


Towards Sustainable Water Management in Sohar, Oman

Master of Hydrology Thesis
Environmental Hydrogeology Track

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1. Introduction

1.1 Oman and water

Oman is located on the eastern tip of the Arabian Peninsula. Along its over 2000 kilometer long coastline one finds the Arabian Sea in the east and the Gulf of Oman more to the north-east. It shares its western border with three neighboring countries. From north to south the United Arab Emirates, Saudi Arabia and Yemen. Much like these neighbors Oman's topography consists primarily of deserts as a result of an arid climate. The most famous exception to this is the country's south-eastern tip, in the Dhofar governate, which has much higher average precipitation due to the monsoon rains.

Figure 1.1

For forty years now Oman has been ruled by Sultan Qaboos Bin Said Al Said. During his rule Oman has experienced an extremely rapid development. There are numerous anecdotes which describe the incredible pace at which this development has taken place. One of the most striking is the fact that before the current Sultan came into power Oman knew only 10 kilometer of tarmac road. This development was largely enabled by the exploitation of the county's most abundant natural resources; oil and gas. However, from the onset of his rule the Sultan has continuously stressed the importance of another natural resource; water. In 1992, on the 22nd anniversary of his rule, the Sultan said 'we must stress that water is an invaluable national resource which must not be thoughtlessly squandered. Its conservation is a sacred national duty for every one of us. The co-operation of you all in our Government policies in this connection is vital'.

With this focus on the preservation of water resources the Sultan honors a long standing Omani tradition. In spite of the lack of significant fresh water bodies in Oman, the Omani's long ago found a way to extract water from aquifers in a sustainable way. They used what are called ‘Aflaj’. They are small channels dug into mountain or hill sides. This is done nearly horizontally until the water table is reached. The small angle at which a Falaj (Falaj = Singular, Aflaj = Plural) is dug enables the water to be carried over long distances, occasionally over tens of kilometers. Figure 1.2 explains the idea of an aflaj more clearly. This system, which is estimated to exist for about 2 millennia in Oman, gave the inhabitants of Oman clean drinking water and moreover allowed them to practice agriculture. To this day many farmers in Oman still rely on this ancient system for irrigation water. The water that flows from the Falaj was traditionally divided among villagers with the help of an intricate time based system which was guided by the positions of stars. The high level of sustainability of this system is proven by the fact that many of the present aflaj are thought to be over 1000 years old yet about 4000 of those still provide a constant flow of water to this day.

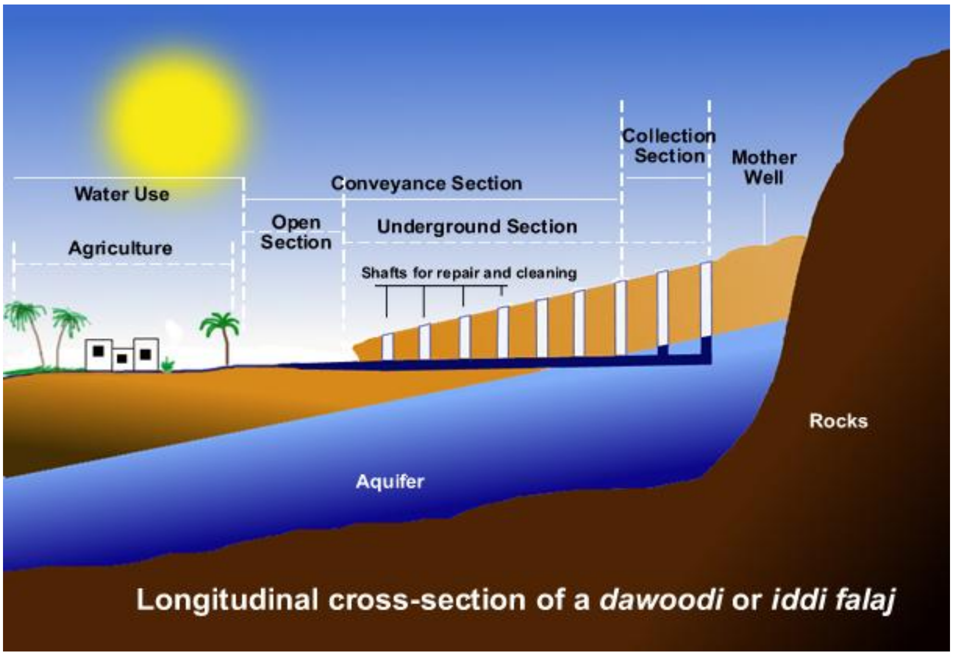


Figure 1.2; The workings of a Falaj (actual picture can be found on the cover of this paper)

As said no significant lakes or rivers exist in Oman. Yet the country is known for intense flash floods in mountain areas which can occur after rainfall events. The streams that form after rainfall are called Wadis and follow dry river beds but the exact paths that they take are hard to predict. When precipitation is sudden and intense these Wadis can cause major damage to infrastructure and can be a real danger to the people. In the last couple of years Oman experienced some of the worst floods in recent history after Hurricane Gonu hit its eastern shore in 2007 and another major hurricane caused heavy flooding in 2009. Despite ongoing efforts by the Omani government to mitigate the threat of these floods, predominantly by building flood protection dams, they still managed to inflict great damage.

