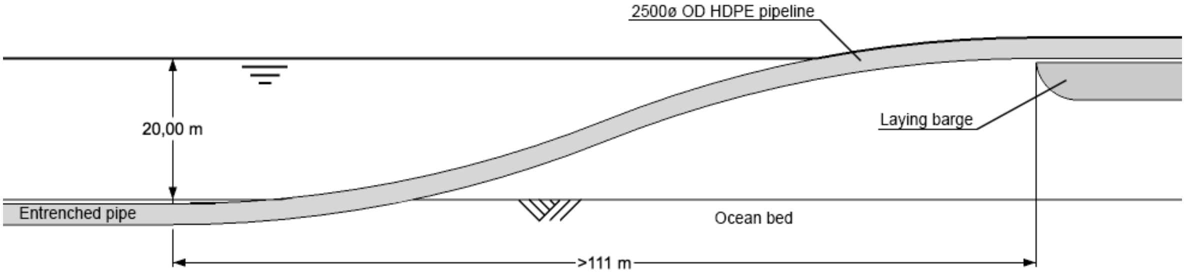


Figure 4.5: S-lay method for pipeline installation.

4.2.9. Expenses

The material of the pipelines contributes heavily to the total amount of costs tied to this project. Based on an inquiry at PipeLife Norway, the price for PE100 grade HDPE pipeline with OD2500 mm is OMR 1,151.85 per meter. Table 4.4 shows a calculation of the total costs for the needed material.

Besides material, another important factor are the installation costs. Section 4.2.3 elaborated e.g. about possible dredging works for the entrenchment of the pipelines and Section 4.2.6 about the necessity of concrete ballast weights. These costs as well as many other have not been precisely quantified; Further consultation with experts needs to accommodate these numbers. Nevertheless a very rough estimation is made as to be able to conclude qualitatively the economic feasibility. An overview of these estimations can be found in Table 4.5 and 4.6.

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Pipeline material	169	439	
Installation costs	20	52	+
Total costs	189	491	

Table 4.5: Qualitative assumptions of costs for materials in large-scale connection

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Pipeline material	53	138	
Installation costs	7	18	+
Total costs	60	156	

Table 4.6: Qualitative assumptions of costs for materials in small-scale connection

4.3. Connection to existing facilities

In this section different options are assessed to find the best configuration to connect the pipelines with the present infrastructure. Preferably this connection is made with no or a few adaptations since the earlier investments in SWIPS I and the recent investment in SWIPS II make it highly desired that as much infrastructure as possible can stay operating in the newly proposed solution.

One option for this is to make the pipelines connect directly to the current existing basin that has its bottom at $CD - 4\ m$. This means that with the lowest astronomical tide, 4 m water column remains in the intake basin. If pipelines are constructed, the friction head loss will decrease this remaining water height. This decrease can only be allowed up to a certain level as the pumps in the intakes need a certain minimum water level to operate properly. The head loss should thus be minimised. This can only be achieved by installing more pipes which is costly. Different mechanisms to bring the water to the shore are described for both a full- and a small-scale connection to facilities existing.

4.3.1. Full-scale connection

Flow accommodation

After consultation with various experts two options have been considered:

1. Connecting the pipe directly to a pump or booster, a so called dry-well. This would mean a closed connection between one or more pumps with the pipeline. An advantage of this method is that the flow can be regulated per pipeline so that pumping can happen efficiently. Disadvantages are the configuration with the currently available system and difficult maintenance. Furthermore, the pump efficiencies of the boosters are rather low causing high operational costs.

2. Constructing a deep fore bay near the coast in the form of a new basin and connecting the pipelines to this new basin. The big advantage of this option is the gravity induced flow that is created when water is pumped out of the existing basin by the clients. The water level in the existing basin then decreases, after which an additional pump will pump water from the new to the existing basin, creating a water level difference compared to the sea level at the intake point which will initiate a shore-directed flow. This option is much better applicable to the existing facilities since it would only involve damming off a part of the current intake basin, placing additional pumps to overcome the height difference with the current basin and laying pipelines from the dam into the sea. Currently existing pumps can be used as well as the existing band screens by small adjustments.

Option 2 was chosen for its applicability and also for its easy integration that is described later in section 4.3.3. When all pipes and pumps (or at least a big part of them) are connected to the same basin, this boasts advantages whenever not the full capacity is needed. With a demand of less than 100%, divided over the same number of pipes the friction head loss drastically reduces (see Table 4.7). Consequently the pumping costs will go down.

Demand/capacity	Friction head loss (m)
100%	5.2
90%	4.2
80%	3.3
70%	2.6
60%	1.9
50%	1.3
40%	0.8
30%	0.5
20%	0.2
10%	0.1
0%	0.0

Table 4.7: The wall friction head loss over the pipes is quadratic with the flow velocity, thus a decrease in demand will lead to a quadratic decrease in head loss. L = 4000 m, D = 2.5 m, e = 5 mm, q = 19,829 m^3/h, Q = 694,000 m^3/h

Basin design

To have the system robust against large water variations, it is best that the pipelines enter the new basin close to the bottom. As the water has not yet passed through a fine filter and solids are assumed to settle now that flow velocities drop, there should however be taken a safety margin (0.5 m) for some silting up of the new basin. The mouths of the additional pumps are also located close to the bottom. Two concerns are the sucking up of silt which can damage the machine when too close to the bottom, or air when too close to the open water level. A safety of 1.5 m, as follows from drawings of the current SWIPS I provided by Majis, from the bottom is taken and the water level is assumed 2 m higher than the additional pump mouths.

The depth of the basin then results from these safety margins plus the maximum friction head loss through the pipes. This maximum friction head loss follows from Section 4.2 and is 5.5 m. The bottom of the new basin is then placed at $CD - 9.5$ m. The highest astronomical tide is 3.4 m higher than the lowest. A little more than the required freeboard against overtopping that is calculated in section D D.8 is assumed so that a safety crest freeboard of 0.5 m is taken.

With such a total height of 13.4 m, the structure will require many struts and a roof as to not fall over. The strength and stability calculations for this structure can form a project on their own and, with limited time in mind, are not included in this report.

From the new basin the water will be pumped by large submerged horizontal screw pumps to both the current SWIPS I and II. The pumps will be placed in both sides of the new basin and have the function of lifting the water to the next basin. The height difference that has to be overcome is easily found by subtracting the difference in water height between the surface sea level and the water level in the existing basin from the total head loss. From calculations it follows that on average the screw pumps have to overcome 1.5 m. The water is then diverted to manifolds that have a task of dividing the water over the existing basins of each pumping station. The schematic cross-section of the proposed full-scale solution and the hydraulic grade line showing the energy losses are given in Figure 4.6. A suggestion for the screw pumps is given in section B.1. As these are used in pump houses in the Netherlands for unfiltered water, their performance is expected to meet standards.

4.3.2. Limited-scale connection

Elements that could accommodate such a shorewards directed flow can make use of electrical power, in the sense of pumps or boosters, or of natural forces in the sense of gravity and atmospheric pressure, possibly in combination with pumps. As described, the natural head difference with the current intake basin is too small so that measures will have to be taken.

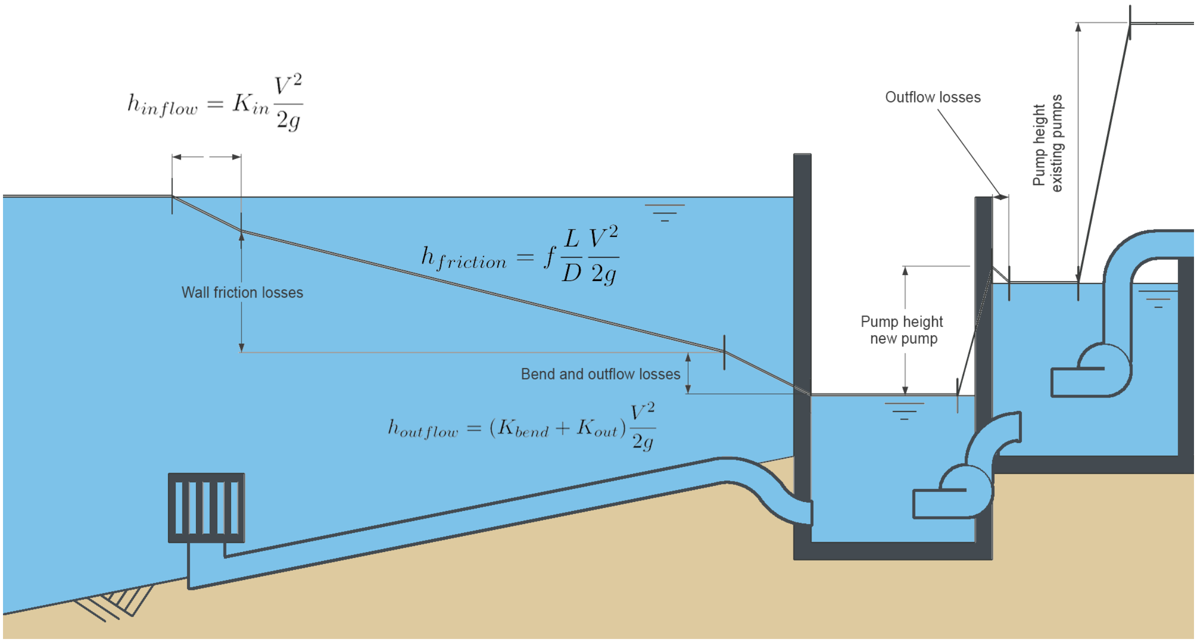


Figure 4.6: Schematic representation of the hydraulic grade line

Flow accommodation

Their are two distinct alternatives possible. The first alternative would consist of constructing all elements directly and only having capital costs whereas the other alternative proposes a solution that also brings operational costs. The characteristics of each option are scrutinised below for a discharge of 219,000 m^3/h for the power plants as follows from Chapter 3:

- Constructing 20 pipelines that bring the flow velocity down to 0.9 m/s so that the head loss is decreased to below 2 m. This is sufficiently low to have a gravitational induced flow through the pipes.
- Constructing 12 pipelines that cover the full discharge with a flow velocity of 1.5 m/s. This results in a maximum head loss of 5.2 m which needs to be accounted for by additional pumps. On average the head loss will be lower than this. Moreover, a small extension to SWIPS I would have to be made in order to let the water become laminar and be pumped away from.

Even though these additional actions have to be taken, option 4.3.2 is considered much more cost effective and is therefore taken in further assumptions when considering the facility-specific connection.

Basin design

It resembles a smaller version of the solution that was described for the scenario where all facilities are coupled as it uses the same principle. The characteristics regarding the basin design and the pumps are therefore assumed to hold, be it in smaller dimensions.

4.3.3. Location

A suggested location and schematic lay-out of the basin when deciding for a connection with all facilities is given in Figure 4.7. This figure shows that there has been opted for a location in between the current pump stations. This strategic location offers multiple benefits during the period of construction. Between SWIPS I and SWIPS II there is enough space for heavy machinery, delivery of construction materials and a construction site. Besides this, the largest advantage of placing the new basin in the middle is the minimal hindrance for the current intake system. Both pumping stations will maintain their access to the intake basin during construction until they are being connected to the pipes coming from the manifold. During some days the water quality might lower but those days can be planned and with enough measures this effect could be minimised. The reduced hindrance and technical feasibility are such large contributors that this option is proposed for the connection to all facilities.

Figure 4.7: Suggested location and lay-out of the wet well

The optimal location for the case where specific facilities would be connected to the intake is just in front of the eastern wing of SWIPS I, the wing where all power plants extract their water. This is not further elaborated on as the design would be a rather simplified and smaller version of the earlier described connection.

4.3.4. Expenses

The connection to the existing all or specific facilities brings costs for its several elements. The newly to construct basin that is proposed and the physical connection by the manifold and pipes bring costs that depend heavily on site conditions, construction material and the hindrance of current operations. An estimation of the accompanying construction and operation costs is made as to be able to conclude qualitatively. This estimation was based on the construction costs of SWIPS II that were equal to 20 mln OMR. Furthermore, the proposed screw pumps bring operational costs. From the quick comparison that was made in Section 4.2, costs for the screw pumps of 354,000 OMR per year per extra meter extra pumping height followed for a discharge of 350,000 m^3/h. In this case, a discharge of 694,000 m^3/h has to be pumped up 2 m, bringing expenses shown in Table 4.9. For the facility-specific discharge this extension of SWIPS I will only cost a portion of the expected costs for a whole new basin. This is amplified as the physical connection does not need difficult installations but consists merely of pumps to the existing basin. Furthermore, the operational costs for the screw pumps can also be halved as the discharge that they need to accommodate is nearly half. The costs can be found in Table 4.8 and 4.9.

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Construction new basin	5	13	
Connection with system	5	13	
Operational costs	0.8 /yr	2.0 /yr	+
Total costs	10 + 0.8 /yr	26 + 2.0 /yr	

Table 4.8: Qualitative assumptions of expenses for full-scale connection to the system

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Construction new basin	2	5	
Operational costs	0.4 /yr	1.0 /yr	+
Total costs	2 + 0.4 /yr	5 + 1.0 /yr	

Table 4.9: Qualitative assumptions of expenses for small-scale connection to the system

4.4. Intake head

SIDE NOTE: This paragraph covers the design of the intake head structure. It was written by Aicha and Salima, our Omani co-workers. During our project we have worked closely together with our entire group but it should be noted that the difference in quality of the produced work is immense. Many improvements on the next paragraph have been made from our side. However, we did not want to destroy the essence of the work of our co-workers and therefore tried to stick with the general layout and contents of their initial findings. Doing so resulted in many (calculation) mistakes and wrong assumptions that are still easily spotted. However, the design of the intake head of the system is considered to be non-crucial with respect to our general feasibility research question. A more concise follow-up study should improve the design of the intake head.

The biggest problem for the environment, due to the deep seawater intake, is the impingement and entrapment of marine life. This could damage the pumps and cause their accumulation in system. The primary objective for the inlet is to keep this environmental impact at a minimum while still being able to take deep sea water to the Port of Sohar.

The intake head design requires two screens to prevent the marine life from entering the water treatment and cooling system. These are a coarser bar screen and a finer band screen. The coarse bar screen is used at the offshore part of the intake and is constructed in an inlet structure connected to the offshore end of the pipelines. The second screen is carried out onshore, but for the finer band screens it was decided to use the already available ones in the Majis company plant.

The design of the seawater intake head depends on the location and other principal design parameters.

4.4.1. Design parameters

Due to the fact that the ocean is dynamic, the force of the waves and the currents may damage the structure. Furthermore, the marine water is highly corrosive and the marine organisms may, in addition, cover the entire structure or even manage to block it completely. These are important factors and need to be taken into account. Moreover, the capacity of the seawater intake system should not only be higher than the expected maximum demand of the customers, but also have certain redundancy for maintenance. For deep seawater intake structures designs must be adapted to available means.

The general design parameters follow directly from [Pita, 2011] and are given below:

- **Direction of the entry flow** - The horizontal flow, see Figure 4.8, reduces the suction of organisms by between 80-90% compared to a vertical flow. Furthermore deposition of any organic or inorganic waste material into the seawater intake circuit is avoided.

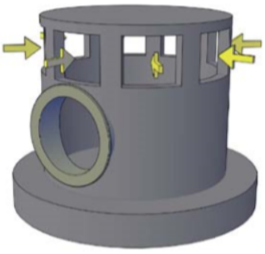


Figure 4.8: Horizontal flow direction [Pita, 2011]

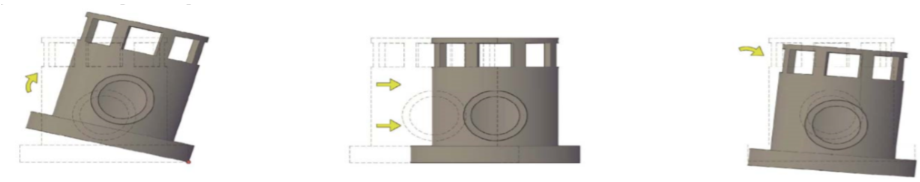
- **Entry velocity** - This will be a function of the total area of the intake windows and the demanded discharge. The impact of the water extraction is minimised when the suction velocity is low. That means that marine life and suspended sediments will less be likely to enter the system. Conditions for the entry velocity, the flow capacity and the size of the windows are fixed parameters and according to the size of the collection structure.

- **Distance from the seabed to the windows** - Due to the water suction, the windows must be located at a sufficient distance from the seabed in order to avoid the entrance of suspended sediments. According to Dr. Eyad of Sohar University, it is recommended to carry out a hydrodynamic model, as shown in Figure D.4, so as to verify the possible suction of material.

- **Depth of the structure** - Sufficient depth should be taken so that floating particles and sestonic species (i.e. jellyfish) that are located close to the water surface are not taken in. In addition, the actions of the waves against the tower are reduced when the depth of the intake tower is bigger. The proposed depth in Chapter 2.4 is expected to meet these requirements. The only disadvantage of placing the intake at great water depths is the costs corresponding with it.

- **Maritime climate** - The wave effect on the works is a highly important variable for the dimensions of the structure. Logically, significant wave force actions require a stronger structure in order to guarantee the stability. The currents and wave climate are described in Chapter 2.4.

- **Geo-technical stability** - A detailed study must be carried out in order to guarantee the geo-technical stability of the structure against overturning 4.9a, sliding 4.9b and sinking 4.9c. The force actions upon the tower are created by waves and currents and by the self-weight of the structure.



(a) Overturning (b) Sliding (c) Foundation bearing failure

Figure 4.9: Three possible failure mechanisms of the intake towers. [Pita, 2011].

- **Structural dimensioning** - The structure must be modelled in order to establish the structural dimensions, so that it is able to support the forces generated by the calculated force actions.

- **Other conditional parameters** - Furthermore, supplementary measures exist in order to improve the design, such as the use of antifouling paints, hypochlorite additions, installation of compressed air or grates in the windows. If these measures are not carried out fouling deposits may be produced, impeding the entrance of water. Accordingly, the measures in order to guarantee the functioning thereof are of vital importance. The hypochlorite additions, whether of a continuous basis or in impulses, kills the surrounding living organisms and impedes that they attach to the walls of the structure, in the same manner as compressed air works. The paints only have a reduced useful life of less than one year, and accordingly their principal mission is impeding the deposits until the start-up of the installation and accordingly until the initiation of the hypochlorite system.

- **Pipeline connection** - The pipeline design in Section 4.2 already provides the following parameters, summarised in Table D.2.

4.4.2. Intake head design

We will develop the inlet design based on the design requirements. The design consists of a bar screen design and the solid inlet structure design.

Bar screen

With the particle size analysis and the historical data of the seawater from Majis, a coarse screen with 30 mm pore size for the inlet was chosen. If the distance between the seabed and the intake screen is larger there will occur less sand suction. We will put the screen window at a suitable distance from the seabed to keep the pressure and velocity difference. The actual level of the windows is $CD-18\ m$. According to the loads on the structure from inside and outside, a duplex steel mesh is taken as a bar screen. In addition, to be on the safe side a double layer of the the duplex steel mesh is placed.

Inlet structure

The hydrostatic pressure on the outside of the structure is the same as the pressure on the inside. The resulting hydrostatic pressure force on the structure will thus be zero. Remaining forces will follow from wave and current actions. The resulting weight of the structure will cause a pressure force on the soil under it.