1.2 Sohar

Sohar is the main city of one of Oman’s second most populous province, Al-Batinah. The Al-Batinah province is situated in the north west of the country and sits on a plain in between the Al Hajar mountain range and the gulf of Oman. The Al Hajar mountain range is about 500 kilometers in length, has its peak at 2980 meters and runs parallel to the coastline. This mountain range has a significant impact on the hydrological cycle of the province. Precipitation in and around these mountains is slightly higher than in the rest of the country which through the years has filled up aquifers below the plains in between the mountains and the coast. This has allowed the province to become the agricultural hart of Oman with many date palm plantations along the coast on the Al-Batinah plain.

The Al-Batinah province, and more specifically Sohar, is economically important to the country for another reason. The city was selected for the development of an industrial port. There were many reasons for choosing Sohar as Oman's major port city, one of them being its location. From Sohar the distance to the capital city of Oman, Muscat, and the metropolitan city of Dubai in the United Arab Emirates is a little over 200 kilometers. This, combined with its strategic position outside of the Strait of Hormuz and proximity to the Indian Ocean was one of the deciding factors in the establishment of an industrial port in the city of Sohar, which aims to be a major hub between the oil rich countries of the Middle East and the large economies of India, Iran and Pakistan.

Another reason was creating job opportunities. Sohar is the second largest city of Oman and the province is the second most populous. As per 2009, the population of Sohar was estimated to be nearly 140000 and increasingly steadily (figure 1.3). The goal is that the port will generate job opportunities for these inhabitants as well boost other sectors of the economy. The final reason was Sohar's history. Oman was once a great seafaring nation and at the heart of this lay the city and port of Sohar. Many famous sailors came from Oman, and by starting this project Oman is trying to regenerate those days.

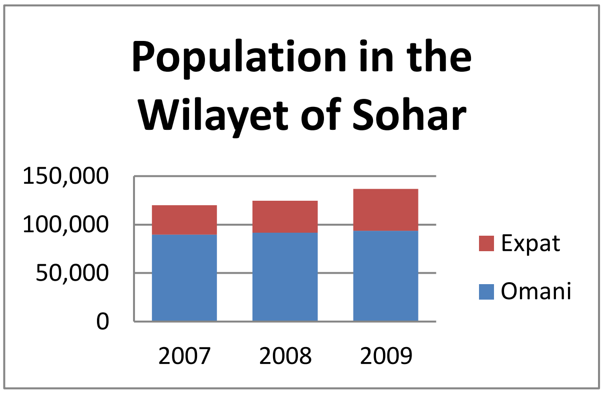


Fig. 1.3; Population in the municipality of Sohar, '07- '09

Thus far, the Port of Sohar may be called a success. Less than a decade after the first vessels docked at the port it has positioned itself to become a strong competitor among other ports of the Middle East. The development of a special economic zone named the Freezone Sohar has also commenced. Together with the Sohar Industrial Estate the Freezone aims to facilitate on shore industries with easy access to international markets by its location next to the port. To further aid the position of Sohar as the main industrial city of Oman and possibly of the whole Gulf region the government of Oman has also decided on the construction of both a railway, connecting Sohar with Muscat and other Gulf countries, as well as an airport for air cargo. All of the industrial areas in Sohar together are referred to as the Greater Sohar Industrial Zone, a map of which can be seen in Appendix I.

1.3 Problem definition and research goals

Traditionally Sohar, and the Al-Batinah province in which it is situated, has been the agricultural heart of Oman due to the presence of a fresh water aquifer in the subsurface of the Al-Batinah plain. All the aforementioned developments in the Sohar area have come at such a rapid pace that they have inevitable altered the delicate water balance in the region. The effects of over extraction can be witnessed already. Significant numbers of wells in the region simply dried up while many others have become unsuitable for irrigation due to seawater intrusion. This has led to many farmers having to either rely on other sources of water or moving further away from the shore. The local population has also expressed its concerns about possible pollution of water resources. Several sources of pollution have indeed been documented and are even being treated or at least monitored.

The government of Oman is acutely aware of the great challenge they face with regards to water availability and management. Establishing more sustainability of water resources is one of their chief priorities. Oman is looking to diversify its economy in order to diminish the country's reliance on oil for income. An important factor in achieving this goal is by promoting a stronger agricultural sector, especially in the Al-Batinah province. This sector is aimed to have a much larger contribution to Oman's GDP in the next decade. Such a goal will be hard to achieve without a new vision for water management which takes greater care of the sparse amount of water resources that are available.

The need for more sustainable water management in Sohar is therefore very important on different levels, both for the local population and businesses as well as the country as a whole. And while the ongoing developments in the area seemingly put a much larger strain on water resources, the presence of the Sohar Industrial Port provides great opportunity as well. In practice water management is often much more than a scientific exercise. Even more so when looking at a relatively large area, and one that is closely interwoven with human activity. The catchments that will be considered in this paper have seen rapid development in recent decades. Therefore, recommendations regarding water management for this area will have to be made based on a sound understanding of the hydrogeological situation as well as the development and interplay of stakeholders in the area. This is done in order to achieve the following four goals.

1. *To give an accurate picture of current hydrogeological situation in the project area*

2. *To assess the local stakeholders interests and needs in local water resources*

3. *To assess the risks/threats of this situation*

4. *To investigate possible measures to mitigate the existing threats*

2. Methods

2.1 The Water Availability Management (WAM) Study

During the last decades strong economic ties have been developed between the Sultanate of Oman and the Netherlands. One of the most well-known examples of these ties is the Port of Sohar, which is a 50/50 joint venture between the Port of Rotterdam and the government of Oman. It is thus not surprising that when an exploratory study was issued into water availability in the Sohar area several Dutch parties were approached. This led to what was called the Water Availability Management Study, or WAM Study. The official proposal for this scoping project, which was written in 2009, states its objective as follows; 'The objective of the scoping project is to prepare a project proposal for Water Availability Management in the Sohar Wadi system, create momentum for such a project and identify possibilities to finance such a project.' (Haskoning Nederland BV., 2009)

Several parties were involved in the WAM project of which Royal Haskoning was the most prominent and most involved. The other parties were DACOM, PA-international and the University Utrecht through the Sultan Qaboos Chair for Quantitative Water Management in Semi-Arid Regions; Prof. Dr. R. Schotting. Through the involvement of the University of Utrecht I was given a chance to go to Oman and conduct the research for my master's thesis as well as doing part of the research and writing for the WAM study itself.

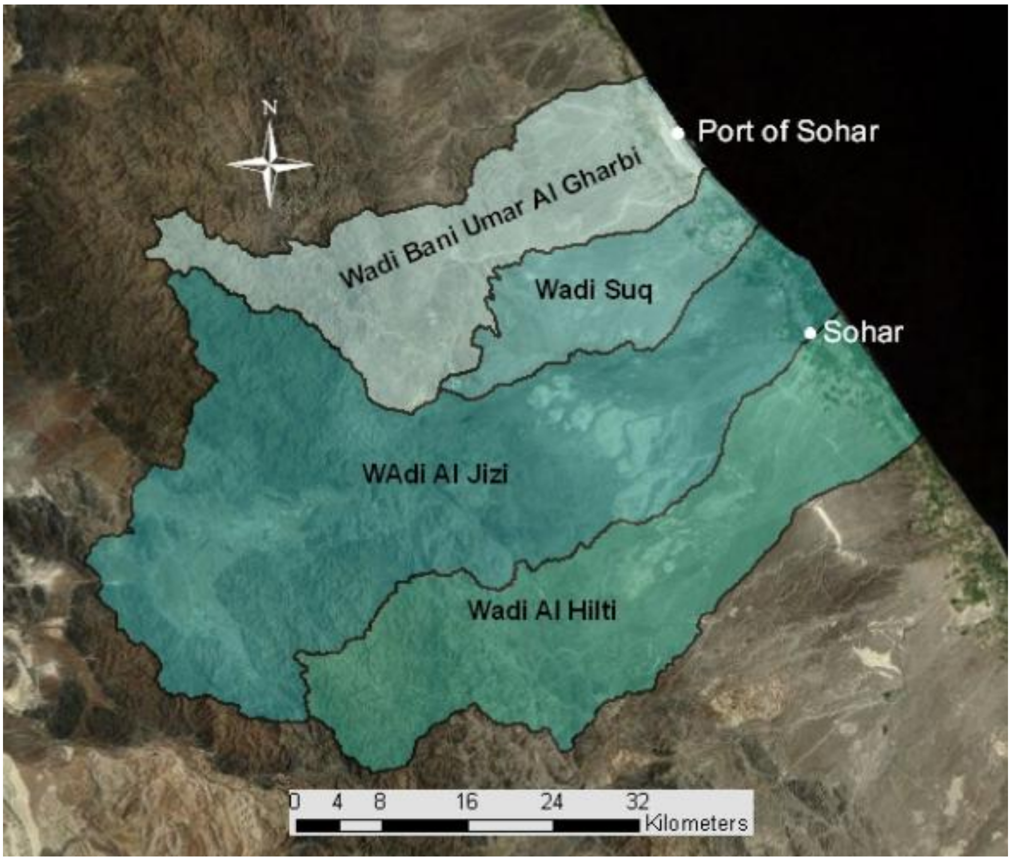


Fig. 2.1; The study area

2.2 Selection of Study Area

One of the first priorities was selecting the boundaries of study area. First of all the study area had to capture all important areas of the Sohar Area; the city itself as well as the port and some agricultural areas. At the same time a smaller project area will allow for a more precise description and therefore more accurate recommendations. Moreover one has to take into account the available data. In Oman data is usually categorized by wadi catchments. Therefore it made sense to use the boundaries of the catchments as boundaries for a project area, rather than more 'arbitrary' boundaries such as that of a province or municipality. Finally the stakeholders were consulted in this matter as well. Royal Haskoning held a workshop on March 16, 2011 were many experts in the field of Omani hydrology, agriculture and representatives of the Port of Sohar (PoS) were present.