Material There are two options for the seawater intake head at the bottom of the seabed; ready-made screening or a reinforced cement concrete (RCC) structure. Based on advice from expert Abdullah Al Sadi (Majis), it was found that current ready-made screening has a limitation on capacity and can not serve high amounts of seawater. Furthermore, most of the construction material is metal which demands extra care against corrosion and chlorine. Also, the installation below sea level is complicated. The RCC, though, shows a great advantage for intake structures, which is the continuous provision of large volumes of water. Big elements of concrete provide a larger stability and require only little extra care against corrosion, disinfection and chlorine. For these reasons, an RCC structure will be applied for the inlet design. This structure is made from different types of material and they follow directly from experts at Majis and are considered to be:

- Concrete - The concretes will be executed according to the local standards (CIRIA publication C577: Guide to Construction of reinforced concrete in the Arabian Peninsula), the tender and the British Standards (Euro code 2 – EC2 Design of concrete structures) Grade C35/45 according to EC2 EN 1992-1 -1:2004. Minimum $f_{ck} = 35\ MPa$ (cylinder)/45 MPa (cube)

- Steel reinforcement - This needs to be added in the inlet structure, to protect it from the cracking because these environmental loads distribute on the structure and causes the cracking. Structural steel reinforcement in the inlet structure will be BS 4360 grade 43. A, minimum yield strength $f_{ck} = 275\ N/mm^2$ or equivalent.

Dimensions The inlet structure will be a cylindrical shape, based on the dynamic load of the waves and currents. The structure is in this way more streamlined and prevents large forces on edges of the structure. The different dimensions and volumes are:

- Concrete cylinder

$$\begin{aligned} h_{inlet} &= 5.0 \text{ m} \\ D_{cylinder} &= 4.0 \text{ m} \\ t_{cylinder} &= 0.40 \text{ m} \\ D_{base} &= 6.0 \text{ m} \\ h_{base} &= 0.50 \text{ m} \end{aligned}$$

To calculate the total window area several calculations are done. These are included in Section D.9.2 and result in a total window area $A_{total,windows}$ of 8.30 m^2. With 8 windows the window area A_{window} becomes 1.04 m^2. Dimension for the coarse screen is $1 \times 1\ m$.

So, from our design assumption, eight windows with coarse screens of $1 \times 1\ m$ will be added in each inlet structure. For maintenance of the structure we put a window in the roof and its dimensions are suitable for maintenance work and big enough to go through. The maintenance window has dimensions $1 \times 1\ m$. A cross section of the definite inlet structure is given in Figure 4.10.

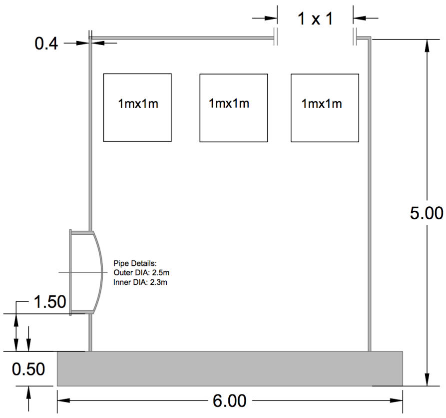


Figure 4.10: Cross section of the intake head.

The volume of the concrete used will be (explained in Section D.9):

$$V_{total} = V_{cylinder} + V_{base} = 15.07 + 14.14 = 29.21 \ m^3$$

- Steel reinforcement
  - The distance between each steel bar is 30 mm
  - The diameter of one steel bar is 20 mm

The total length of steel reinforcement bars needed is calculated in Section D.9. This is 4198 m.

To protect the steel reinforcement bars from environmental impacts as corrosion, marine life etc., a coating material is added on the reinforcement steels. The thickness of the coating material around the steel is 10 mm. [of Transportation, 2007].

Foundation

Based on the soil composition, (Figure 2.9), the upper layer of soil is silty sand. Pile foundation is needed for each structure and consists of two piles with a length of 15 meters.

4.4.3. Construction

The transportation and sinking of the concrete structures consists of several stages: transport by ships, use auxiliary floats and sinking in deep seawater with keeping the structure safe. In Figures D.5, D.6 and D.7 the different stages are represented.

4.4.4. Expenses

The costs concerning the material and construction of the inlet system are estimated. These are composed of costs for the concrete structure, the super duplex mesh, the coating material, the pile foundation and the construction. The detailed cost estimations are given in Section E and in Table EE.11 the costs are summarised.

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Foundation	0.12	0.31	
Materials	0.12	0.32	
Construction	0.05	0.13	+
Total costs	0.3	0.8	

Table 4.10: Qualitative assumptions of costs of intake heads with large-scale connection

	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Foundation	0.04	0.1	
Materials	0.04	0.1	
Construction	0.02	0.05	+
Total costs	0.1	0.3	

Table 4.11: Qualitative assumptions of costs of intake heads with small-scale connection

4.5. Maintenance and operation

The inlet structure of the pipeline should under normal circumstances be investigated on a yearly basis by divers. Whenever cleaning and/or maintenance is necessary this is usually done by hand. Fouling inside the pipelines must not exceed certain levels, this can be achieved in two ways: prevention and mitigation.

Chlorination

It is recommended that prevention of bio-fouling is achieved by adding chlorine to the water at the offshore intake. This can either be done by continuous chlorination with a low concentration of shocked chlorination every set period with a high concentration. The choice which one is preferred is dependant on the port preference and is not by definition the same for all pipelines. It is recommended that inside or on top of the pipes the chlorination tubes are connected that should dispense the chlorine into the pipe.

Pigging

If chlorination alone can not guarantee bio-fouling from staying below certain levels, pigging measures need to be taken in the design of the pipe. Pigs are cleaning devices with a diameter slightly smaller than the inner diameter of the pipeline. They are inserted in a pig launcher upstream and propelled by the normally occurring flow in the pipes towards a downstream pig receiver. By moving through the pipes the pigs scratch away any debris on the pipe walls. HDPE is relatively weak compared to alloy pipes and therefore special 'soft' pigs are necessary [Palmer and King, 2008].

Bio-fouling thickness (mm)	d (m)	v (m/s)	Re	f	h_f (m)
0.0	2.309	1.40	3,078,667	0.0291	6.30
10.0	2.289	1.42	3,132,701	0.0291	5.79
20.0	2.269	1.45	3,188,171	0.0291	5.99
30.0	2.249	1.48	3,245,126	0.0291	6.21
40.0	2.229	1.50	3,303,622	0.0291	6.66
50.0	2.209	1.53	3,363,714	0.0291	6.91

Table 4.12: Biofouling, L = 4000 m, ϵ = 10 mm, Q = 5.862 $m^3/pipe/s$

Biofouling

In Table 4.12 the results of various fouling scenarios are shown. Fouling is caused by marine life that attaches itself to the walls of the pipeline. The model assumes the same discharge for every scenario and (very high) pipe roughness (ϵ) of 10 mm for varying fouling thicknesses. The results show an increased friction head loss with increased fouling but this increase is, even with 50 mm fouling, acceptable.

New basin

At the downstream end there will be a new basin constructed in front of the band screens (see Figure 4.7). Since the ocean water will be retained in this new basin for some time, the particles in the water will (partly) settle. The amount of particle settling in this basin needs to be investigated. It is recommended that future research sheds a light on this.

5

Economic feasibility

Summary This chapter discusses the economical feasibility of the project. The expenses consist for a major part of the material of the pipelines. The installation of the pipelines, construction of the connection with existing facilities and finally the inlet structures also cover considerable parts of the expected total costs. The project offers many benefits and opportunities. The revenues that have been calculated for both the RO-plants and the power plants are considerable and make up the largest part of the value this project creates. With a discount rate of 10% over a period of 22 years into the future as input for the financial model, this results in different Net Present Values for the options of connecting all facilities or only specific facilities to the deep seawater.

The economic feasibility of the project highly depends on the benefits for the RO-plant. Because the presumed benefits for benefits have not (yet) been validated with measurements, an additional case was considered where no benefits for the RO-plants are realised.

It turned out to be difficult to quantify the positive effects on the environment, the attraction of new businesses, the possible extension of the land reclamation and the strategic opportunities that are generated. Based on the benefits that were quantified have been collected it was concluded that the project is not economically feasible. The many uncertain factors should be examined in order to come to a more thorough conclusion.

Introduction

The feasibility of this project is largely determined by the expected costs and profits. As many parties are involved, a cost-benefit sheet consists of many different (dis)advantages for all stakeholders. In this chapter a division is made between the costs and the profits as the expenses cannot be easily divided among the stakeholders and will need high-level arrangements. They are described and quantified here for all different elements within the technical design. The expected profits however have been calculated in chapter 3 per opportunity and are merely summed up to find the correct input for the financial model that has been made. The chapter concludes with the background and outcome of this model. It should be taken into account when reading this chapter that the found numbers might fall in a wide range and are mainly useful for giving a qualitative idea of the financial feasibility.

5.1. Project costs

The project costs have been denoted in chapter 4.2 for every single element. This section is merely a summary of all calculated numbers. The expenses have been collected in two tables, 5.1 and 5.2, that differentiate between the two observed cases of connecting all industries or only RO-plants and power plants.

Specification	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Pipeline material	169	430	
Installation costs	20	52	
Construction new basin	5	13	
Connection with system	5	13	
Operational costs	0.8 /yr	2.0 /yr	
Intake heads	0.3	0.8	+
Total costs	199.3 + 0.8 /yr	508.8 + 2.0 /yr	

Table 5.1: Qualitative assumptions of costs for large-scale connection

Specification	Costs ($\times 10^6$ OMR)	Costs ($\times 10^6$ USD)	
Pipeline material	53	138	
Installation costs	7	18	
Construction new basin	2	5	
Operational costs	0.4 /yr	1.0 /yr	
Intake heads	0.1	0.3	+
Total costs	62.1 + 0.4 /yr	161.3 + 1.0 /yr	

Table 5.2: Qualitative assumptions of costs for limited-scale connection

5.2. Financial benefits

The financial benefits have been denoted in Chapter 3 for every single opportunity. As one can see, both for the full-scale connection as for the facility-specific connection the profits for RO-plants are listed. As is described in Chapter 3, the benefits for RO-plants might even be 0 OMR in case measurements show no water quality improvement. In tables 5.3 and 5.4 a line has therefore been added excluding these RO-benefits.

Specification	Profits ($\times 10^6$ OMR)	Profits ($\times 10^6$ USD)	
Additional value infrastructure	4.7	12.2	
Avert construction of new inlet	17.0	44.2	
Gained efficiency power plants	2.6 /yr	6.8 /yr	
Decrease pumping electricity	3.1 /yr	8.1 /yr	
RO-savings	3.5 /yr	9.0 /yr	
Increased RO-production	0.4 /yr	0.9 /yr	+
Total profits	21.7 + 9.6 /yr	56.4 + 24.8 /yr	
Total profits without RO	21.7 + 5.7 /yr	56.4 + 14.9 /yr	

Table 5.3: Quantifiable assumption of profits for large-scale connection

Specification	Profits ($\times 10^6$ OMR)	Profits ($\times 10^6$ USD)	
Gained efficiency power plants	2.6 /yr	6.8 /yr	
RO-savings	3.5 /yr	9.0 /yr	
Increased RO-production	0.4 /yr	0.9 /yr	+
Total profits	6.5 /yr	16.7 /yr	
Total profits without RO	2.6 /yr	6.8 /yr	

Table 5.4: Quantifiable assumption of profits for limited-scale connection

5.3. Financial model

With these found costs and revenues, a model can be made that calculates the Net Present Value (NPV) of the project for both scenarios. The NPV usually is an important number to base the decision of investment on and it can be seen as a tool to find the present value of the future benefits, that can then be compared to the project expenses. To translate these future benefits, that are subjected to inflation and cannot be used to invest with, to a present value, one requires a discount rate. After consultation with an expert from SIPC that is closely involved in long term investments a discount rate for the project of 10% was taken. This discount rate can be understood as the percentage that the value of future benefits would decrease every year that receiving them is further away from the present. With such a discount rate, after a period of X years the present value of the future benefits is negligible. In this model, 22 years are taken. Impressions of the model for both the large-scale connection and the facility-specific connection can be seen in Section E.6.

The costs made during this project are mainly capital costs, such as for the pipelines, installation costs, for construction of the new basin and for connection to the system. This capital investment is assumed to be paid in the first three years after the start of the project, which is normal for investments. Moreover, also operational costs are made. The screw pumps that form the connection between the new and the current basin will require electricity, making yearly expenses. All separate parts of the total expected costs have been scrutinised in the different chapters. Together they make up $199.3 + 0.8\ /yr$ mln OMR which is equal to $508.8 + 2.0\ /yr$ mln USD for a connection to all facilities. When only connecting the RO-plants and power plants, costs can be found of $62.1 + 0.4\ /yr$ mln OMR corresponding to $161.3 + 1.0\ /yr$ mln USD.

All project earnings have been well described in the earlier chapters. For now, the RO-plants are taken to have financial benefits. It was found that the total expected profits are $21.7 + 9.6\ /yr$ mln which coincides with $56.4 + 24.8\ /yr$ mln USD for a full-scale connection where all facilities are provided with deep seawater. For the limited-scale connection where only the RO-plants and power plants are provided expected profits were found of 6.5 mln OMR which corresponds to 16.7 mln USD/yr. These financial benefits have been put into the model.

With the mentioned period and discount rate, the NPVs that are found are listed in Table 5.5.

Specification	NPV ($\times 10^6$ OMR)	NPV ($\times 10^6$ USD)
Large-scale with RO	-80.4	-208.8
Large-scale without RO	-116.2	-301.8
Limited-scale with RO	-1.5	-3.8
Limited-scale without RO	-37.2	-96.7

Table 5.5: Net Present Value for different connection options and ranges

These negative values show that from an economic perspective, the project is not feasible. Due to the uncertain factors that play a role it should however only be seen as an indicator to base future research on. Furthermore it appears to be clear that a limited-scale connection to only the power plants, and possibly RO-plants in case of measurements showing better water quality, is more suitable from an economic point of view.

6

Risk analysis

Summary Two specific categories of risks are considered, being technical and project risks. Technical risks concern the structural and functional risks both during construction and during the lifetime of the intake heads, the pipelines and the connection basin. The project risks include uncertainties concerning both assumptions and future predictions that could possibly affect the success of this project. Measures have been given for each risk with the goal of minimising any risk and thereby maximising the opportunities this project brings.

6.1. Introduction

In this chapter the uncertainties and possible impacts regarding the proposed project are covered. The risk analysis is split up in two components, technical and project risks. The first comprises problems that may arise threatening the water supply to the port. The latter discusses uncertainties for the water demand and quality.

6.2. Technical risks

The technical risks section focuses on situations in which the proposed offshore intake is unable to provide service in the way it is designed. The characteristics of the water at $CD-17\ m$ should not change on its way to the existing pumping stations. Any failure to deliver colder and cleaner water comes at a high price; There are billion dollar industries that depend on the water for their processes and large penalties are inflicted on Majis if the security of water supply is at stake. Both situations during construction and during operation are considered.

6.2.1. During construction

During construction it is not accepted that the water supply to the companies experiences nuisance. The construction of the new basin between the existing pumping facilities might affect the water quality. Increased turbidity would result in temporarily higher costs for the RO-plants. A dry dock will thus be constructed quickly, after which the turbidity will return to normal. The new basin can then be built inside the dry dock so that only after erection of inlet heads, pipelines and screw pumps a phased connection of the new system with the old should be made. This way changes in the water quality are minimised.

A different risk during construction is caused by the untrained personnel and heavy machinery that will operate near the Majis facilities. If heavy machinery is not controlled in the right way, in the limited space that exists between the pumping stations, existing facilities could be damaged with downtime and financial harm as consequences. Furthermore, personnel of a construction company might not be experienced with working on a pumping station which might cause unsafe situations. To minimise these risks, proper safety training should be arranged for employees and measures as lining and signs should be placed for the heavy machinery and its drivers. Moreover, human failures in construction are also minimised by having skilled and trained personnel.

As described in section 4.2.7, the both longitudinal and lateral buckling of pipelines are different risks during construction. By placing the pipeline only with the right hydraulic and weather conditions, having trained personnel and the right machinery these risks can be excluded. Furthermore, during construction continuous measurements should be carried out to keep track of the pressure difference and the bending of the pipeline element.

6.2.2. Lifetime risks

During its lifetime other risks threaten the serviceability of the structure. The risks can be classified into two different groups: Instantaneous risks such as ship collision or fishing net entanglement with the pipeline or intake head. Even though the proposed trajectory is a prohibited area to shipping and fishing, with a 100 year lifetime such accidents need to be taken into account. certain collisions result in unavailability of one, or at most a few pipelines and should be countered by installing enough redundancy pipelines. This will not provide a solution against large natural disasters such as earthquakes, tsunamis and cyclones. If one pipeline collapses due to one of these causes, it is very likely that others will too. Some measures that can be taken are choosing a flexible pipeline material (HDPE) and entrenching the pipelines in the ground. However, a risks analysis on those hazards is recommended to be made more extensively. To make sure the downtime after such major catastrophes is not too long, a back up system has to be in place. It is proposed that the new full system can be uncoupled from the existing facilities within a reasonable time and so that these can be directly connected with the ocean water again, thereby switching back to the current system.

The other group consists of functional risks. These are the result of biogrowth, unexpected wear and tear and human mistakes. Biogrowth will lead to fouling within and eventually clogging of the pipelines. Although measures are taken by chlorine dosing, it is difficult to do inspections and to see whether the desired effect is truly realised. This risk should be minimised by proper maintenance and installation. Secondly, unexpected wear and tear of the pumps and the manifolds might lead to failure. It is of high importance that inspections at regular intervals are carried out so as to prevent this. If during these inspections notion is made of wear and tear, this should be well documented and be put into action of repairing or replacing the damaged element of the system.

6.3. Project risks

In the previous section technical risks have been analysed that threaten the serviceability of the project. On the other hand there are uncertainties more related to future predictions and assumptions made on the project side.

6.3.1. Forecasts

An existing risk for the project are numbers that follow from forecasts and that have now been used as input. Forecasts show a large spread and are subject to even more underlying assumptions. One of these assumptions for example is the water demand per customer. New cooling techniques such as cooling water towers use significantly less water during the winter than, currently most used in the port, once-through cooling systems. The new 1,700 MW Shinas power plant makes use of this system. For the summer the cooling towers do not prove to be more efficient and are even assumed to be very inefficient. The forecasted water demand depends heavily on these (in)efficiencies and on the decisions that industries make regarding cooling water. From interviews and agreements, conclusions can be drawn that would minimise the risk of again over or under dimensioning the system.

One opportunity that has been described that comes with a certain risk is the land reclamation. The earlier mentioned flexibility during natural disasters contradicts with the extension of the land reclamation. If, after more research on natural disasters, there is decided to extend the land reclamation, care should be taken with regards to the pipeline underneath. A clear plan should be made to overcome the risk of harming the pipelines during construction of the land reclamation or when preparing the foundation for new industries. Enough spacing between the pipelines should be realised so that there is sufficient room for foundation piles between them.

6.3.2. Characteristics

Most of the calculations that have been done are partially based on assumptions. Those assumptions have been verified where possible within two months but many have not yet been validated. These concern f.e. water characteristics and seasonality of data. Moreover, many of the project costs are estimated and will have to be observed more closely by experts as they might lead to different outcomes, f.e. when determining between a dry well and a wet well. To decrease uncertainties in the technical design that has been made and thereby decrease risks of over or under dimensioning, these assumptions should be the subject of future research.

7

Conclusions/Recommendations

7.1. Conclusions

This feasibility study was carried out to answer the following question: 'What is the optimal, technically and economically feasible design for a deep seawater intake, providing colder and cleaner water for the port of Sohar?' To answer this research question, sub-research questions were answered in the report.

Based on the results of the site investigation a shore normal trajectory of pipelines with a length of 4 km is advised. At the offshore inflow, the inlet water depth is CD-17 m, reaching below the thermocline. The yearly average ΔT between the surface and CD-17m is 5.4 °C. Measured dissolved oxygen concentrations and salinity levels at this depth are less compared to the surface values. Chlorophyll-a concentrations and turbidity levels show an increase at this depth. Different HAB species are observed in the Gulf of Oman, including up to 20 m water depth vertically migrating species. This would cancel out the benefit of a deep seawater intake at CD-17 m. Though, no exact numbers on HAB occurrences are known for Sohar Port surrounding waters. More site specific research on the HAB occurrences around Sohar Port is necessary.