Fig. 2.1 shows the extent of the project area that was decided upon. It contains 4 major Wadi catchments. From north to south they are; Wadi Bani Umar al Ghabri, Wadi Suq, Wadi Al Jizi and Wadi Hilti. In total this sums up to an area of 2491 km^2. Of these Wadi Al Jizi is by far the largest with a total area of 1151 km^2 whereas Wadi Suq is the smallest with 212 km^2.

2.3 Stakeholder Identification & Interviews

During the initial stages of the WAM study it became clear that local stakeholder involvement and cooperation would play an integral part in achieving the ultimate goal of further developing water management in the Sohar area. The sometimes intricate interplay of authorities and interests in water management needed to be defined and taken into account in order to come up with achievable proposals for water resources management in the project area. In dialogue with the Ministry of Regional Municipalities and Water Resources a preliminary list of stakeholders with the highest interest in water availability and/or the ability to influence water availability was established.

Stakeholder Name	Abbreviation
Sohar Industrial Port Company / Port of Sohar	SIPC / PoS
Freezone Sohar	FZS
Ministry of Regional Municipalities and Water Resources	MRMWR
Majis Industrial Services Company	MISC
Sohar Development Office	SDO
Public Authority of Electricity and Water	PAEW
Supreme Committee for Town Planning	SCTP
Ministry of Environment and Climate Affairs	MECA
Sohar Environmental Unit	SEU
Ministry of Agriculture and Forests	MOAF
Al-Batinah Farmers Society	ABFS
Ministry of National Economy	MONE

Table 2.1; List of stakeholders

Using a questionnaire, stakeholders on this list as well as others whose significance only became apparent later on in the study were then interviewed. The goal of these interviews was to define each stakeholder's respective interests and needs in water management as well as their mandate/authority when it comes to influencing water availability management in the project area. Table 2.1 shows the list of stakeholders that were interviewed in this manner as well the abbreviation that will be used to address them in this paper. The questionnaire used during the interviews can be found in appendix II.

2.4 Data Collection

All data was collected through other parties. No actual field data was directly collected for this study. Data was obtained mainly through the archives of both local and national governmental institutions as well as companies in the PoS and requested during the interviews or in separate meetings. Besides raw data many external reports were obtained.

2.5 Physical description of study area

The physical description of the study area will cover the following topics;

- Topography
- Geology
- Meteorology
- Wadi Flow
- Groundwater
- Seawater Intrusion

Most of these topics were covered by literature review of other works. The hydrology section contains maps and figures composed with the raw hydrological data of the aquifers, most importantly the maps of groundwater depth over time and that of salinity levels over time. These were made using well data and interpolated using the ordinary kriging interpolation method. A geostatisical method of interpolation was chosen over a physical method as the amount data for required for such a method is much higher. The resolution the available data on for example hydraulic conductivity and porosity was too low to be able to make use of a physical or modeling approach. However, ordinary kriging was shown to be an effective substitute the physical methods by Kumar and Rumadevi (2006) as well as Yang et al. (2008).

Since the late 70's Oman became aware of the importance of an effective groundwater monitoring system. The oldest hydrogeological data is therefore from that era, but in order to interpolate effectively one needs a significant number of measurement points. Taking that into account analysis of historical data in this paper starts in the year 1985.

The total number of wells used for the salinity maps is exactly 100. Their locations can be seen in Figure 2.2. Due to their proximity close to the sea it was impossible to create a accurate picture of salinity levels further inland. 115 wells were available with usable measurements of groundwater depth. They were scattered somewhat wider over the entire study area which allowed for larger maps to be created, covering a larger extent of all four catchments. In order to create a map of groundwater depth as accurate as possible some wells outside of the project area were included as well. Figure 2.3 shows their spread and locations.