RO-plants can possibly benefit from the proposed solution through an increase of production capacity and decreases of downtime, electricity, chemicals and spare parts if the water quality improves with increasing water depth. The total potential savings could be as high as 3.8 mln OMR/yr but are expected to be much less because the water quality measurements from a site nearby are not showing the expected quality improvements.

Colder water leads to a higher efficiency of the steam turbines in power plants with which they will be able to achieve the same production, but use less natural gas. The estimated benefits range between 0.38 mln OMR/yr and 2.6 mln OMR/yr depending on the calculation method.

The cooling water consumers make up 40% of the current total water demand. The total water reduction is calculated to be 2% in the winter and 16% in the summer, resulting in expected pumping cost savings of 3.1 mln OMR/yr.

In addition to directly quantifiable benefits, there will be large advantages for the environment and the future growth of the port.

It was found that a total of 37 pipelines is needed to supply all the industries with colder water in the future. As power plants and RO-plants show the largest possible benefits compared to the required water, the scenario to only supply these, with 12 pipelines, is considered. It results that a vast part of the total costs is taken up by the construction of the pipelines. For a connection to all industries costs are found of 169 mln OMR while for a limited connection costs are found of 53 mln OMR.

It followed that a new basin has to be constructed to serve as a connection between the pipelines and the current facilities. This basin serves as a gravitational induced wet-well from where large underwater horizontal pumps pump the water through the band screens into the basins of SWIPS I & II.

From an economic perspective, the project is not feasible. Furthermore it appears to be clear that a limited-scale connection to only the power plants and RO-plants is more suitable from an economic point of view than a large-scale connection to all industries. A limited-scale project would however decrease the reduced impact on marine life and limit the benefits regarding future opportunities for the port.

7.2. Recommendations

Throughout this report certain recommendations have come up that deserve attention in future research. These are listed below and mainly evolve around additional, sound measurements. Moreover policy makers play an important role in the implementation of this project.

Data validation

To support the calculated benefits related to decreased downtime for the RO-plants, it is necessary to know up to what extend the newly proposed intake is exposed to harmful algal blooms. A measurement needs to be prepared that can be started directly when HABs appear. This measurement should aim to conclude on the relation between off-shore distance, water depth and the presence of algae. It should be carried out both during the day and the night as it seems that algae migrate over the water column. Moreover, the benefits of RO-plants depend completely on a supposed increase in water quality with increasing water depth. From the irregular measurements provided it was shown that this water quality improves for the parameters dissolved oxygen and salinity but that turbidity and chlorophyll-a do not show improvements and might even worsen. Recommendations are made to carry out an experiment that proofs the water quality over the different seasons within a year. These two measurements would then prove the feasibility of including RO-plants in the proposed solution.

System analysis

Also the inclusion of industries and power plants in the proposed solution depends on several, more policy wise, factors. In this report, estimations and calculations have been made based on the assumption that industries will use less cooling water in their systems when temperatures drop. It is not clear however whether those industries will have to adapt their systems to the new water and if there exists any willingness to cooperate. To conclude on the feasibility of this project, arrangements should be made with the different stakeholders to measure level of support to this sustainable solution. Furthermore, a considerable part of the economic benefits is taken by the increased production of the power plants. These benefits should be verified by running an analysis with their models and provided water characteristics as input.

Investment

Research should be conducted into finding up to what extend companies are willing to pay for their assumed benefits. This will have an influence on the financial feasibility.

Outfall temperature

The increased capacity of assets can only be realised when the same temperature difference can be discharged throughout the year. In winter, when the deep seawater has a comparable temperature to the surface water, the ΔT of $10°C$ should then be increased to obtain the same temperature difference as in summer. This requires a change in environmental policy. It is therefore recommended to do an assessment of the effects this increased ΔT would have on the local marine life.

Technical feasibility

The technical feasibility is currently supported by calculations containing many estimations. To make the design more sound, several aspects should be subjected to future research. A hydraulic flow model should be made to better estimate friction losses and to predict sedimentation in the system. With these numbers known the design of the intake, pipeline and new basin could be optimised, thereby saving costs, materials and manpower. Moreover, structural calculations and a cost estimation should be made for the new basin.

After consultation of reference projects the redundancy has been estimated on 20%. It is recommended that a more detailed risk, operation and maintenance analysis is carried out. The accuracy of this estimation should be improved to find the ideal redundancy level.

Concrete solution

A rather unconventional material for pipelines was suggested. Concrete conveyors are not typically used for the purpose we intend it to. Due to the large amount of water and possible benefits regarding friction, constructing concrete conveyors potentially has interesting opportunities. Some of the (many) things that need to be investigated for the concrete option are sizing, corrosion resistance, lifetime, biofouling, construction opportunities and costs. It is furthermore recommended to carry out a scaled research to the flow pattern in concrete conveyors to have a better ground to base this suggestion on.

A

Organisational structure

Florian Laurens

- Technical design
- Pipelines
- Financial model

Servaas Kievits

- Current system
- Connection to facilities
- Economic feasibility

Salima Al Behdi
Aisha Algufaili

- Design and dimensions of inlet system
- Pre-treatment
- Size and locations of screens

Munira Almoqbali
Wesal Alkhanbashi

- Research on change in effect on marine life at intake and outfall between current and future situation

Paul Botman

- Efficiency calculation
- Soil investigation
- Future plans

Isabel Gerritsma

- Bathymetry
- Site investigation
- Environmental effects (with Munira and Wesal)

Figure A.1: Organisational structure of team members

B

Site investigation

B.1. Stakeholder analysis

In the following paragraphs a more elaborated view is given on the different stakeholders.

SIPC

The port authority of SOHAR Port and Freezone. It is their responsibility to create the best possible circumstances for the existing and future industries accommodated in Sohar port. Also, their interest in new sustainable projects in the port is large. By providing cooler water to the prominent, large energy consuming industries in the port (logistics, petrochemicals and metals), a big opportunity is created in terms of energy savings, that is, sustainability.

Majis

The main water utility company of the port. They are responsible for supplying large amounts of water to the industries. The main reason Majis wants to contribute to this project is the better water quality of deep seawater, maybe even without the algal blooms (Section 2.4.3). Also, the current water outfall is violating environmental rules. Majis has requested to reconstruct the outfall by adding pipelines further offshore to prevent negative influence on marine life nearshore. Though, not needing to invest in such a project, but resolving the problem differently is a benefit for them.

The government of Oman

They have a large number of shares in the port and industries located there. For them it is important to have a competitive port for the sake of regional trade. Also, for example the Ministry of Environment and Climate Affairs have an interest in the way the environment is affected by the intake and outfall.

Power plants

Currently, a large part of the cooling water goes to the power plants in Sohar port. A distribution of cooler water to the power plants enables an increase in electricity production by the steam turbines. [Kim and Jeong, 2013]. With this increased power production they can make more revenue or will save costs on gas usage.

RO plants

A more efficient RO-process thanks to cleaner water results in cost savings. This could be a big advantage for the RO plants. Though, they do not have such a big influence as Majis, since Majis is actually the owner of the seawater intake system.

Remaining port industries

The industries in the port possess cooling systems that might need to be changed if the deep seawater intake is actually realised. High adaption costs would create much resistance. Yet, it could be a possibility to concentrate on new clients.

Fishermen
The main income source for the communities that live on the coast of Oman, is fishery. It is the largest source of revenue in Oman besides oil exports. To remain strong in this sector the water quality of the coastal area is not allowed to be downgraded. This project can be an opportunity to make the quality even better.

B.2. Intake analysis

Figure B.1: Proposed horizontal screw pumps

B.2.1. Desalination process by Majis

The water that enters the RO-plant is first led under pressure through a series of micro-filters that serve to remove solid particles from the source seawater. This step is followed by pressurised passage of the water through RO-membranes that will remove the dissolved solids. A second division is then made between water that will serve as potable water and process water. The potable water flows out and is further treated elsewhere. The water that is destined as process water is led back into the system to have a second passage through the RO-membranes. This second passage is required as ions and organics in the process water would wear down the pipe network within the different industries. After this step the process water is diverted to the different companies.

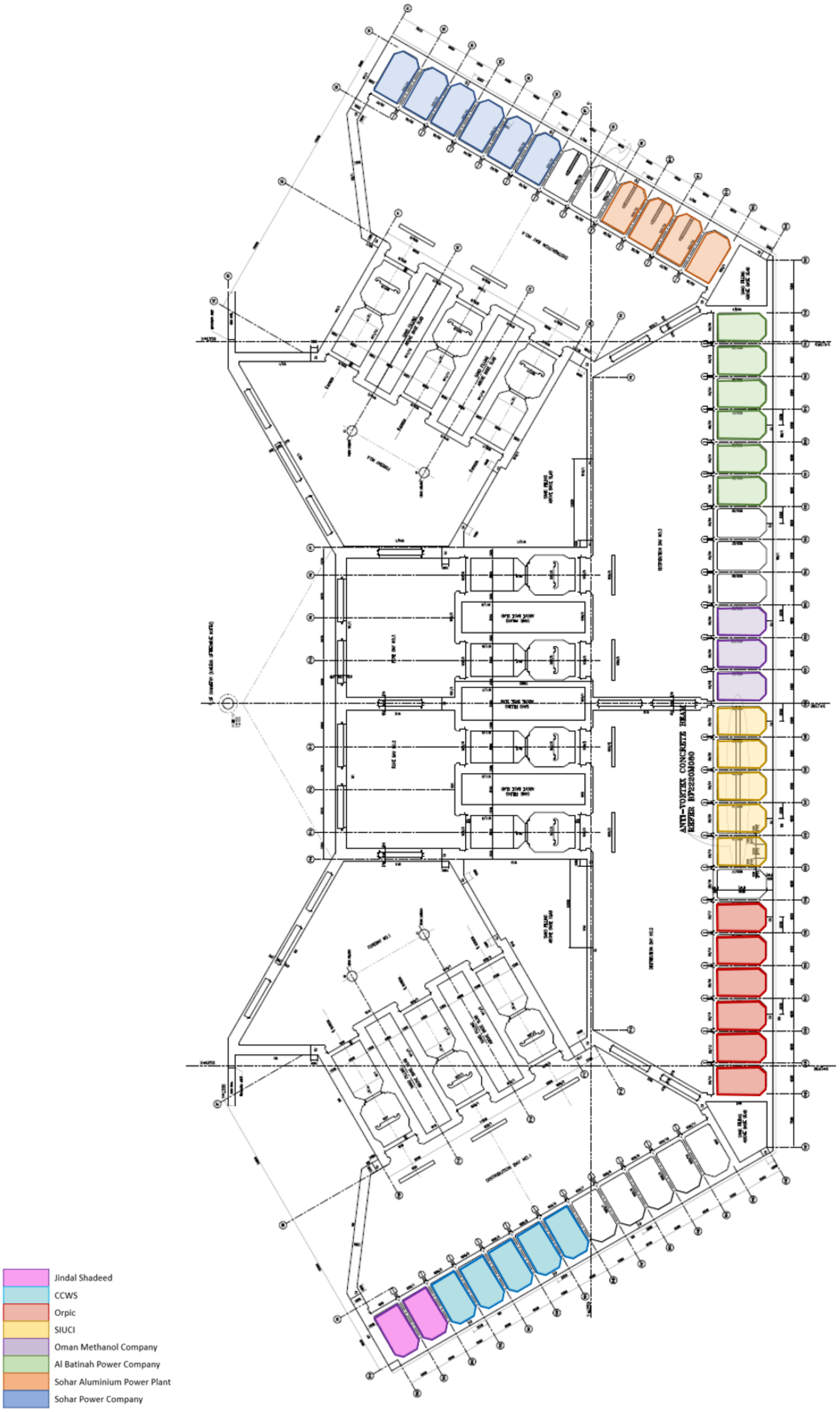


Figure B.2: Composition of pump facilities in SWIPS 1

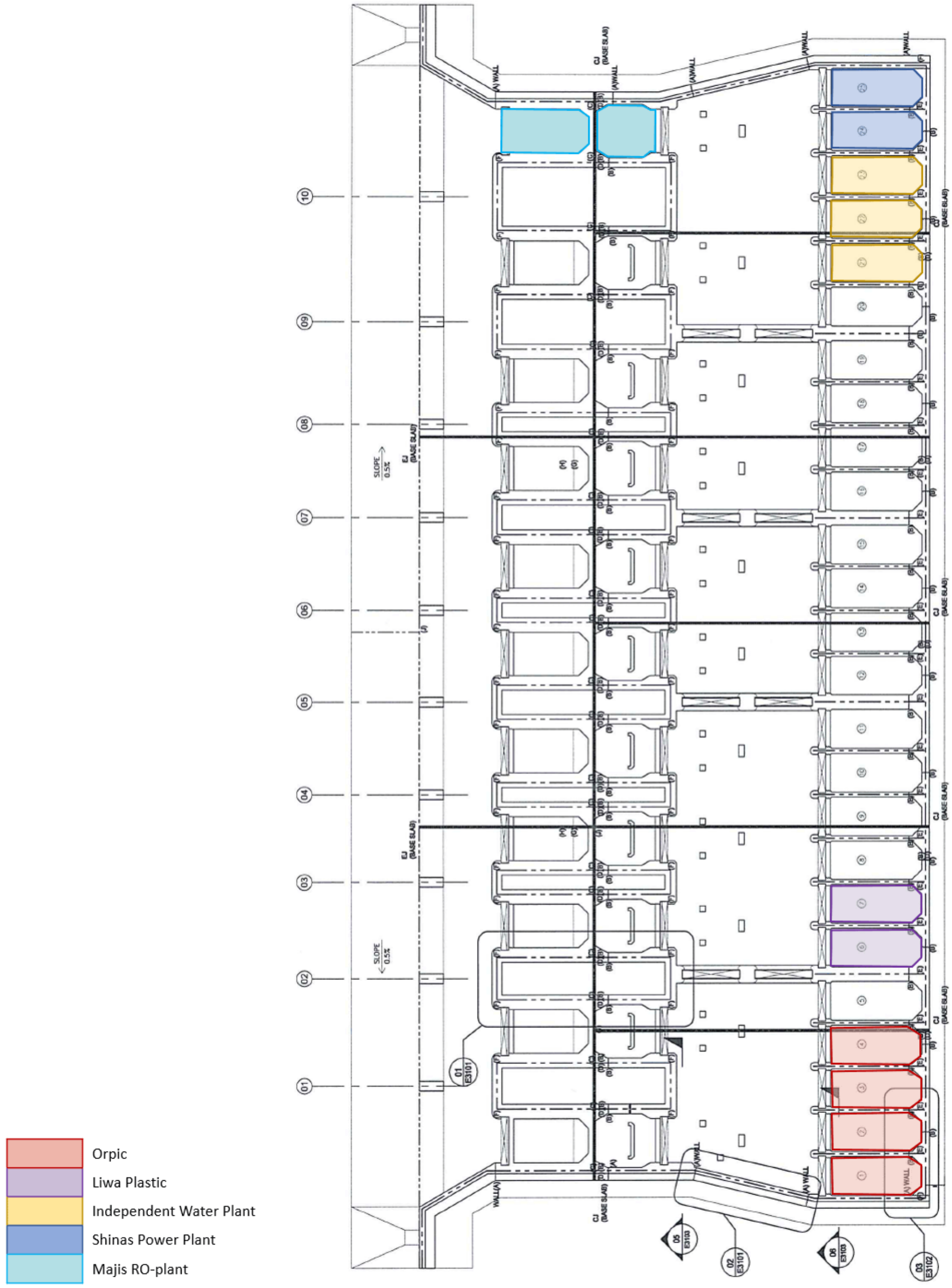


Figure B.3: Composition of pump facilities in SWIPS 2

B.3. Environmental analysis

B.3.1. Water temperature

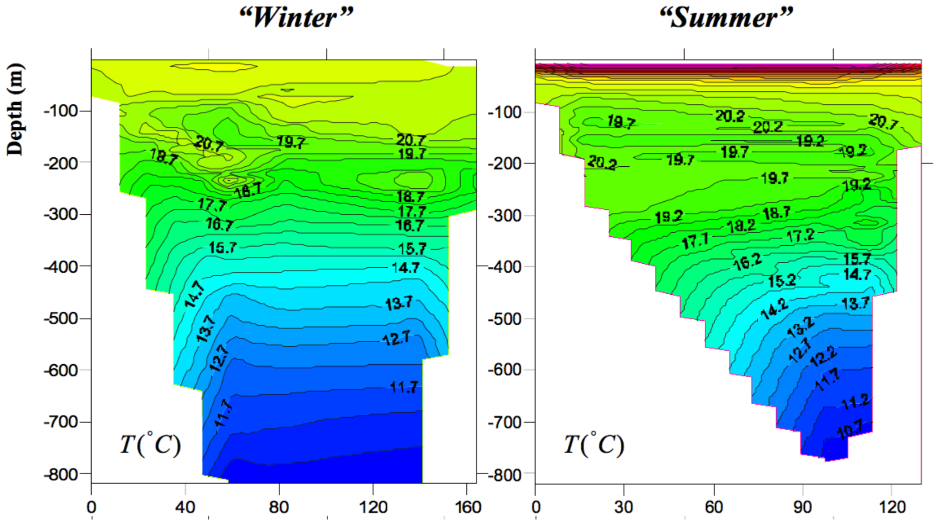
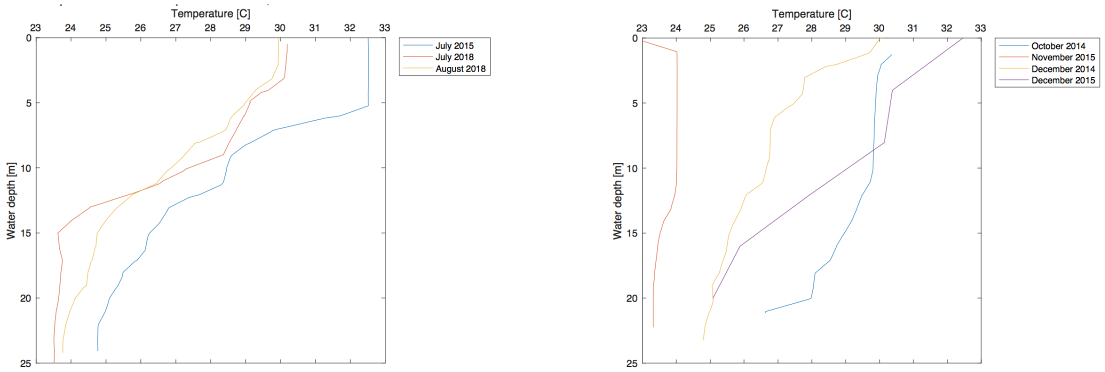
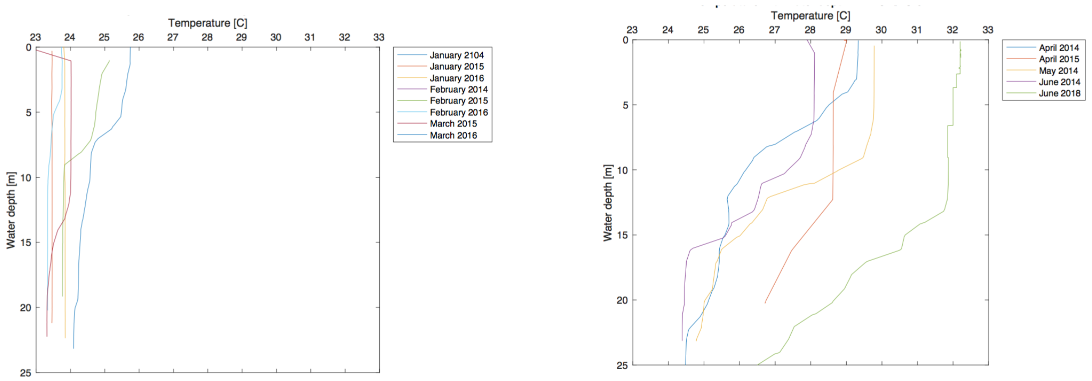


Figure B.4: Water temperature along depth [Bidokhti and Ezam, 2009]



(a) Summer: July, August and September

(b) Autumn: October, November and December



(c) Winter: January, February and March

(d) Spring: April, May and June

Figure B.5: Water temperature with depth.