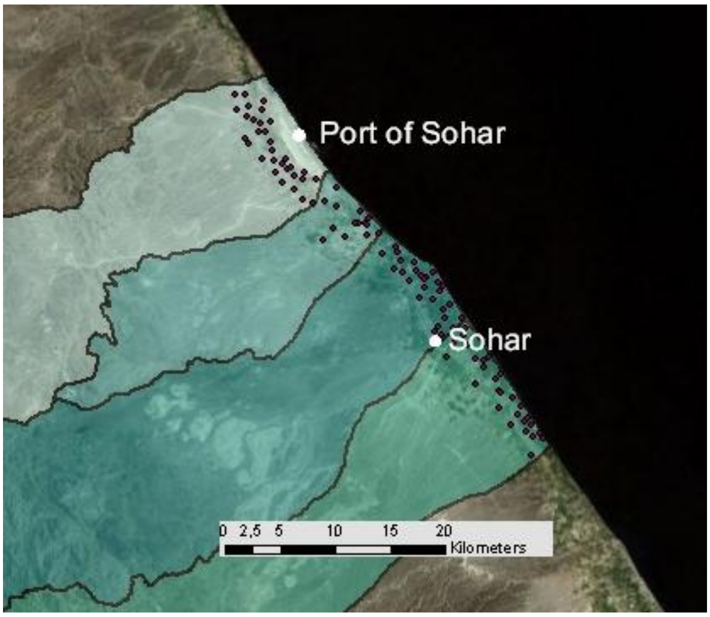


Fig. 2.2; Locations of the salinity measurement wells used

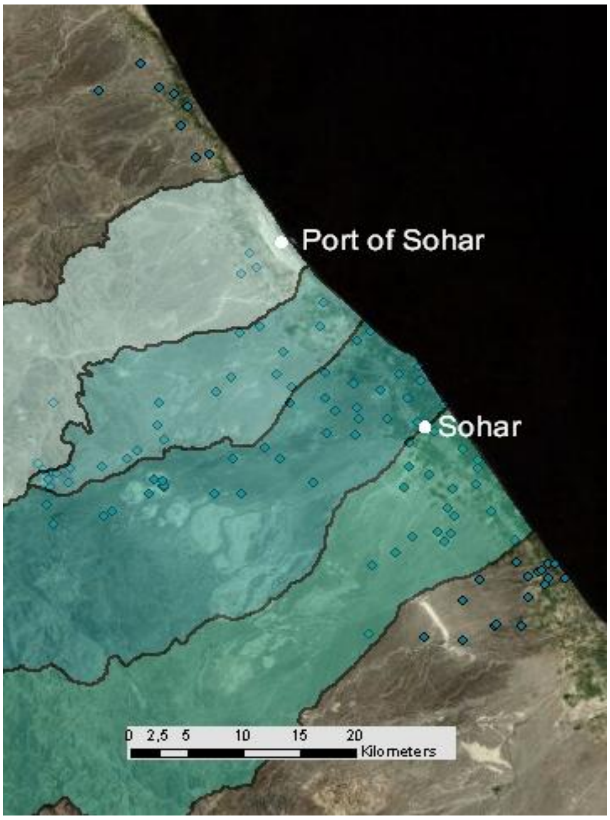


Fig. 2.3; Locations of the GW measurements wells used

The salinity of the groundwater was measured in electrical conductivity (EC). EC measurements are simple and therefore common form of measuring salinity levels. The unit in which EC is most often measured is micro Siemens per cm; $\mu S/cm$. As dissolve salts conduct electricity they electrical conductivity can indicate the total dissolved salts (TDS) in water. In the study area most agricultural area consists of date palms. These are relatively resistant to high salinity levels in their irrigation (Grattan, 2002). In the same study another common Omani crop, lemon, is shown to have a small tolerance to soil salinity. Table 2.2 shows at different salinity levels which percentage of their normal yield a crop type can reach.

	Yield Potential ($\mu S/cm$)			
Crop type	**100 %**	**90%**	**75%**	**50%**
Date palm	2700	4500	7300	12000
Lemon tree	1000	1500	2300	3600

Table 2.2; Yield potential of two common Omani crops (Grattan, 2002).

2.6 Water balance

One of the most pressings concerns in the study area is the threat of a depleting aquifer. The aquifer below the Al-Batinah plain has been and still is an important source of irrigation water and this has made the Al-Batinah province the agricultural hart of Oman. When Oman began to prosper quickly as a nation this led to an increasing demand of agricultural produce and therefore more water had to be extracted. Due to its arid climate with low rainfall and high evaporation this aquifer is showing signs of being depleted. The water level in wells seemed to be diminishing whereas others simply depleted.

A problematic side effect of over extraction is the danger of seawater intrusion. When the water balance in coastal areas is disrupted by over extracted this will be compensated by seawater creeping further and further in land. This process, depicted in Figure 2.4, has been a problem in coastal communities in Oman for some years now as groundwater on which inhabitants formerly relied on for irrigation is no longer suitable.