B.3.2. Soil composition

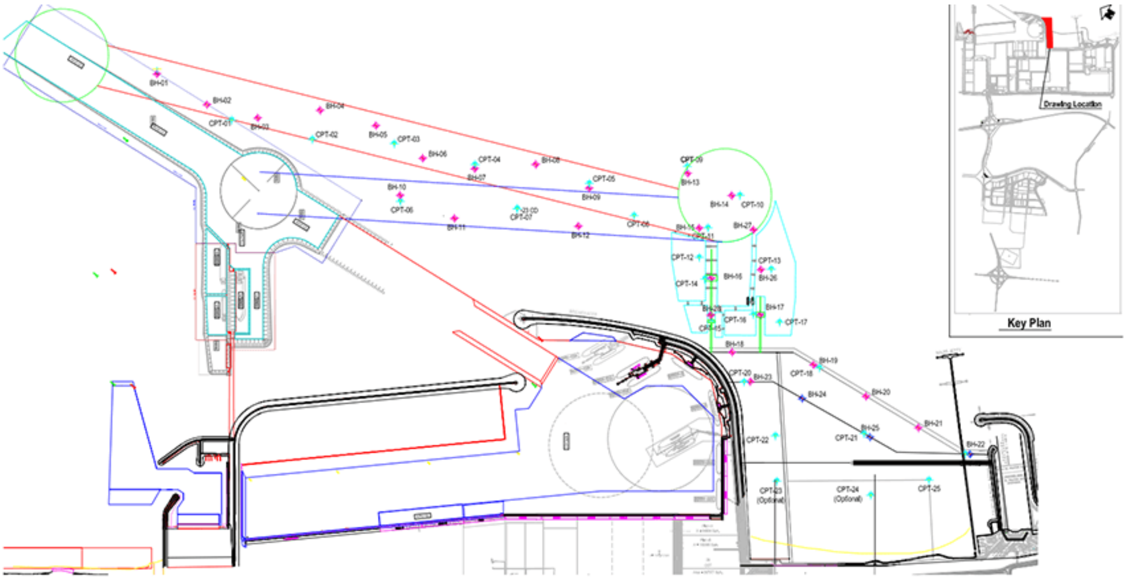
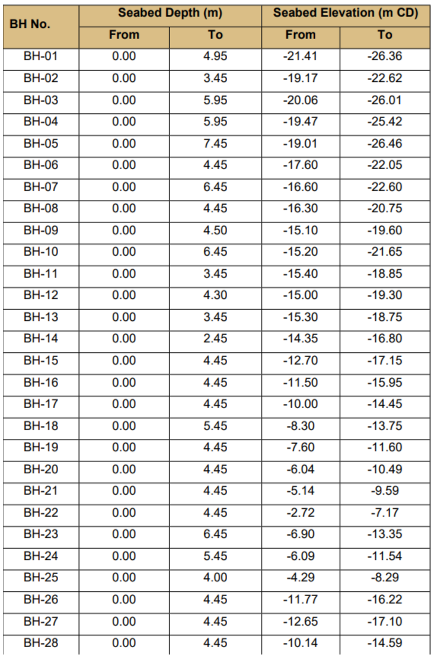


Figure B.6: Test locations of the CPTs and SPTs. [Fugro and LLC, 2017]



BH No.	Seabed Depth (m)		Seabed Elevation (m CD)	
	From	To	From	To
BH-01	0.00	4.95	-21.41	-26.36
BH-02	0.00	3.45	-19.17	-22.62
BH-03	0.00	5.95	-20.06	-26.01
BH-04	0.00	5.95	-19.47	-25.42
BH-05	0.00	7.45	-19.01	-26.46
BH-06	0.00	4.45	-17.60	-22.05
BH-07	0.00	6.45	-16.60	-22.60
BH-08	0.00	4.45	-16.30	-20.75
BH-09	0.00	4.50	-15.10	-19.60
BH-10	0.00	6.45	-15.20	-21.65
BH-11	0.00	3.45	-15.40	-18.85
BH-12	0.00	4.30	-15.00	-19.30
BH-13	0.00	3.45	-15.30	-18.75
BH-14	0.00	2.45	-14.35	-16.80
BH-15	0.00	4.45	-12.70	-17.15
BH-16	0.00	4.45	-11.50	-15.95
BH-17	0.00	4.45	-10.00	-14.45
BH-18	0.00	5.45	-8.30	-13.75
BH-19	0.00	4.45	-7.60	-11.60
BH-20	0.00	4.45	-6.04	-10.49
BH-21	0.00	4.45	-5.14	-9.59
BH-22	0.00	4.45	-2.72	-7.17
BH-23	0.00	6.45	-6.90	-13.35
BH-24	0.00	5.45	-6.09	-11.54
BH-25	0.00	4.00	-4.29	-8.29
BH-26	0.00	4.45	-11.77	-16.22
BH-27	0.00	4.45	-12.65	-17.10
BH-28	0.00	4.45	-10.14	-14.59

Figure B.7: Density of the soil at different levels. [Fugro and LLC, 2017]

B.3.3. Hydraulic conditions

The offshore wave data consists of the significant wave height H_s, mean wave direction MWD and peak wave period T_p, presented in Figure B.8. By converting this data to nearshore wave conditions with numerical models, the normal wave conditions (Figure B.9) and the extreme wave conditions (Table B.1 and B.2) are obtained. Figure B.9 provides the wave roses for the significant wave height and the peak wave period.

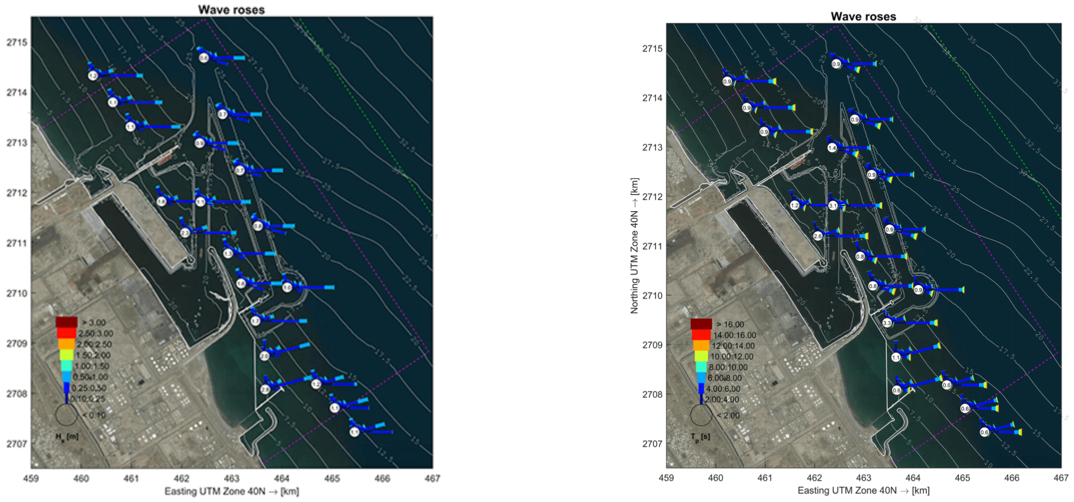
For six return periods (1, 5 ,10, 20, 50 and 100 year) the significant wave height and the peak wave period for three directional sectors are modelled. H_s and T_p for these return periods are summarised in Table B.1 and B.2 respectively.

Return period (yr)	Sector NW (300 - 15)	Sector NE (15 - 85)	Sector SE (85 - 150)
1	1.05 (1.01 - 1.09)	1.34 (1.28 - 1.39)	1.35 (1.30 - 1.39)
5	1.41 (1.31 - 1.52)	1.76 (1.58 - 1.97)	2.02 (1.80 - 2.25)
10	1.58 (1.43 - 1.73)	1.95 (1.67 - 2.30)	2.33 (2.01 - 2.66)
20	1.74 (1.54 - 1.95)	2.15 (1.76 - 2.70)	2.64 (2.24 - 3.06)
50	1.95 (1.65 - 2.31)	2.42 (1.86 - 3.35)	3.06 (2.55 - 3.60)
100	2.13 (1.74 - 2.64)	2.63 (1.93 - 3.96)	3.38 (2.78 - 4.00)

Table B.1: Nearshore extreme wave heights.

Return period (yr)	Sector NW (300 - 15)	Sector NE (15 - 85)	Sector SE (85 - 150)
1	4.9 (4.9 - 5.0)	6.2 (6.1 - 6.2)	7.5 (7.4 - 7.5)
5	5.5 (5.3 - 5.6)	6.7 (6.5 -7.0)	8.2 (8.0 - 8.3)
10	5.7 (5.5 - 5.9)	6.9 (6.6 - 7.4)	8.4 (8.2 - 8.6)
20	5.9 (5.7 - 6.2)	7.2 (6.8 - 7.7)	8.6 (8.3 - 9.1)
50	6.2 (5.7 - 6.6)	7.5 (6.8 - 8.5)	9.0 (8.5 - 9.6)
100	6.3 (5.9 - 6.9)	7.7 (6.9 - 9.2)	9.3 (8.8 - 9.9)

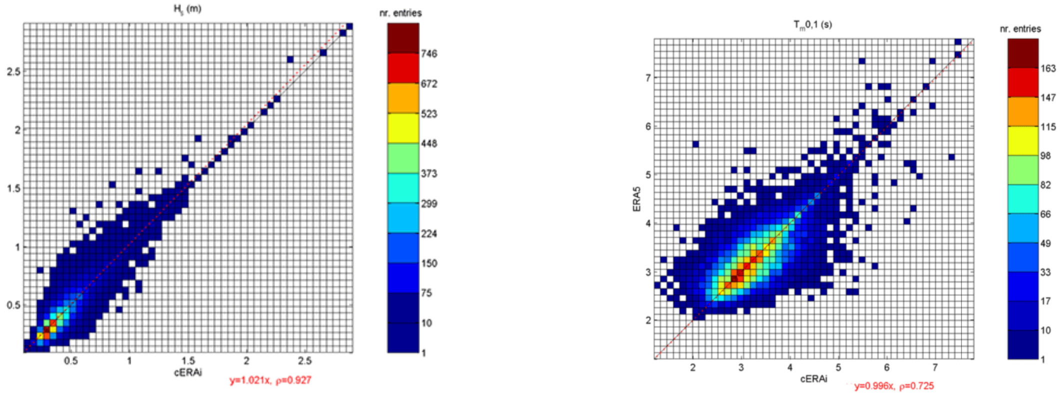
Table B.2: Nearshore extreme peak wave periods.



(a) Significant wave height H_s

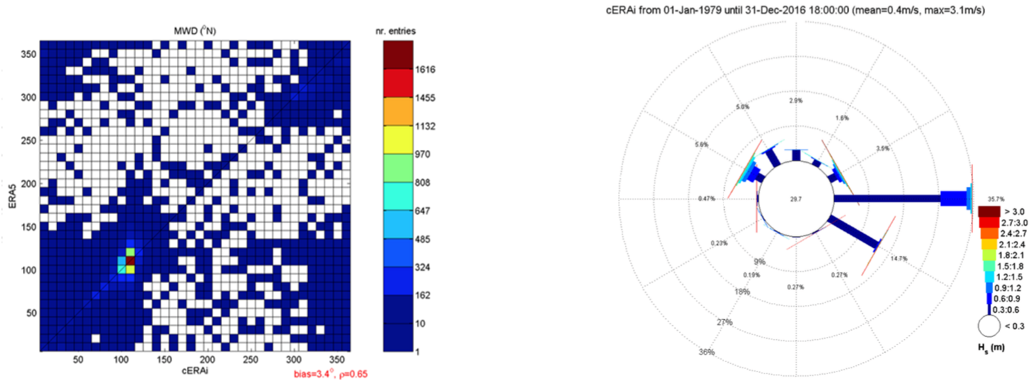
(b) Mean wave period $T_{m-1,0}$

Figure B.9: Normal wave conditions around the Port of Sohar. [Deltares, 2018].



(a) Significant wave height H_s

(b) Mean wave period $T_{m-1,0}$

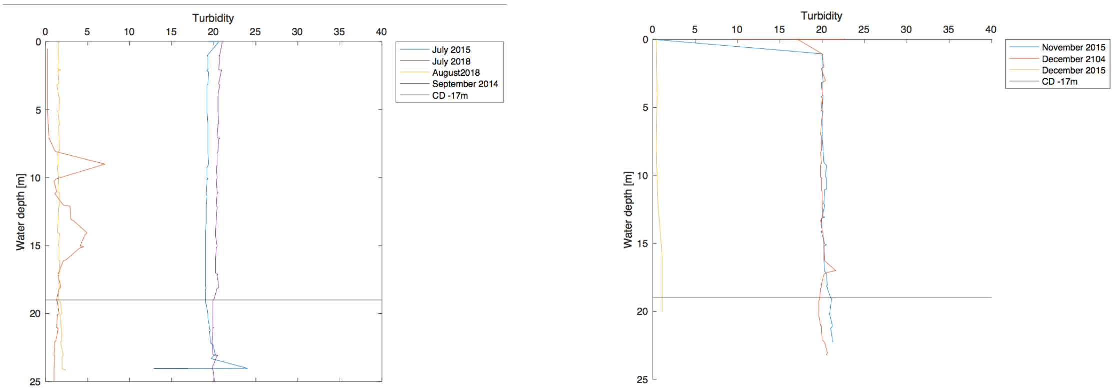


(c) Mean Water Direction MWD

(d) Wave rose for the offshore location.

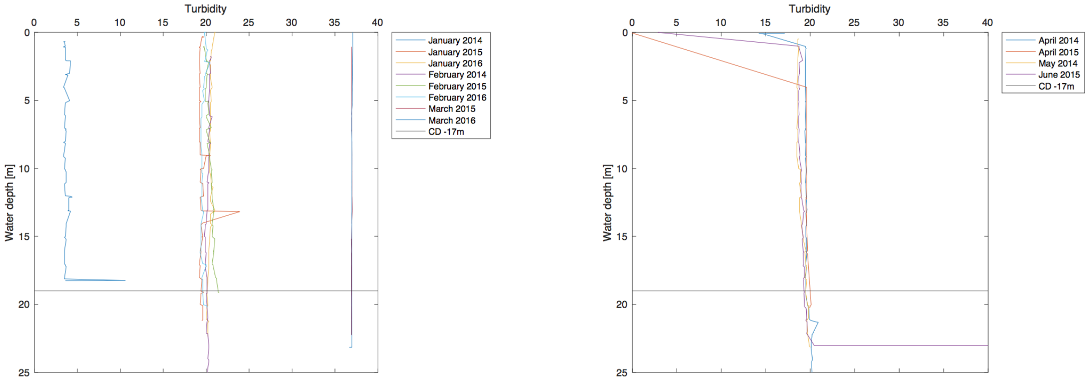
Figure B.8: Mean wave parameters [Deltares, 2018].

B.3.4. Water quality



(a) Summer: July, August and September

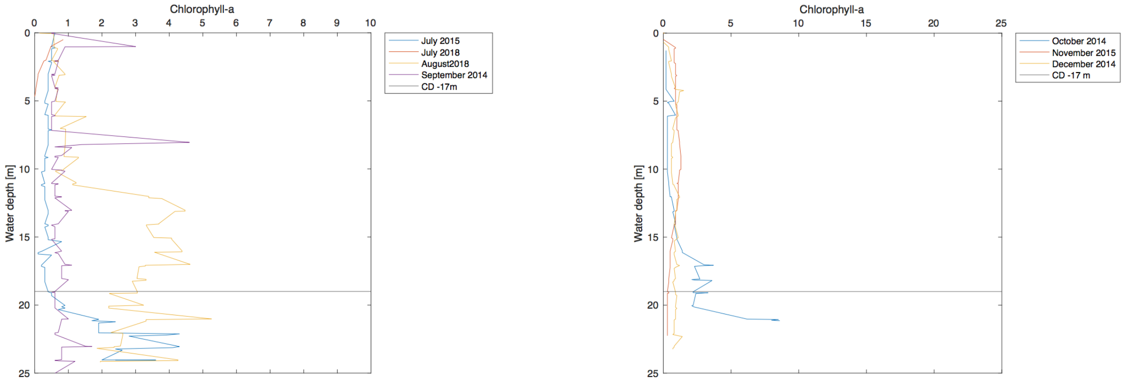
(b) Autumn: October, November and December



(c) Winter: January, February and March

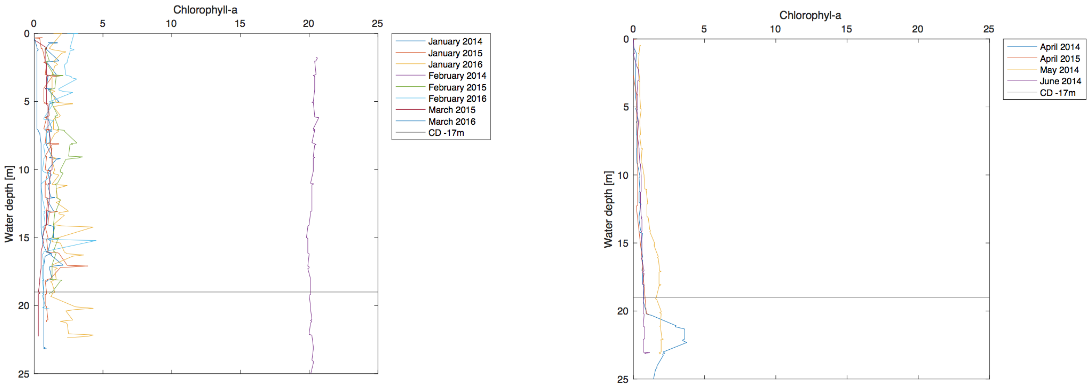
(d) Spring: April, May and June

Figure B.10: Turbidity with depth.



(a) Summer: July, August and September

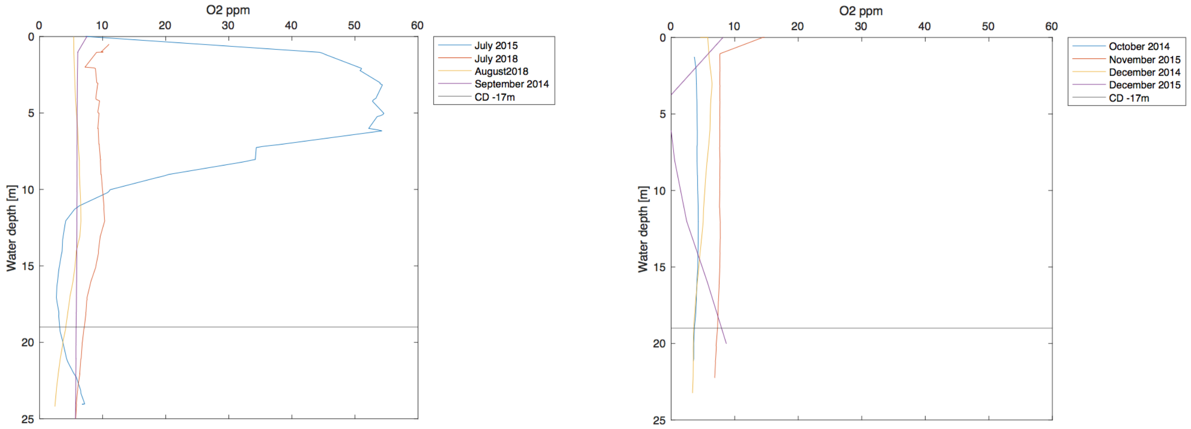
(b) Autumn: October, November and December



(c) Winter: January, February and March

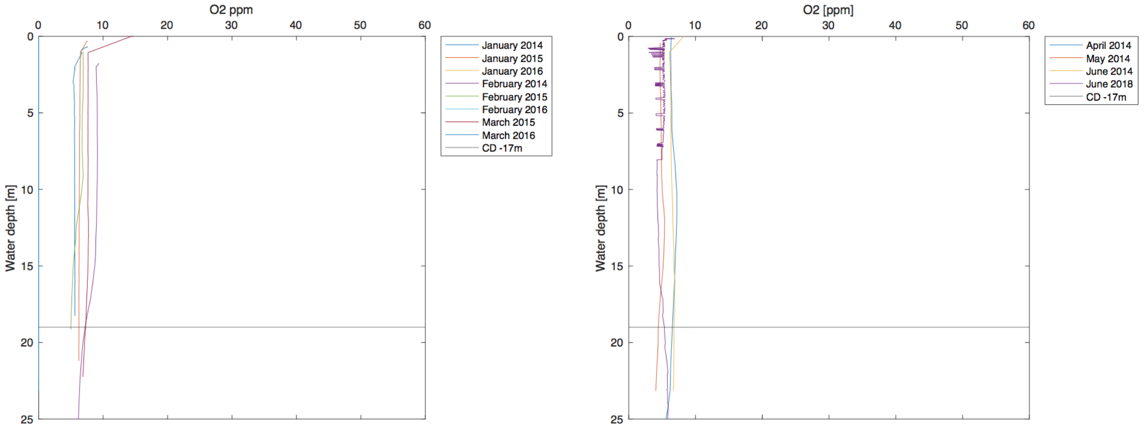
(d) Spring: April, May and June

Figure B.11: Chlorophyll-a concentration with depth.