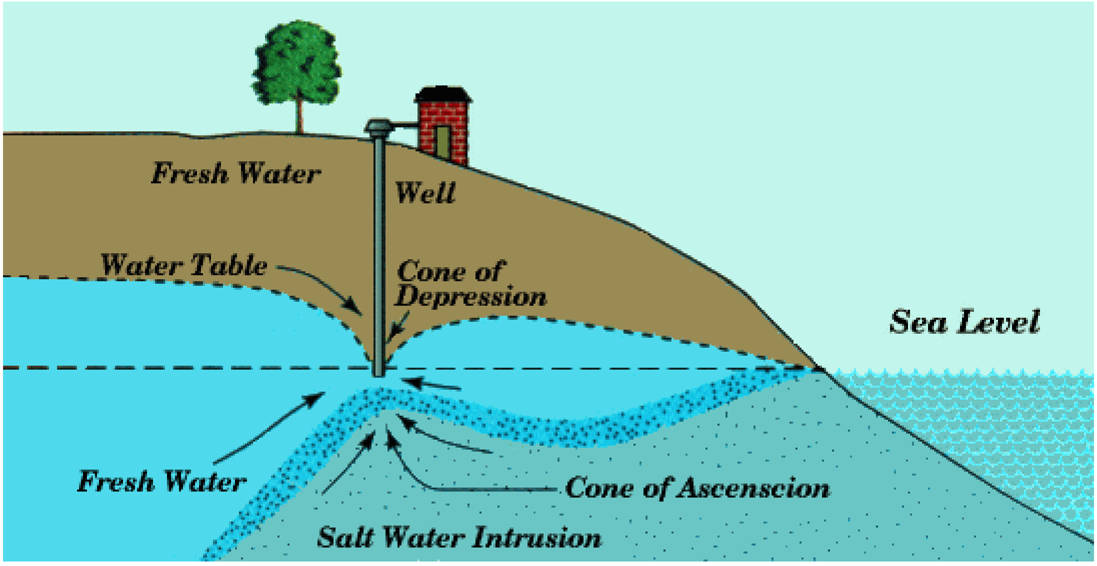


Fig. 2.4; Seawater intrusion

To tackle these problems one needs to estimate the amount of water that is being extracted which cannot be replenished by precipitation. Such a calculation is known as a water balance. Most water balances are effectively summations of sources of water loss as well as sources of water replenishment. Generally they take the form of

$$\Delta S = P - E - Qr - Qw$$

where $\Delta S =$ the change in storage of the aquifer, $P =$ precipitation, $E =$ evapotranspiration, $Qr =$ runoff and $Qw =$ the amount that was extracted through wells. In this manner the change in storage can be roughly estimated depending on the detail level of the water balance over a set period of time.

For the purpose of this study constructing a water balance using this method was unfavorable as several of the elements in the equation were unavailable or lacking detail. Most importantly there was a lack of data on the amount of water that is being extracted and from where. While there is much data available on the numbers of farmers, the area of their farmland and what type of crop they grow, there is no data on how much water they use for irrigation and the exact location of their farmland.

For this reason an alternative approach was used using the data that was most abundant and is being measured the longest, the groundwater level. By looking at changes in groundwater levels over time one can estimate what the change in storage ΔS is. For each catchment as well as for the entire study area the average groundwater depth for each year from 1985 onwards was calculated, $\overline{H}_t$ $[m]$. Extracting this value from the average groundwater depth of the following year $\overline{H}_{t+1}$ $[m]$ gives the change in average groundwater depth for that year. Multiplying this by the total area A $[m^2]$ of the catchment in question gives an approximation of the total change in cubic meters over a given year. The following formula describes the method:

$$\Delta S_t = (\overline{H}_t - \overline{H}_{t+1}) \cdot A$$

Calculating the average change over a year also allowed for computing the trend of groundwater change over the course of 1985 until 2009. Such a trend line can be used in water management to look at when and where possible countermeasures would be most effective and necessary.

3. Results

3.1 Physical description of the study area

3.1.1 Topography

The study area can be roughly divided in to two sections, the hilly/mountainous area to the southwest and the flat plain to the northeast. The elevation of this plain increases very gradually to about 20 to 40 kilometers inland, after which it starts to increase steeply. The highest mountains in the study area reach about 1500 meters above sea level (Fig.3.1.1).

Figure 3.1.1 also shows the wadi channels. The wadis form in the slightly lower lying areas of the mountain range. There the different source streams merge together into the four wadis of the study area. Upon reaching the plains the stream branch out again as the stream beds become more and more shallow. In essence this mimics the behavior of a river delta but on a very small scale.

The course the wadi streams take towards the sea can be very unpredictable and is subject to change. Especially on the plain where wadi beds are already very shallow sedimentation can cause the wadi beds to rise further leading to subsequent wadis taking other pathways. Another dominant reason for the wadis taking other pathways is anthropogenic activity along the stream bed. Often this is done purposefully, in order to protect property from the dangers of flash floods. It does however add to the unpredictability of the wadis which can be a danger during a flood event.

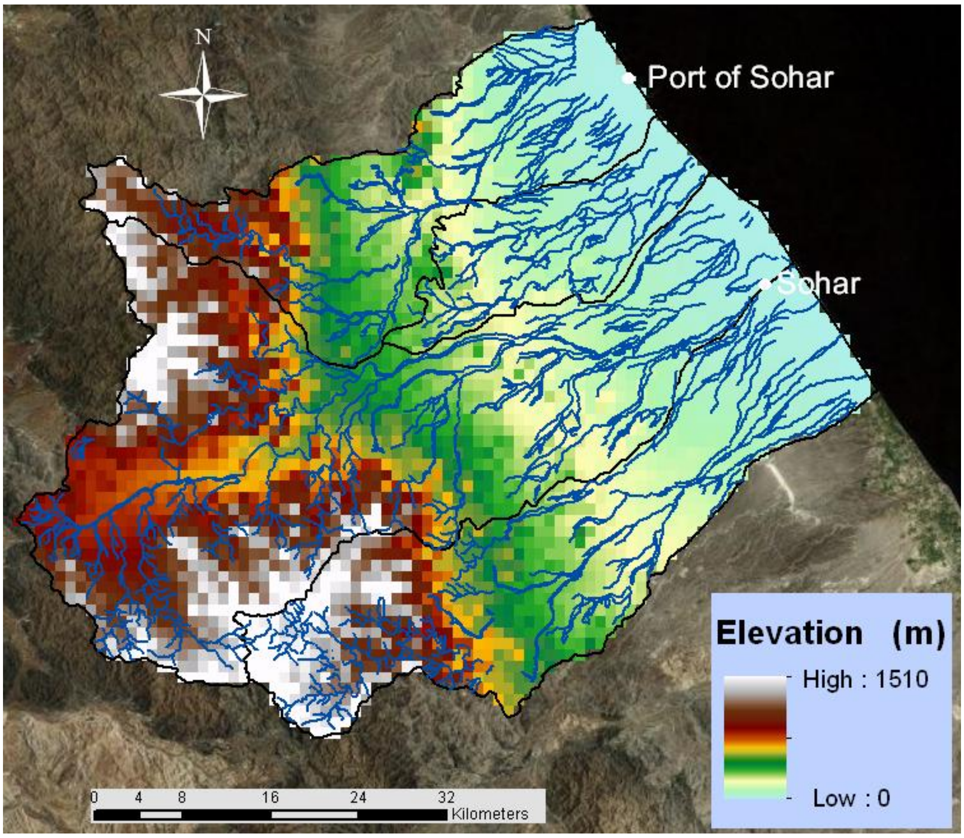


Fig. 3.1.1; Map showing elevation and wadi channels (Data: MRMWR)

3.1.2 Geology

Geologically the study area can be divided in two main formations that cover nearly all of the study area. The plain to the east is an alluvial deposit that has been brought down through erosion from the mountains over many years. It consists of a combination of sand, gravel and silt. Figure 3.1.2 shows the location of this layer, which in reality is not as homogeneous as the picture suggests. The alluvial deposit is crisscrossed by rocky outcrops and shows different levels of cementation at different locations. The depth of this layer varies. It is at its thickest near the coast where can be more than 300 meter deep. Its depth decreases gradually towards the mountains. At the foot of the mountainous area it is only about 10 to 15 meters deep (HMR Consultants, LEA Associates South Asia Pvt. Ltd, Perkins+Will, 2010).

At the foot of the mountains the second main formation of the study area appears, which is also the formation below the alluvial plain. This ophiolite formation used to be a part of the oceanic crust and upper mantle of the earth but has been uplifted unto the continent. The mountains of Oman are famous for having such well exposed ophiolites.