(a) Summer: July, August and September

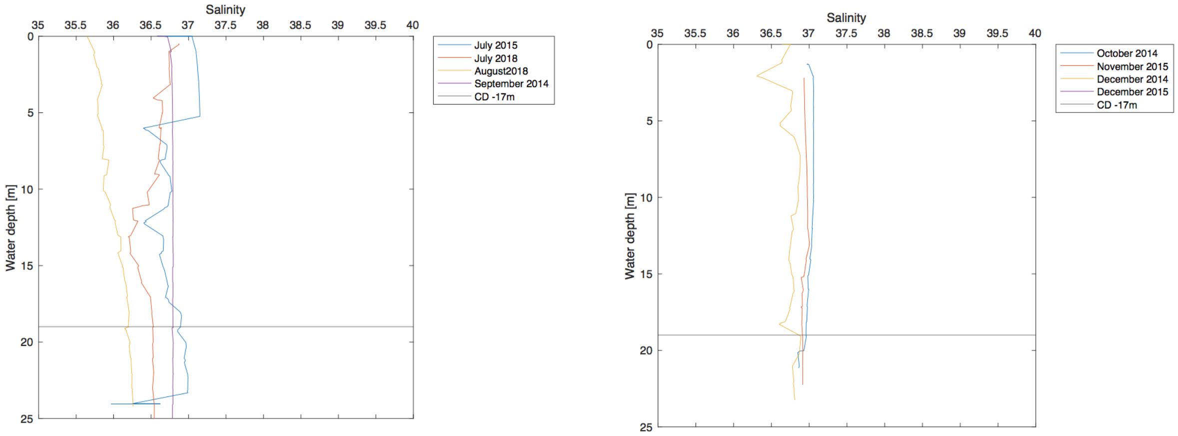
(b) Autumn: October, November and December



(c) Winter: January, February and March

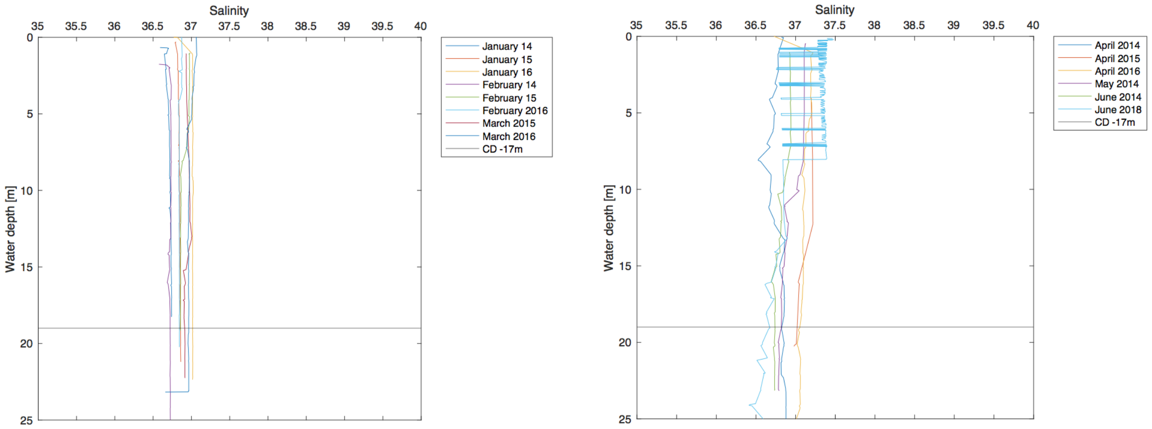
(d) Spring: April, May and June

Figure B.12: Dissolved oxygen concentration with depth.



(a) Summer: July, August and September

(b) Autumn: October, November and December



(c) Winter: January, February and March

(d) Spring: April, May and June

Figure B.13: Salinity with depth.

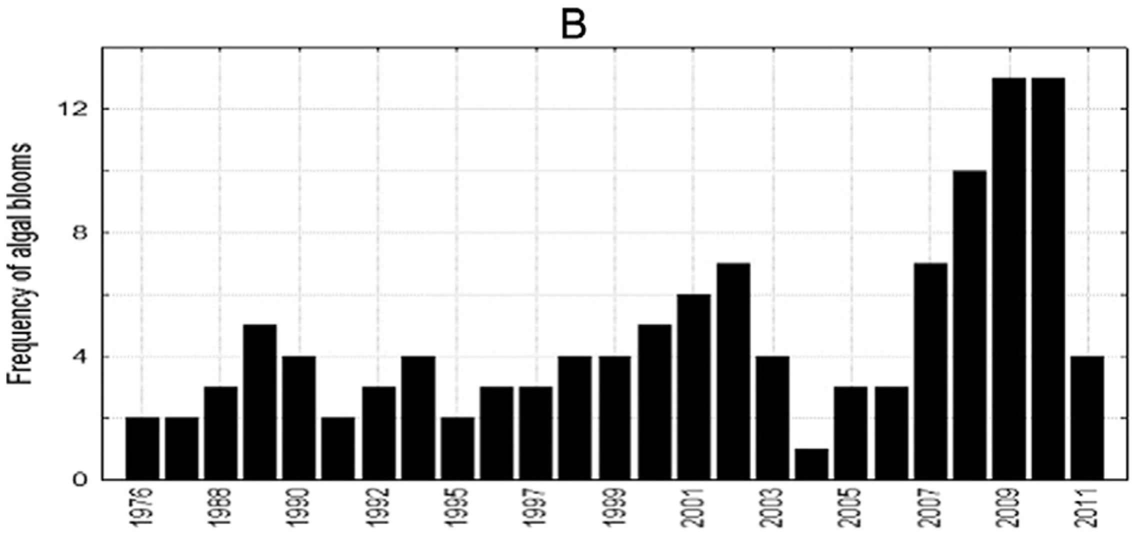


Figure B.14: Yearly changes of the cumulative frequency of HABs along the Omani coast (1988-2010). Piontkovski et al. [2012]

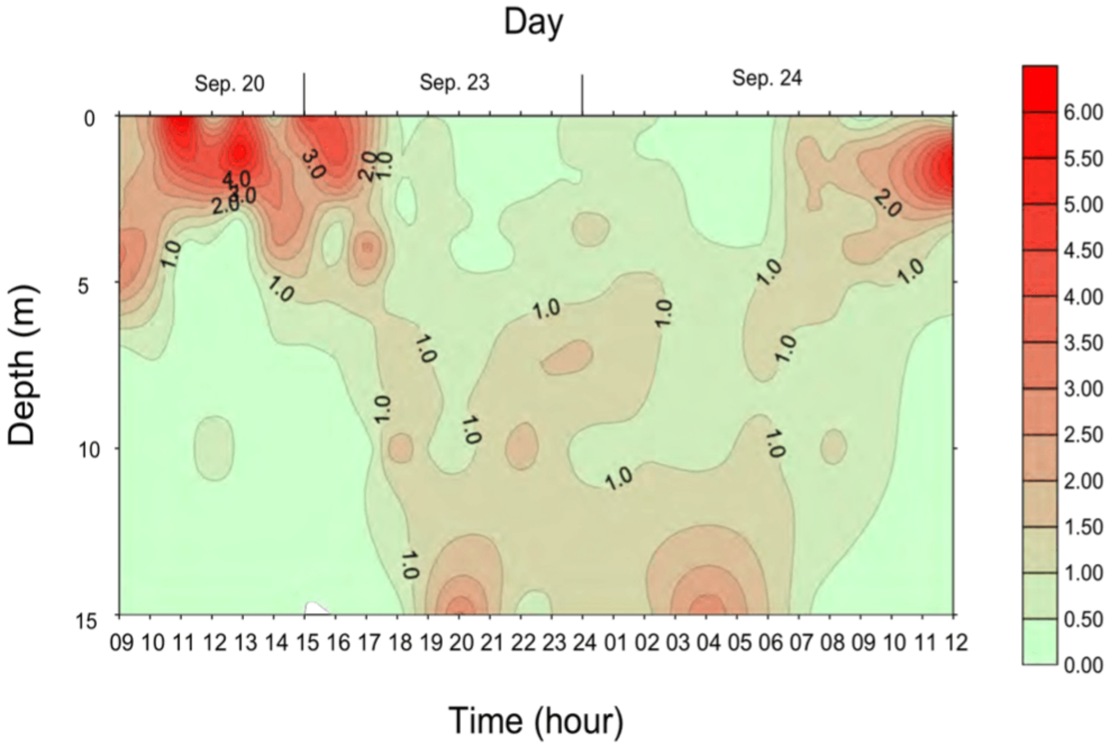


Figure B.15: Temporal changes in the vertical distribution of a HAB species in Korea. The colors indicate the relative densities: ratios of amount of cells at specific depths to the average amount of cells along the water depth. Modified from Park et al. 2001. [UNESCO, 2017].

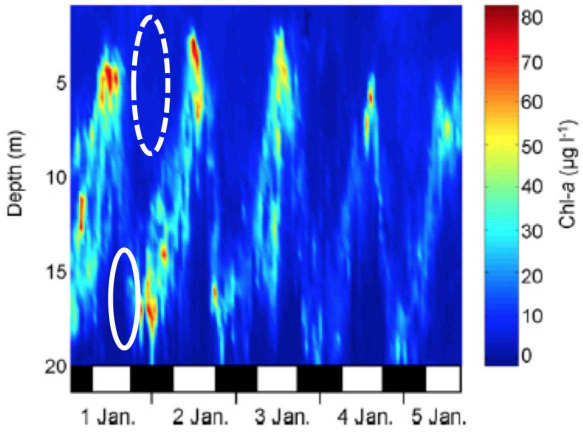
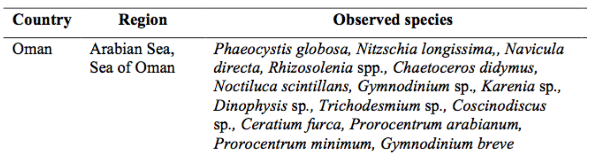


Figure B.16: Chlorophyll-a profiles, showing diel vertical migration of phytoplankton in a water column with 20 m depth. The white bars on the x-axis represent day and black bars indicate night. Data from CSIRO Huon Estuary Study (modified from Doblin et al. 2006). [UNESCO, 2017].



Country	Region	Observed species
Oman	Arabian Sea, Sea of Oman	*Phaeocystis globosa, Nitzschia longissima,, Navicula directa, Rhizosolenia* spp.*, Chaetoceros didymus, Noctiluca scintillans, Gymnodinium* sp.*, Karenia* sp.*, Dinophysis* sp.*, Trichodesmium* sp.*, Coscinodiscus* sp.*, Ceratium furca, Prorocentrum arabianum, Prorocentrum minimum, Gymnodinium breve*

Figure B.17: Algal species observed in the Arabian sea and the sea of Oman. [UNESCO, 2017].

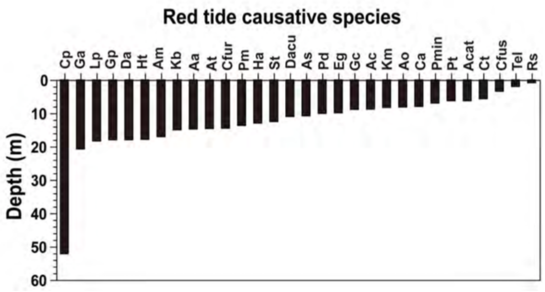


Figure B.18: The depth to which different algal species can swim in 10 hours. [UNESCO, 2017].

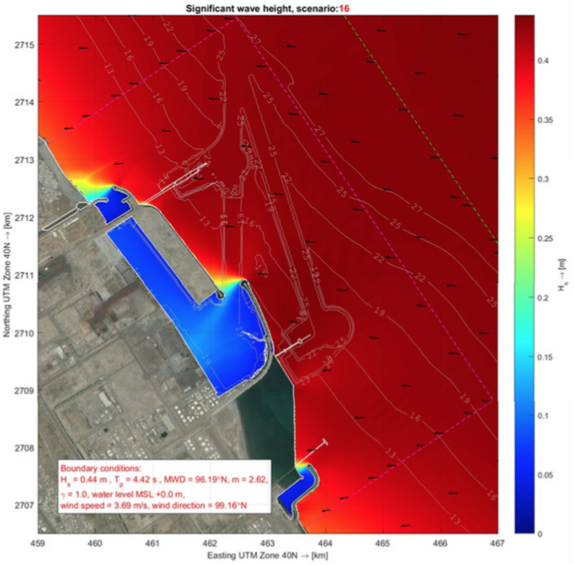


Figure B.19: Significant waveheight around the Port of Sohar

C

Project opportunities

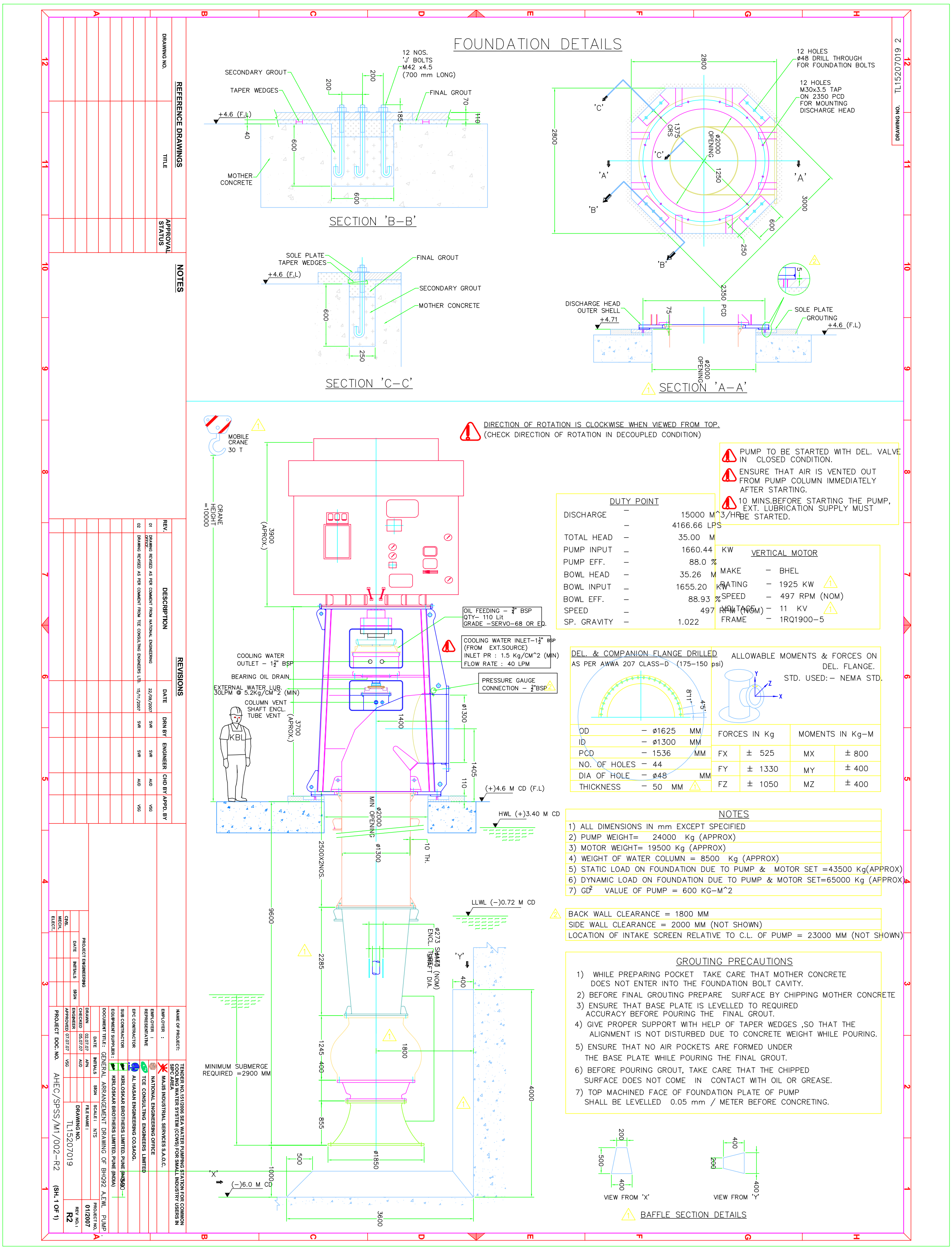


Figure C.1: Technical drawing of a distribution pump. (Majis)

According to Kim and Jeong [2013], the efficiency gain thanks to colder cooling water, comes from the steam turbines and can be calculated with a simplified steam Rankine cycle. Figure C.2 shows a higher thermal efficiency if the condenser pressure is lower, which is dependent on the cooling water temperature. The temperature of the condenser pressure is about 10 – 15°C higher than the cooling water. Cooling water of 20 °C results in condensate temperature is around 35°C. This has a corresponding saturation pressure of 0.006 MPa. With this saturation pressure a thermal efficiency of the cycle of 32 % is found. If the cooling water is at 35 °C, the condenser is at about 50°C and 0.013 MPa. The thermal efficiency of the cycle would be 30 %. Increase of cooling seawater temperature by 15°C results in a 2 percentage-point loss of efficiency and about a 6 % power loss. [Kim and Jeong, 2013].

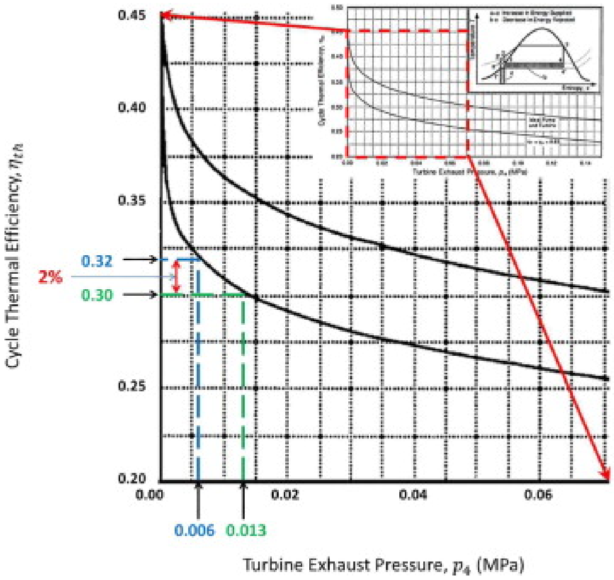
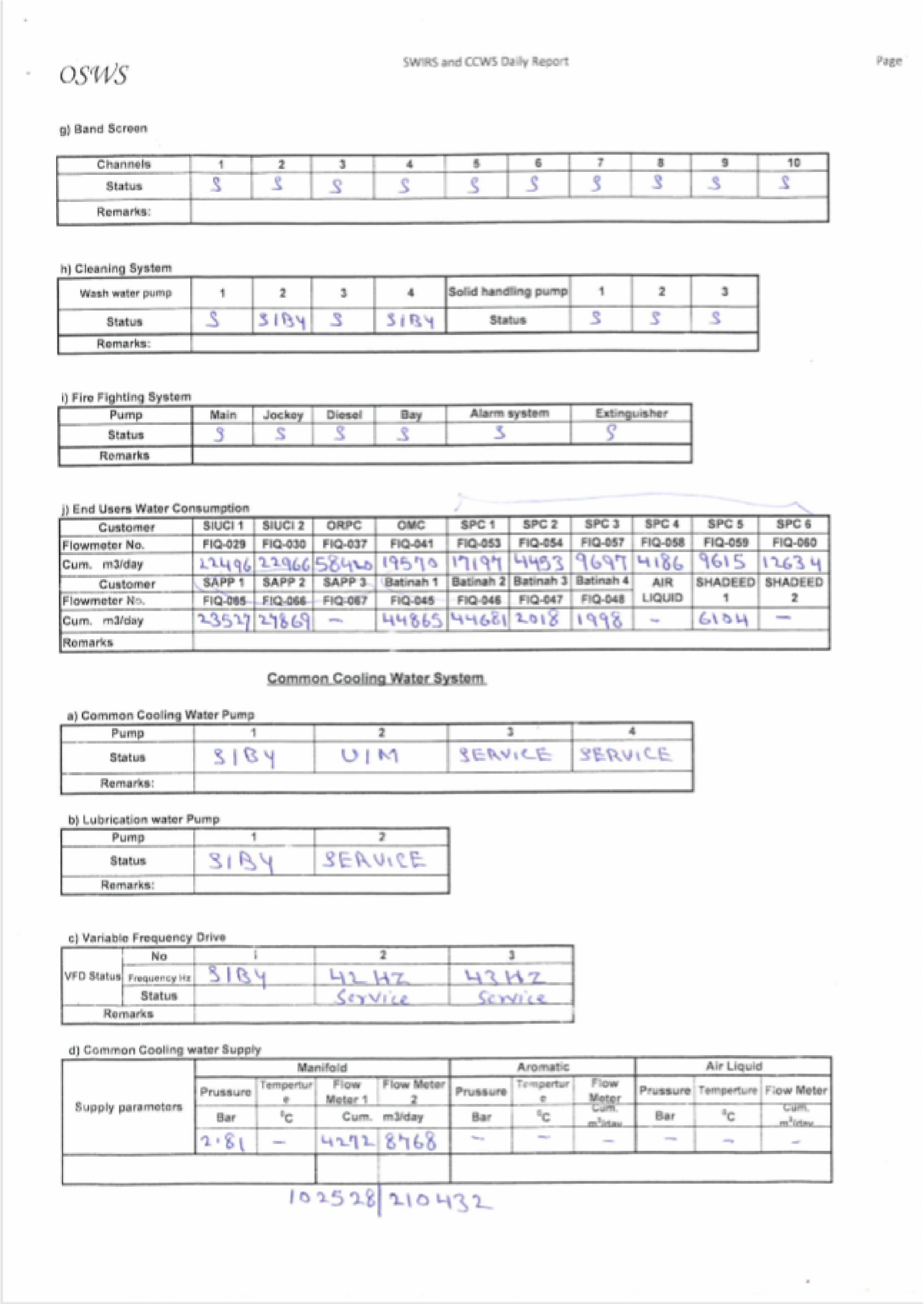


Figure C.2: Thermal efficiency of Rankine Cycle for a saturated turbine inlet state for varying turbine outlet pressure. [Kim and Jeong, 2013]



OSWS

SWIRS and CCWS Daily Report

Page

g) Band Screen

Channels	1	2	3	4	5	6	7	8	9	10
Status	S	S	S	S	S	S	S	S	S	S
Remarks:										

h) Cleaning System

Wash water pump	1	2	3	4	Solid handling pump	1	2	3
Status	S	S/BY	S	S/BY	Status	S	S	S
Remarks:								

i) Fire Fighting System

Pump	Main	Jockey	Diesel	Bay	Alarm system	Extinguisher
Status	S	S	S	S	S	S
Remarks						

j) End Users Water Consumption

Customer	SIUCI 1	SIUCI 2	ORPC	OMC	SPC 1	SPC 2	SPC 3	SPC 4	SPC 5	SPC 6
Flowmeter No.	FIQ-029	FIQ-030	FIQ-037	FIQ-041	FIQ-053	FIQ-054	FIQ-057	FIQ-058	FIQ-059	FIQ-060
Cum. m3/day	22496	22966	58420	19570	17194	4493	9697	4186	9615	12634
Customer	SAPP 1	SAPP 2	SAPP 3	Batinah 1	Batinah 2	Batinah 3	Batinah 4	AIR LIQUID	SHADEED 1	SHADEED 2
Flowmeter No.	FIQ-065	FIQ-066	FIQ-067	FIQ-045	FIQ-046	FIQ-047	FIQ-048			
Cum. m3/day	23527	24869	–	44865	44681	2018	1998	–	6104	–
Remarks										

Common Cooling Water System

a) Common Cooling Water Pump

Pump	1	2	3	4
Status	S/BY	U/M	SERVICE	SERVICE
Remarks:				

b) Lubrication water Pump

Pump	1	2
Status	S/BY	SERVICE
Remarks:		

c) Variable Frequency Drive

	No	1	2	3
VFD Status	Frequency Hz	S/BY	42 HZ	43 HZ
	Status		Service	Service
Remarks				

d) Common Cooling water Supply

	Manifold				Aromatic			Air Liquid		
Supply parameters	Prussure	Temperture	Flow Meter 1	Flow Meter 2	Prussure	Temperture	Flow Meter	Prussure	Temperture	Flow Meter
	Bar	°C	Cum. m3/day		Bar	°C	Cum. m³/day	Bar	°C	Cum. m³/day
	2.81	–	4272	8468	–	–	–	–	–	–

102528 | 210432

Figure C.3: A overview of the discharges to the different factories on a day.

D

Technical design deep seawater intake

D.1. Pressure head loss

The pressure head loss over a pipeline consists of the friction of the pipe-wall, inflow losses, outflow losses and losses due to (sharp) bends in the pipe trajectory. This is clarified in (D.1).

$$h_{tot} = h_f + h_{in} + h_{out} + h_{bend} \tag{D.1}$$

Where:

h_{tot} = total pressure head loss
h_f = head loss due to pipe wall friction
h_{in} = head loss due to inflow (inlet system)
h_{out} = head loss due to outflow
h_{bend} = head loss due to bends in pipeline

The total pressure head loss is calculated with Darcy-Weisbach in combination with a contribution formula for the various other loss elements (D.2). The Darcy friction factor f is calculated with Cole-Whitebrook (D.3) for turbulent flow, and the Reynolds number is calculated with (D.4). For all cases considered the flow was turbulent.

$$h_{tot} = f \frac{L}{D} \frac{V^2}{2g} + (K_1 + K_2 + K_3 + ...) \frac{V^2}{2g} \tag{D.2}$$

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\epsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right) \tag{D.3}$$

$$Re = \frac{VD_h}{\nu} \tag{D.4}$$

Where:

f = the Darcy friction factor $(-)$
L = length of pipeline (m)
D = the hydraulic diameter (m)
V = the flow velocity (m/s)
$K_1, K_2, ...$ = head loss coefficient for various pipe elements $(-)$
ϵ = the hydraulic roughness (m)
D_h = the hydraulic diameter (m)
Re = the Reynolds number $(-)$
ν = the kinematic viscosity (m^2/s)

Figure D.1: An example of weight design for HDPE pipelines (PipeLife)

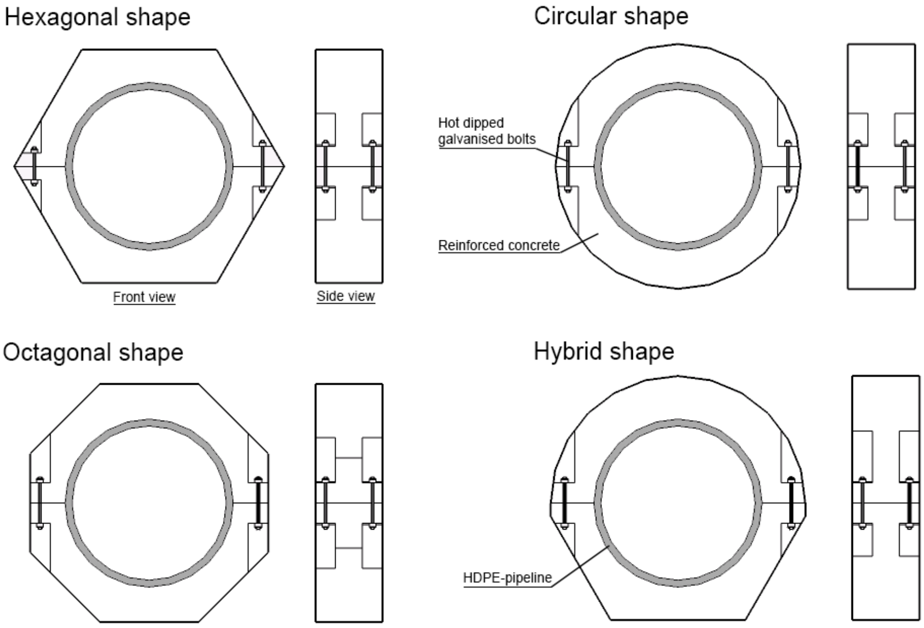


Figure D.2: Overview of various shapes of concrete ballasting weights.

D.2. Concrete anchor weights

Since the density of HDPE is only 960 kg/m^3, it will float even when filled with water. Therefore, some ballasting will be required depending on wave and current forces, as well as whether the pipe is placed directly on the sea bed or in a (backfilled) trench. The amount of loading applied largely depends on the water depth and on the location of the pipeline. A common weighting is in the range of 20-45% of the pipe's displacement with 3 - 6 m intervals between each anchor block [PipeLife, 2016]. Finally, the formation of gas inside the pipeline should not be able to cause flotation of the pipe.

Further analysis should provide which exact numbers have to be taken. Data about for example extreme wave conditions, ocean flow and fishing activity is necessary to give a more concise answer to this question. For now an average scenario is assumed, with weighing equal to 30% of the displacement, 5 m intervals and 1 m width. The pipe is submerged in the soil for the nearshore part and placed in an open trench for the rest of the trajectory. The concrete ballasts are usually casted on-site and comprises two parts. After the concrete reached its design strength the weights are transported to the pipeline where the two parts are connected with hot dipped galvanised steel bolts.

A possible concrete weighing block can take many different shapes, depending on what is preferred for the specific case. For this project four different types of weighing blocks were compared: hexagonal, circular, octagonal and hybrid shaped blocks (see Figure D.2). Hexagonal and octagonal blocks have a more stable connection with the sea bed but are more likely to get entangled (e.g., by fishing nets). The lateral stability with the sea bed is slightly less for circular blocks, but the risk of damage due to entanglement is also much smaller. Another possibility is using a hybrid shape. The specifications of the above mentioned shapes are shown in Table D.1. In a future analysis the risks regarding stability and entanglement with respect to the weight block shape has to be calculated and based on this a design decision should be made. If it is decided to entrench the pipeline, it is common practice to use circular shaped weights.

	Width (m)	Diameter (m)	Flange (m)	Weight (t)
Hexagonal shape	1	4.02	2.01	7.547
Circular shape	1	3.65	-	7.547
Octagonal shape	1	3.85	1.47	7.547
Hybrid shape	1	3.82	1.91	7.547

Table D.1: Example of concrete weight sizes. Hexagonal shaped weights provide more stability on the seabed whereas circular shapes are less likely to become entangled by fishing nets.

D.3. Design for external pressure

When the pipe is in position at the ocean floor it will be subject to buckling forces from the ocean water (and the soil in case of a buried pipe). Failure occurs if compressive forces exceed resistance from the material. Buckling strength, P_{buc-w}, of an unsupported pipe can be calculated using (D.5).

$$P_{buc-w} = \frac{2Ekt^3}{(1-\nu^2)(d-t)^3F} \tag{D.5}$$

Where:

t = Minimum wall thickness of the pipe (95.5 mm)
E = Young's Modulus for PE 100 HDPE (1.05×10^6 kPa)
F = Factor of safety, assumed as 2
k = Reduction factor due to ovalling of the pipe (0.65)
ν = Poisson's ratio of PE 100 HDPE (0.45)

$$P_{buc-w} = \frac{2 \times 1.05 \times 10^6 \times 0.65 \times 95.5^3}{(1-0.45^2)(2309-95.5)^3 \times 2} = 69\ kPa$$

From the above it can be noted that the buckling strength of the material is 69 kPa (7 m head). The maximum pressure on the pipe is calculated as outside pressure - inside pressure. If the pipe is at 100% vacuum at e.g. 20 m depth the total head is 10.33 + 20 = 30.33 m, which will cause buckling of the pipe. This needs to be taken into account during construction and pressure inside the pipe should be levelled with outside pressure during installation. The buckling strength in reality will be much larger if the concrete ballast weights around the pipe are taken into account. The concrete weights stabilise the deformation of the pipe and have a positive effect on the buckling strength. Burying the pipes in the sea bed also drastically increases the buckling strength of the pipelines.

D.4. Design for temperature stress

Any material subject to temperature changes will contract or expand based on the temperature difference with respect to normal. This contraction/expansion can be calculated using formula (D.6), that is based on a material dependant coefficient, the pipe length and a maximum difference in temperature. For a worst case scenario we consider sea temperature fluctuations between 20 and 33 degrees Celsius: $\Delta T = 13$ °C

$$\Delta L = \alpha L_0 \Delta T \tag{D.6}$$

Where:

α = Thermal expansion coefficient for HDPE (0.2×10^{-3} °C^{-1})
L_0 = Initial pipeline length
ΔT = Change in temperature (13°C)

Assuming that the pipe is entirely fixed, the stresses will be in the longitudinal direction of the pipe. The stress is calculated in (D.7) and results in a maximum compressive pressure of 2730 kPa. This number is lower than 6300 kPa which is the design compressive strength of the material after 50 years. Hence, no failure due to temperature stresses will occur.

$$\sigma_t = E\alpha\Delta T \tag{D.7}$$

D.5. Design for bending stress

During installation the pipelines will be subject to bending stresses.

$$\sigma_b = \frac{ED}{2R} \tag{D.8}$$

E = Young's Modulus for PE 100 HDPE (1.05×10^6 kPa)
D = the hydraulic diameter (m)
R = the radius of curvature (m)

The maximum bending stresses depend on the E-Modulus of the material, the pipe outside diameter (2500 mm) and the radius of the curvature of the pipe. The short time maximum allowable stress of PE100 grade HDPE is 9400 kPa, resulting in a minimum radius of the curvature of the pipe of 140 m. During installation the curvature should always be less than this. In case of 3 meter of trench dredging and a water depth of 20 meter this results in a minimum distance of 111 meter between the laying barge and the location where the pipes touch the ground (see Figure 4.5).

D.6. Design for pipeline stability on the seabed

Certain wave and current forces will act on the pipeline. For this analysis those forces are considered uniformly distributed along the pipelines. Wave forces are not considered since the pipelines will be entrenched for the entire stretch where wave forces are of influence. Moreover, the wave forces act in longitudinal direction of the pipeline, whereas perpendicular forces are more important for the stability (for longitudinal direction the $sin\ \alpha$ becomes 0, see (D.9) and (D.10)). Currents however do play an important role for the stability. Drag and lift forces per meter pipe length are calculated in (D.9) and (D.10) respectively.

$$F_D = \frac{C_D \rho v^2 D\ sin^2\alpha}{2} \tag{D.9}$$

$$F_L = \frac{C_L \rho v^2 D\ sin^2\alpha}{2} \tag{D.10}$$

Where:

ρ = Density of seawater (1035 kg/m^3)
v = Design current velocity (1 m/s)
D = Outside diameter of pipeline (2500 mm)
α = Angle of current incidence
C_D = Current drag coefficient
C_L = Current lift coefficient

C_D and C_L are 0.7 and 0.6, respectively, and are both derived from figures A.4.5.2 and A.4.5.3 of the technical catalogue of PipeLife Norway [PipeLife, 2002]. From (D.9) and (D.10) it follows that the angle of incidence of the currents is of major influence to the forces acting on the pipes. Unfortunately, the direction of the pipeline is perpendicular to the prevailing direction of the currents, leading to maximum forces. It needs to be noted that the current lift coefficient C_L largely depends on the distance of the pipe to the seabed. The number 0.6 is based on a pipeline lying directly on the seabed, while in case of a pipeline-seabed distance of $0.5 \times D$, this number is reduced by a factor 10 already. The design flow velocity (1 m/s) is based on scarce data

at water surface level from a jetty located 500 m off the coast. At this location the maximum measured flow velocity is 0.5 m/s over a year and a safety factor 2 was used to result in the above mentioned 1.0 m/s. Filling in the parameters leads to $F_D = 897\ N/m$ and $F_L = 769\ N/m$.
Next the vertical forces on the seabed are calculated, the vertical forces consist of 4 parts: 1) The upward lift due to the density difference between HDPE and seawater. 2) Upward lift force from currents 3) upward lift from air, trapped inside the pipeline. 4) The downward force from concrete ballast weights. The four contributors and the acting direction of the forces are combined in (D.11).

$$F_v = \uparrow F_{HDPE} + \uparrow F_L + \uparrow F_{air} + \downarrow F_{concrete} \tag{D.11}$$

The design of the concrete weights is treated in D.2. The submerged weight of the blocks is 7,545 kg with one block every 5 meters. The force of the concrete weights per meter is subsequently calculated by multiplication with gravitational constant g and division by 5 resulting in a load of 14808 N/m. The upward directed force originating from the HDPE material is calculated in (D.12).

$$\begin{aligned} F_{HDPE} &= \pi t(D-t)(\rho_{sea} - \rho_{hdpe}) \\ &= \pi \times 0.0995(2.5 - 0.0995) \times (1025 - 960) \\ &= 478\ N/m \end{aligned} \tag{D.12}$$

Where t is the flange thickness (0.0995 m) of the HDPE pipes, D the outside diameter (2.5 m), and ρ_{sea} and ρ_{hdpe} the density of seawater and HDPE respectively. Combining the above leads to a net downward force F_v:

$$F_v = -478 - 769 - 0 + 14808 = 13560\ N$$

For vertical instability of the pipeline a buoyancy force equal to or larger than this force needs to be present. The area of air (A_a) inside the pipe necessary to do so is 13560/9.81/1025 = 1.35 m^2. The inner area of the pipe (A_i) equals $\pi/4(D-2t) = 4.16\ m^2$. The air filling rate of the pipe ($A_a/A_i \times 100\%$)and must be lower than 32% for vertical stability. This rate is defined as the areal percentage of air in a section of pipe divided by the inner volume. Another check is conducted for horizontal stability. The pipeline resistance to horizontal current forces is defined as R = μF_v. With μ = the friction coefficient between the anchor blocks and the seabed. This value is approximately 0.2 for circular weights according to table A.4.2.1 from the PipeLife technical brochure. Horizontal instability occurs if horizontal current forces exceed horizontal resistance:

$$F_h \geq R = \mu F_v = 0.2 \times 13560 = 2712\ N/m$$

Since the horizontal current forces are only 897 N/m, the structure is safe with a factor of safety of 3. This safety factor changes when air pockets are present in the pipeline but as long as the air filling rate does not exceed 22%, no horizontal movement of the pipes will occur.

D.7. Design concrete water conveyor

For the concrete scenario, using reinforced concrete as a pipeline material was investigated. This is merely done in a superficial way to give a (very) rough estimation of the possibility of using concrete. We contacted an expert at Dura Vermeer who advised us to no further investigate this option for the following reasons:

- An entire construction yard needs to be built (with dikes) with an opening door to sea to float the elements for transport.
- Producing all the elements and sinking them at the proposed location would take years, leading to extensive building costs.
- The bed of the ocean needs to be equalised for the entire stretch of 4 km.

He added that with the tunnel element sizes we had proposed to him the costs would be comparable to many dutch river tunnels and would probably be over 1 billion USD, much more than HDPE.

On top of the above, this project would be even more expensive since additional protection of the reinforcement steel against corrosion needs to be installed: Not only against salinity but also against the disinfecting chloride used to prevent fouling.

In contrast with the costs and the corrosion resistance, concrete tunnels show good opportunity when it comes to friction head losses. Losses scale in a relation 1:1/x with the hydraulic diameter of the pipe. The hydraulic diameter for a rectangular concrete tunnel is defined as the cross-sectional area of the flow divided by the wetted perimeter. If the concrete is casted in large shapes, the hydraulic diameter increases and consequently does the friction decrease. In Figure D.3 friction head losses versus velocity are shown for two HDPE pipelines and a concrete pipeline. Taking all of this into account the decision was made to no longer investigate the concrete scenario.

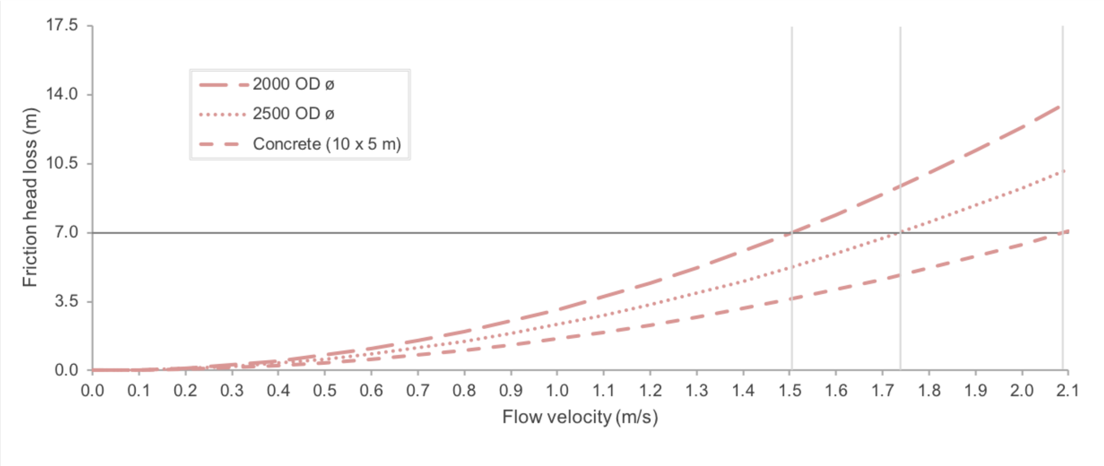


Figure D.3: Friction head losses calculated for different flow velocities. Two HDPE pipelines and a concrete conveyor are compared.

D.8. Connection to the system

As overtopping is allowed to some extent, a short calculation of the crest freeboard using the European Overtopping Manual [der Meer et al., 2016] is calculated according to D.13.

$$\frac{q}{\sqrt{g \times H_{m0}^3}} = a \times e^{(-(b \times \frac{R_c}{\gamma \times H_{m0}})^{1.3})} \tag{D.13}$$

Where:

q = specific discharge ($m^3 \times m^{-1} \times s^{-1}$)
g = gravitational acceleration, 9.81 (m/s^2)
H_{m0} = significant wave height (m)
a, b, c = empirical coefficients, 0.047; 2.35, 1.3 (−)
R_c = crest freeboard (m)
γ = geometrical parameter, 1 (−)

For the specific discharge a value of 0.2 $m^3/m/s$ is assumed as the crest of the sea wall is well protected. This follows directly from the European Overtopping Manual ([der Meer et al., 2016]). From Figure B.19 a significant wave height inside the breakwaters of 0.05 m can be seen. By extrapolating to the significant wave height of Hs < 1 m that is observed 98% of the time, a significant wave height inside the breakwaters of 0.11 m can be found. With these numbers a required crest freeboard of $R_c = 0.12$ m is found.

D.9. Intake head

D.9.1. Design parameters

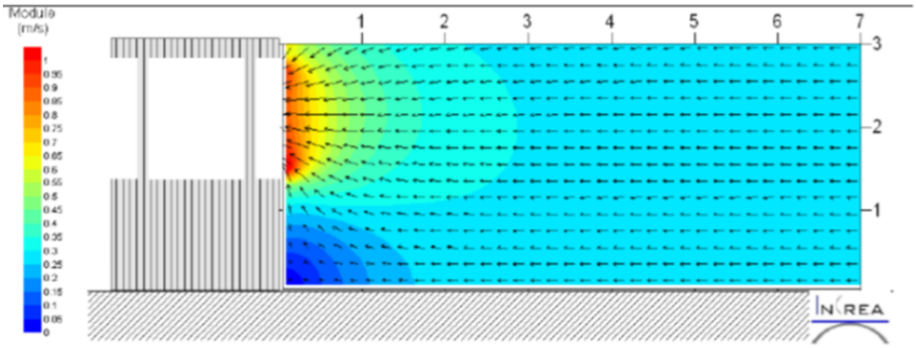


Figure D.4: Hydrodynamic model of a reference water intake. [Pita, 2011]

Item	
Velocity in the pipeline (m/s)	0.60 - 1.50
Outer diameter (m)	2.50
Inner diameter (m)	2.30
Opening area (m^2)	4.15
TWall thickness pipeline (m)	0.10

Table D.2: Pipeline specifications

D.9.2. Intake head design

Window area estimation

The maximum discharge trough the pipeline is

$$Q = V_{pipe} \times A_{pipe} = 1.5 \times 4.15 = 6.23 m^3$$

This means that the discharge through the bar screens must also be 6.2 m^3. Flow velocity through the windows will be half of pipe velocity because of the seiphon principle. So,

$$V_{intake} = \frac{V_{pipe}}{2} = \frac{1.5}{2} = 0.75 m/s$$

As the flow velocity through the band screen is 0.75 m/s, the total window area needs to be:

$$A_{total,windows} = \frac{Q}{V} = \frac{6.23}{0.75} = 8.30 m^2$$

Volume of concrete

- The total cylinder volume $V_{cylinder}$ is:

$$V_{cylinder} = V_{solid} - V_{windows} - V_{open,pipe} =$$

$$((\pi \times (r_{outer}^2 - r_{inner}^2) \times h_{cylinder}) - (A_{total,windows} \times t_{cylinder}) - (\pi \times r_{pipe,outer}^2 \times t_{cylinder}) =$$

$$((\pi \times (2^2 - 1.6^2)) \times 4.5) - (8.30 \times 0.4) - (\pi \times 1.25^2 \times 0.4) = 15.07 m^3$$

- The base volume V_{base} is:

$$V_{base} = \pi \times r_{base}^2 \times h_{base} =$$

$$\pi \times 3^2 \times 0.5 = 14.14 m^3$$

Adding up the two volumes will result in a total volume of the inlet structure V_{total} of:

$$V_{total} = V_{cylinder} + V_{base} = 15.07 + 14.14 = 29.21 m^3$$

Steel reinforcement

- **Cylinder** - A steel duplex mesh is placed on the outer diameter of the cylinder. For simplicity, the windows are neglected at first, but subtracted in the end of the calculation. First the circumference of the cylinder is estimated.

  $$O_{cylinder} = 2 \times \pi \times r_{outer} = 2 \times \pi\ 2 = 12.57\ m$$

  The bars have a diameter of 20 mm and the space between each bar is 30 mm.

  The number of vertical placed bars is:

  $$bars = \frac{12.57}{0.05} - 1 = 250\ bars$$

  With corresponding length:

  $$L_{cylinder,vert} = 250 * 4.5 = 1125\ m$$

  Horizontal, circular bars:

  $$bars = \frac{4.5}{0.05} = 90\ bars$$

  With corresponding length:

  $$L_{cylinder,hor} = bars \times O_{cylinder} = 90 \times 12.57 = 1131\ m$$

  To subtract the steel bars in the window area:

  $$L_{windows} = 2 \times (8 \times (\frac{l_{window}}{0.05}) \times 1) = 320\ m$$

  Total length of both the vertical and the horizontal bars:

  $$L_{cylinder,total} = L_{cylinder,vert} + L_{cylinder,hor} - L_{windows} = 1125 + 1131 - 320 - = 1936\ m$$

- **Base** - For the base two steel meshes are used. One on the upside of the base and one on the downside. The proportion of the circular area to the rectangular area with 6 m diameter and 6 × 6 m respectively is:

  $$\frac{\pi \times\ r^2_{base}}{b \times l} = \frac{28.27}{36} = 0.7854$$

  Then first the total length of the steel reinforcement bars is calculated for the entire rectangle and then it is multiplied by the circle/rectangle proportion.

  $$bars = (\frac{6}{0.05}) \times 2 = 240$$

  $$L_{base,mesh} = 240 \times L_{bar} = 240 \times 6 = 1440\ m$$

  Upside and downside meshes for the circle area:

  $$L_{base,total} = ((1440 \times 2)) \times 0.7854 = 2262\ m$$

- **Intake head** The total length of the steel bars in the duplex meshes in the entire structure is the sum of the length of the steel bars in the cylinder and in the base:

  $$L_{total} = L_{cylinder,total} + L_{base,total} = 1936 + 2262 = 4198\ m$$

D.9.3. Construction

Figure D.5: Transportation of the structures.

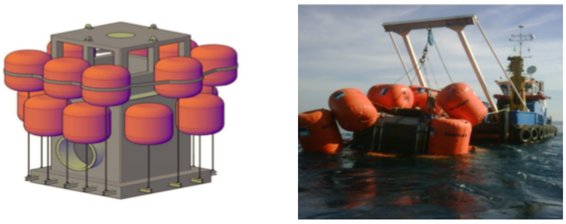


Figure D.6: Auxiliary floats.

Figure D.7: Sinking of the structures.

E

Economic Feasibility

E.1. CRT-model

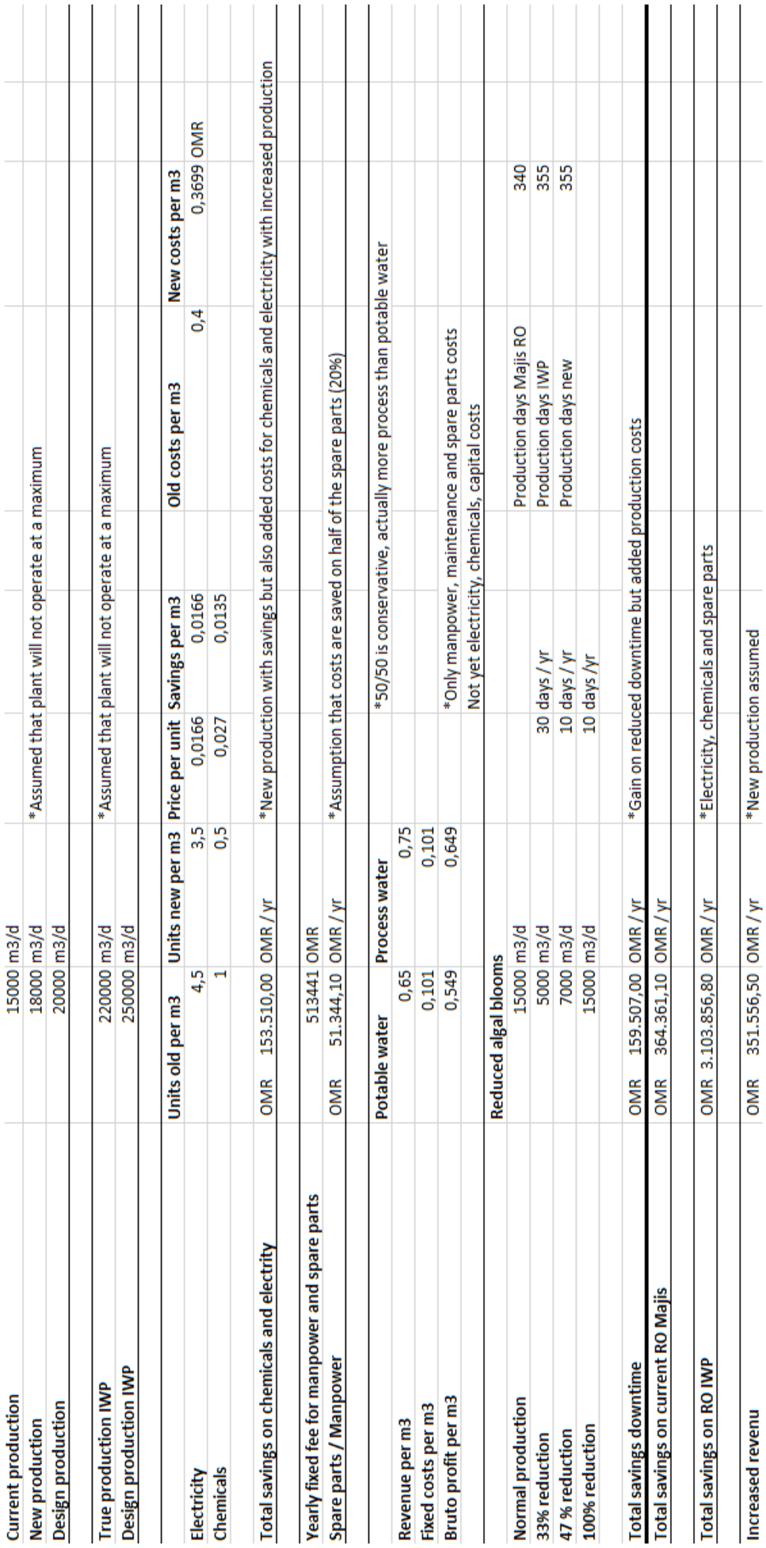
The costs for electricity differ over the time of the day and over the year. The costs are based on Cost Reflective Tariff (CRT) and were collected from [MEDC Oman, 2018]. The prices accordingly have been averaged over the months and the data is summarised in Table E.1. The prices in the summer months are higher than the prices in the winter months. This is because the electricity usage in these months is higher due to mainly air conditioning.

No incremental price is considered in this model. CRT increased the original electricity price to the full cost of supplying electricity excluding the governmental subsidy.

Month	Price electricity generation (OMR/KWh)	Transmission charge (kW peak load)	Distribution charge (OMR/KWh)
Jan	0.0120	1.05	0.007
Feb	0.0120	1.05	0.007
Mar	0.0120	1.05	0.007
Apr	0.0140	1.05	0.007
May	0.0255	1.05	0.007
Jun	0.0255	1.05	0.007
Jul	0.0255	1.05	0.007
Aug	0.0175	1.05	0.007
Sep	0.0175	1.05	0.007
Oct	0.0140	1.05	0.007
Nov	0.0120	1.05	0.007
Dec	0.0120	1.05	0.007

Table E.1: Electricity prices per month

E.2. RO-plant



Current production	15000	m3/d						
New production	18000	m3/d	*Assumed that plant will not operate at a maximum					
Design production	20000	m3/d						
True production IWP	220000	m3/d	*Assumed that plant will not operate at a maximum					
Design production IWP	250000	m3/d						
	Units old per m3	**Units new per m3**	**Price per unit**	**Savings per m3**		**Old costs per m3**	**New costs per m3**	
Electricity	4,5	3,5	0,0166	0,0166		0,4	0,3699	OMR
Chemicals	1	0,5	0,027	0,0135				
Total savings on chemicals and electrity	OMR 153.510,00	OMR / yr	*New production with savings but also added costs for chemicals and electricity with increased production					
Yearly fixed fee for manpower and spare parts	513441	OMR						
Spare parts / Manpower	OMR 51.344,10	OMR / yr	*Assumption that costs are saved on half of the spare parts (20%)					
	Potable water	**Process water**		*50/50 is conservative, actually more process than potable water				
Revenue per m3	0,65	0,75						
Fixed costs per m3	0,101	0,101						
Bruto profit per m3	0,549	0,649		*Only manpower, maintenance and spare parts costs				
				Not yet electricity, chemicals, capital costs				
	Reduced algal blooms							
Normal production	15000	m3/d				Production days Majis RO	340	
33% reduction	5000	m3/d	30	days / yr		Production days IWP	355	
47 % reduction	7000	m3/d	10	days / yr		Production days new	355	
100% reduction	15000	m3/d	10	days /yr				
Total savings downtime	OMR 159.507,00	OMR / yr	*Gain on reduced downtime but added production costs					
Total savings on current RO Majis	OMR 364.361,10	OMR / yr						
Total savings on RO IWP	OMR 3.103.856,80	OMR / yr	*Electricity, chemicals and spare parts					
Increased revenu	OMR 351.556,50	OMR / yr	*New production assumed					

Figure E.1: Computation of the gains for the RO-plants

For both the Majis RO-plant and the IWP the assumed true productions were taken for computations. Currently the first, respectively, cannot produce its design capacity due to the poor water quality of the extracted water. Majis Business developer Abdullah Al Sadi expects that this will change with the deep seawater and based on his expectations it is assumed that the production will increase from 15,000 m^3/d to 18,000 m^3/d. There is however little data to back this up, and the data that is available contradicts these expectations. The enclosed bay offers long retention times for the water so that turbidity can sink to the bottom. The water at the intake is therefore rather free of turbidity, compared to the water at the proposed deep seawater intake. As the data on this topic is considered insufficient, it is recommended to dive into this with future research. A hypothetical calculation is now made for the possible benefits for the RO-plants.

All input numbers in this calculation were provided by Majis as contact with the right people at the IWP was not established within the project span. Some outcomes are extrapolated to the IWP as they are expected to also be beneficial there. This will be highlighted in the explanation below.

From the same interview with mr. Al Sadi it followed that with cleaner water, an estimated 1 kWh per m^3 and half of the dosed chemicals can be saved. Multiplied with the price for each, provided by Majis, this gives a saving of 153,510 OMR/yr. The costs for the manpower and spare parts are set and do not vary with the produced amount of water. This means that it is even paid when nothing is produced, f.e. during downtime caused by algal blooms. With less solids in the water, the filters will clog less, will need less maintenance and less repairs. The costs that can be saved are 51,344 OMR/yr.

More research has to be done on HABs, as is described in Chapter 2.4. The savings that occur if downtime of the RO-plant can be prevented are therefore mainly hypothetical. These costs are only taken for the Majis RO-plant as it is assumed that the IWP, being a newer and more modern plant, copes better with algal blooms. The days of downtime and reduction give the gain in production that can be achieved. This increased production leads to an increased revenue of 159,507 OMR/yr.

For the IWP, having a much larger true production of 220,000 m^3/d these found results can be extrapolated. The savings on electricity, chemicals, manpower and spare parts, together with the assumed resistance against algal blooms, results in total assumed savings for the IWP of 3,103,857 OMR/yr.

The revenue created by the increased production consists of the price of sold cubic metres minus the productions costs. Concluding, in total the savings then make up 3,468,218 OMR/yr and the increased production covers 351,557 OMR/yr.

The unknown parameters in these calculations are the true productions of both plants and the fact whether the IWP is affected by algal blooms and to what extent. Furthermore, the choice to take the produced amounts potable water and process water equal is a rather conservative one. In reality 60% of the production will be process water and 40% potable water. This will account for some safety margin.

E.3. Power plants

For the power plants the costs will be won through the fact that the power plants can produce energy more efficiently. There are two ways to calculate the benefits for the power plants with the more efficient production. Firstly costs can be saved on gas usage. When this manner is used it is than assumed that the demand for energy does not change. The increased production of the more efficient working steam turbines should be able to make up for the decrease of production in the gas turbines when less gas is used.

Efficiency per degree / industry	0,40%
Real efficiency per degree	0,13%
Temperature diff. Summer	7,7
Efficiency gain Summer	**1,03%**
Temperature diff. Winter	3,2
Efficiency gain Winter	**0,43%**
Average efficiency gain	**0,73%**

Table E.2: Efficiency gain power plants through temperature difference

Through the efficiency gain the in Table E.2, the increase in power production can be calculated through the known power production from the reports Sohar Aluminium, Al Batinah Power and Sohar Power Plant. The efficiency gain is multiplied with these. The efficiency gain in the summer is 1.03% and in the winter 0.43%. In the winter the the power plants works on 85% [Sohar Power Plant] of its capacity. This can be seen in the production rates in the winter. In Table E.3 the increased power plant production can be found.

	Summer		**Winter**		**Average**	
Power plant efficiency	Old Power	New Power	Old Power	New Power	Old Power	New Power
Sohar Power Plant	585	591	497	499	541	545
Al Batinah Power Company	737	745	627	630	682	687
Sohar Aluminium Power Plant	1000	1010	850	854	925	932
Total	2322	2346	1974	1982	2148	2164

Table E.3: Power gain per Power plant

It is assumed that the demand for energy does not change and will be 2148 MW for these three power plants. From the power production 2/3 is from the gas turbines and 1/3 is from the steam turbines. This means of the total power 1432 MW is from gas turbines and 716 is from steam turbines. To calculate the new contribution of gas with the increased efficiency of the steam turbines, 2148 MW is divided by 1.0073 and multiplied with 2/3. The new contribution through gas is 1422 MW and the new contribution through steam is 726 MW.

	Old (MW)	New (MW)
Power production gas turbines	1432	1422
Power production steam turbines	716	726

Table E.4: New gas and steam turbine contribution

In Table E.4 the savings on the gas can be found. The gas price is 3.22 USD per 293.1 kWh [gas]. The costs for producing the new amount of gas were subtracted form the old costs. When this multiplied for over the whole year an amount of 1 million USD will be saved.

The second way of calculating the benefits was by multiplying the extra produced electricity with the price of electricity generation of the CRT-costs in Table E.1. This can be done because in the CRT-table the costs are shown to produce electricity. The results can be seen in Table E.5 and E.6.

Month	CRT-costs (OMR/kW)	Power production (MW)	Revenue per month ($\times 10^6$ OMR/$month$)
Jan	0,0120	1974	1.71
Feb	0,0120	1974	1.71
Mar	0,0120	1974	1.71
Apr	0,0140	2322	2.34
May	0,0255	2322	4.26
Jun	0,0255	2322	4.26
Jul	0,0255	2322	4.26
Aug	0,0175	2322	2.92
Sep	0,0175	2322	2.92
Oct	0,0140	1974	1.98
Nov	0,0120	1974	1.71
Dec	0,0120	1974	1.71
Total			31.50

Table E.5: Revenue with the CRT-model with the current Power production

Month	CRT-costs (OMR/kW)	Power production (MW)	Revenue per month ($\times 10^6$ OMR/month)
Jan	0.0120	1982	1.71
Feb	0.0120	1982	1.71
Mar	0.0120	1982	1.71
Apr	0.0140	2346	2.37
May	0.0255	2346	4.31
Jun	0.0255	2346	4.31
Jul	0.0255	2346	4.31
Aug	0.0175	2346	2.96
Sep	0.0175	2346	2.96
Oct	0.0140	1982	2.00
Nov	0.0120	1982	1.71
Dec	0.0120	1982	1.71
Total			31.76

Table E.6: Revenue with the CRT-model with the new Power production

E.4. Heat dissipation capacity

With the calculated reduce in flow and pumping power the decrease of costs in electricity can be calculated. This is done by multiplying the decrease of pumping energy with the Electricity costs per hour and distribution charge per hour of the CRT-model in Table E.1. Thereafter the costs are multiplied with 24h and 30 days to get the total costs of electricity usage in a month. In Table E.7, E.8, E.9 and E.10 the costs per month and the total costs per year can be seen. Table E.7 and E.8 are for the present situation. Table E.9 and E.10 are for the future situation when SWIPS I and SWIPS II are both fully occupied.

Month	Pumping Energy (MW)	CRT-Costs (OMR/hour)	Distribution charge (OMR/$hour$)	Total (OMR/$month$)
Jan	16	187	109	212,760
Feb	16	187	109	212,760
Mar	16	187	109	212,760
Apr	16	218	109	235,156
May	16	397	109	363,931
Jun	16	397	109	363,931
Jul	16	397	109	363,931
Aug	16	272	109	274,348
Sep	16	272	109	274,348
Oct	16	218	109	235,156
Nov	16	187	109	212,760
Dec	16	187	109	212,760
Total				3,174,602

Table E.7: Present costs heat dissipation water

Month	Pumping Energy (MW)	CRT-Costs (OMR/hour)	Distribution charge (OMR/$hour$)	Total (OMR/$month$)
Jan	15	178	104	202,629
Feb	15	178	104	202,629
Mar	15	178	104	202,629
Apr	12	161	81	174,189
May	12	294	81	269,579
Jun	12	294	81	269,579
Jul	9	242	66	221,909
Aug	9	166	66	167,286
Sep	9	166	66	167,286
Oct	11	157	78	169,177
Nov	11	134	78	153,065
Dec	11	134	78	153,065
Total	141	2281	987	2,353,020

Table E.8: Costs heat dissipation water with deep sea water intake for present situation

Month	Pumping Energy (MW)	CRT-Costs (OMR/hour)	Distribution charge (OMR/$hour$)	Total (OMR/$month$)
Jan	59	707	412	805,448
Feb	59	707	412	805,448
Mar	59	707	412	805,448
Apr	59	824	412	890,232
May	59	1501	412	1,377,741
Jun	59	1501	412	1,377,741
Jul	59	1501	412	1,377,741
Aug	59	1030	412	1,038,604
Sep	59	1030	412	1,038,604
Oct	59	824	412	890,232
Nov	59	707	412	805,448
Dec	59	707	412	805,448
Total				12,018,138

Table E.9: Future costs heat dissipation water

Month	Pumping Energy (MW)	CRT-Costs (OMR/hour)	Distribution charge (OMR/$hour$)	Total (OMR/$month$)
Jan	56	673	393	767,094
Feb	56	673	393	767,094
Mar	56	673	393	767,094
Apr	44	611	305	659,431
May	44	1112	305	1,020,549
Jun	44	1112	305	1,020,549
Jul	36	915	251	840,086
Aug	36	628	251	633,295
Sep	36	628	251	633,295
Oct	42	593	297	640,455
Nov	42	508	297	579,459
Dec	42	508	297	579,459
Total				8,907,860

Table E.10: Costs heat dissipation water with deep sea water intake for future situation

E.5. Intake head

Precast concrete
Precast concrete is per 1 m^3 18 OMR.

$$C_{concrete} = 24 \times V_{total,concrete} \times 18 = 29.21 \times 18 = 12618,.72\ OMR$$

Steel reinforcement
The steel bars have a weight per running meter of 2,47 kg/m. 1 ton of steel bars is 240 OMR.

$$C_{reinforcement} = 24 \times L_{total,reinf} \times 2,47 \times 0.0011 \times 240 = 65836.8\ OMR$$

Band screen
1 m^2 of super duplex steel mesh is 5 OMR. There are eight windows with dimensions 1 × 1 m in one intake head so the costs for the band screens are:

$$C_{screen} = 24 \times 8 \times 5 = 960\ OMR$$

Pile foundation
1 m^3 of pile filling (concrete) is 720 OMR. Rates are given by Abdullah Al Sadi (Majis).

$$C_{foundation} = 24 \times \pi \times 0.3^2 \times 15 \times 720 = 73286.88$$

Construction
Consists of transportation and sinking costs and is estimated on 1200 OMR. For 24 intake heads this becomes 28800 OMR.

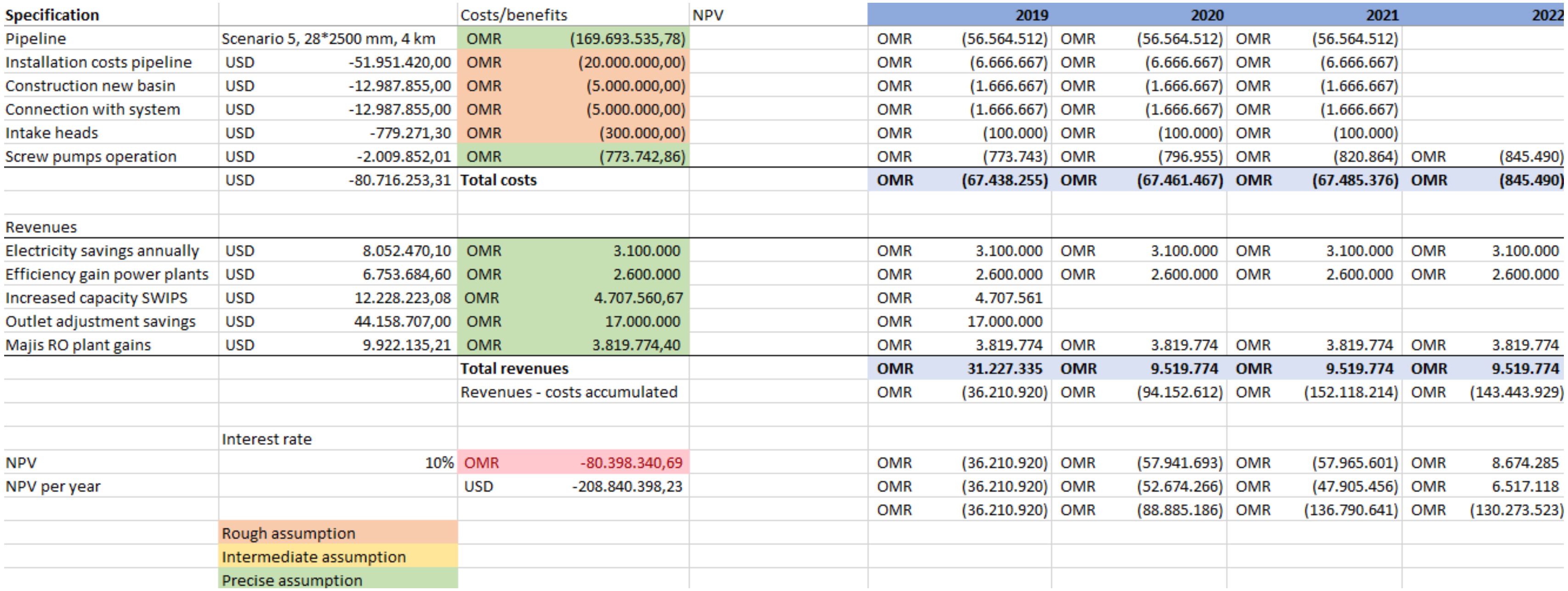
Total costs
Table E.11 gives the cost estimation results if 24 pipelines are installed, and consequently, 24 intake heads.

$$1\ OMR = 2.6\ USD$$

Item	Costs ($\times 10^3$ OMR)	Costs ($\times 10^3$ USD)	
Precast concrete	12.6	32.8	
Steel reinforcement	65.8	17.1	
Band screen	1.0	2.6	
Pile foundation	73.3	190.6	
Construction	28.8	74.9	+
Total	181.5	471.9	

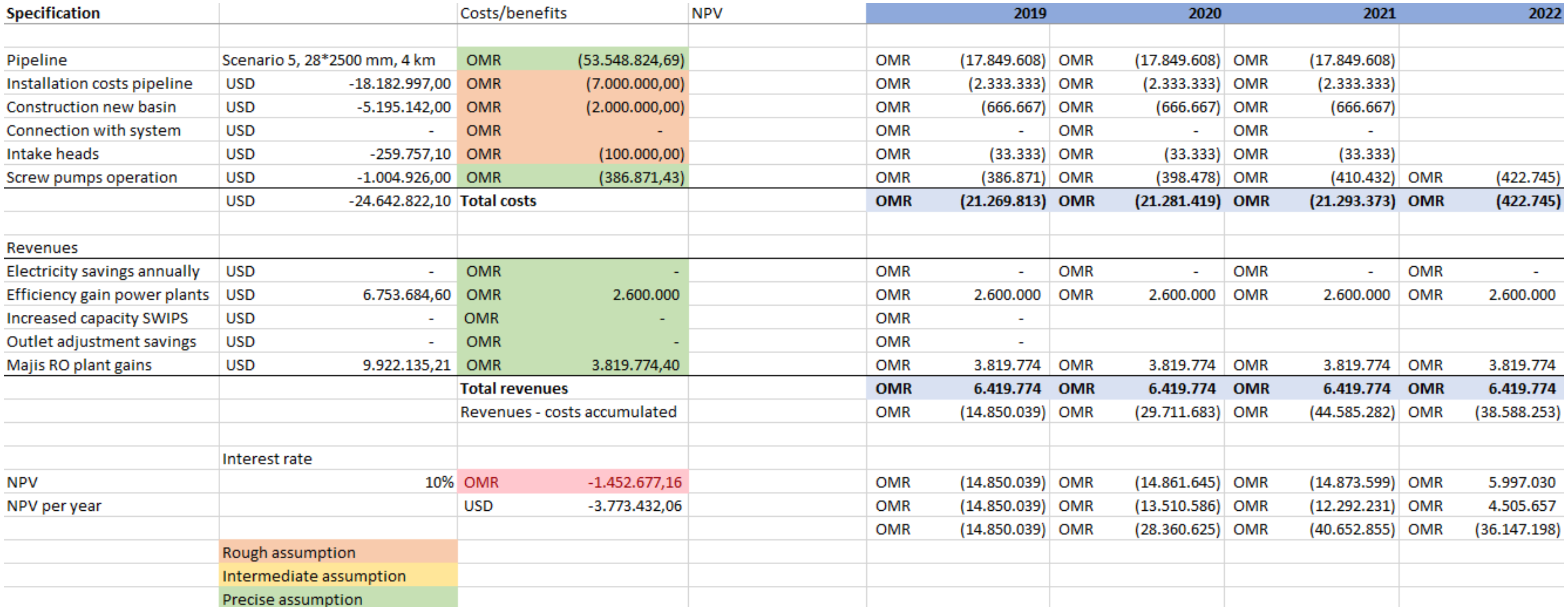
Table E.11: Cost estimation for 24 intake heads.

E.6. Financial model



Specification			Costs/benefits		NPV		**2019**		**2020**		**2021**		**2022**
Pipeline	Scenario 5, 28*2500 mm, 4 km		OMR	(169.693.535,78)		OMR	(56.564.512)	OMR	(56.564.512)	OMR	(56.564.512)		
Installation costs pipeline	USD	-51.951.420,00	OMR	(20.000.000,00)		OMR	(6.666.667)	OMR	(6.666.667)	OMR	(6.666.667)		
Construction new basin	USD	-12.987.855,00	OMR	(5.000.000,00)		OMR	(1.666.667)	OMR	(1.666.667)	OMR	(1.666.667)		
Connection with system	USD	-12.987.855,00	OMR	(5.000.000,00)		OMR	(1.666.667)	OMR	(1.666.667)	OMR	(1.666.667)		
Intake heads	USD	-779.271,30	OMR	(300.000,00)		OMR	(100.000)	OMR	(100.000)	OMR	(100.000)		
Screw pumps operation	USD	-2.009.852,01	OMR	(773.742,86)		OMR	(773.743)	OMR	(796.955)	OMR	(820.864)	OMR	(845.490)
	USD	-80.716.253,31	**Total costs**			**OMR**	**(67.438.255)**	**OMR**	**(67.461.467)**	**OMR**	**(67.485.376)**	**OMR**	**(845.490)**
Revenues													
Electricity savings annually	USD	8.052.470,10	OMR	3.100.000		OMR	3.100.000	OMR	3.100.000	OMR	3.100.000	OMR	3.100.000
Efficiency gain power plants	USD	6.753.684,60	OMR	2.600.000		OMR	2.600.000	OMR	2.600.000	OMR	2.600.000	OMR	2.600.000
Increased capacity SWIPS	USD	12.228.223,08	OMR	4.707.560,67		OMR	4.707.561						
Outlet adjustment savings	USD	44.158.707,00	OMR	17.000.000		OMR	17.000.000						
Majis RO plant gains	USD	9.922.135,21	OMR	3.819.774,40		OMR	3.819.774	OMR	3.819.774	OMR	3.819.774	OMR	3.819.774
			Total revenues			**OMR**	**31.227.335**	**OMR**	**9.519.774**	**OMR**	**9.519.774**	**OMR**	**9.519.774**
			Revenues - costs accumulated			OMR	(36.210.920)	OMR	(94.152.612)	OMR	(152.118.214)	OMR	(143.443.929)
	Interest rate												
NPV		10%	OMR	-80.398.340,69		OMR	(36.210.920)	OMR	(57.941.693)	OMR	(57.965.601)	OMR	8.674.285
NPV per year			USD	-208.840.398,23		OMR	(36.210.920)	OMR	(52.674.266)	OMR	(47.905.456)	OMR	6.517.118
						OMR	(36.210.920)	OMR	(88.885.186)	OMR	(136.790.641)	OMR	(130.273.523)
	Rough assumption												
	Intermediate assumption												
	Precise assumption												

Figure E.2: Impression of the model that was used to compute the NPV for the large-scale connection



Specification			Costs/benefits		NPV		2019		2020		2021		2022
Pipeline	Scenario 5, 28*2500 mm, 4 km		OMR	(53.548.824,69)		OMR	(17.849.608)	OMR	(17.849.608)	OMR	(17.849.608)		
Installation costs pipeline	USD	-18.182.997,00	OMR	(7.000.000,00)		OMR	(2.333.333)	OMR	(2.333.333)	OMR	(2.333.333)		
Construction new basin	USD	-5.195.142,00	OMR	(2.000.000,00)		OMR	(666.667)	OMR	(666.667)	OMR	(666.667)		
Connection with system	USD	-	OMR	-		OMR	-	OMR	-	OMR	-		
Intake heads	USD	-259.757,10	OMR	(100.000,00)		OMR	(33.333)	OMR	(33.333)	OMR	(33.333)		
Screw pumps operation	USD	-1.004.926,00	OMR	(386.871,43)		OMR	(386.871)	OMR	(398.478)	OMR	(410.432)	OMR	(422.745)
	USD	-24.642.822,10	**Total costs**			**OMR**	**(21.269.813)**	**OMR**	**(21.281.419)**	**OMR**	**(21.293.373)**	**OMR**	**(422.745)**
Revenues													
Electricity savings annually	USD	-	OMR	-		OMR	-	OMR	-	OMR	-	OMR	-
Efficiency gain power plants	USD	6.753.684,60	OMR	2.600.000		OMR	2.600.000	OMR	2.600.000	OMR	2.600.000	OMR	2.600.000
Increased capacity SWIPS	USD	-	OMR	-		OMR	-						
Outlet adjustment savings	USD	-	OMR	-		OMR	-						
Majis RO plant gains	USD	9.922.135,21	OMR	3.819.774,40		OMR	3.819.774	OMR	3.819.774	OMR	3.819.774	OMR	3.819.774
			Total revenues			**OMR**	**6.419.774**	**OMR**	**6.419.774**	**OMR**	**6.419.774**	**OMR**	**6.419.774**
			Revenues - costs accumulated			OMR	(14.850.039)	OMR	(29.711.683)	OMR	(44.585.282)	OMR	(38.588.253)
	Interest rate												
NPV		10%	OMR	-1.452.677,16		OMR	(14.850.039)	OMR	(14.861.645)	OMR	(14.873.599)	OMR	5.997.030
NPV per year			USD	-3.773.432,06		OMR	(14.850.039)	OMR	(13.510.586)	OMR	(12.292.231)	OMR	4.505.657
						OMR	(14.850.039)	OMR	(28.360.625)	OMR	(40.652.855)	OMR	(36.147.198)
	Rough assumption												
	Intermediate assumption												
	Precise assumption												

Figure E.3: Impression of the model that was used to compute the NPV for the limited-scale connection

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