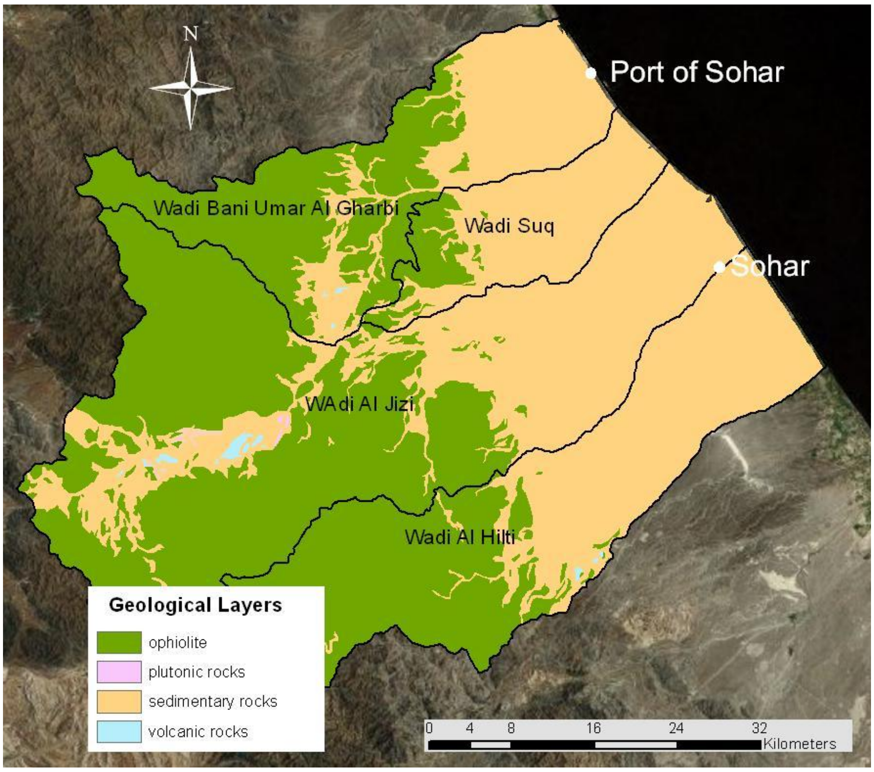


Fig. 3.1.2; Geological formations of the project area

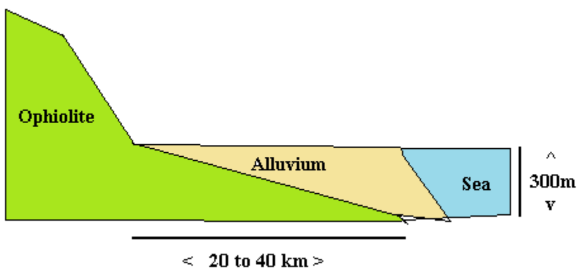


Fig. 3.1.3; Typical vertical cross section of the study area

3.1.3 Hydrology

As expected precipitation in the study area is low. Data provided by MISC show that average precipitation in the coastal area was 95.35 mm. Figure 3.1.4 shows the yearly average precipitation in the coastal zone of the study area. Precipitation in the mountains is expected to be slightly higher than that.

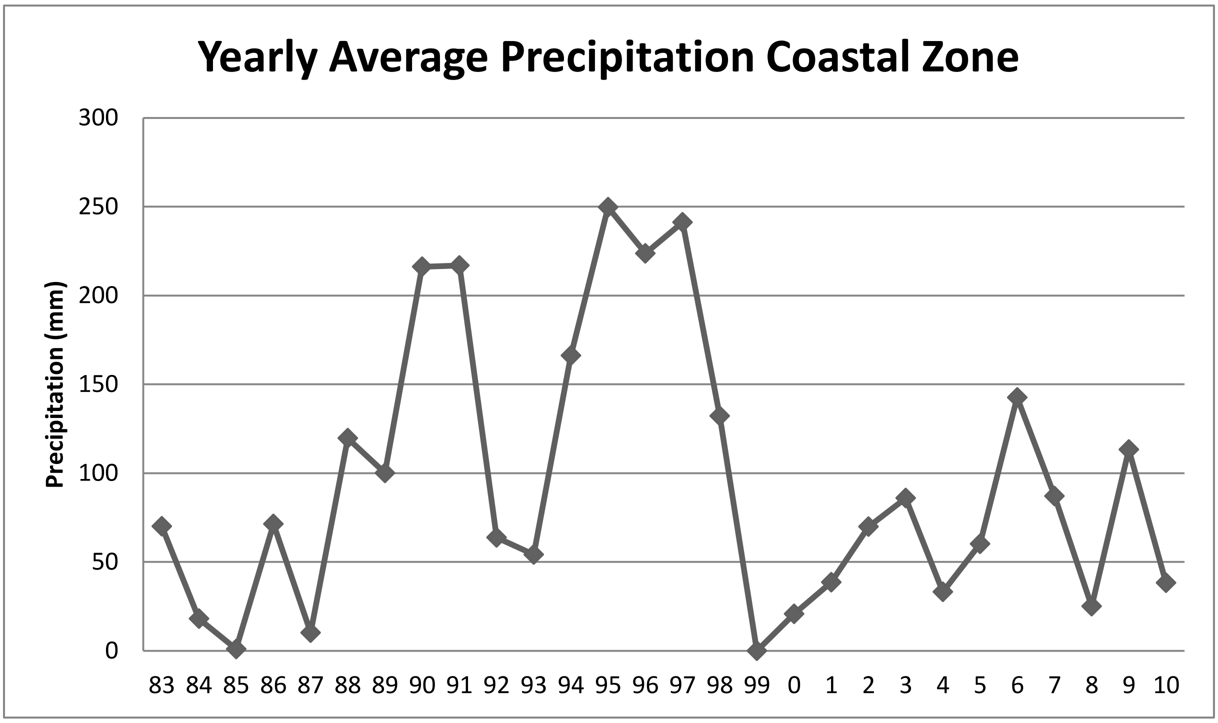


Fig. 3.1.4; Yearly Average Precipitation (Data; MISC)

The rainfall climate in the study area is very irregular. Most precipitation occurs during short and intense storms. Figure 3.1.4 shows that it is not uncommon to have years without any precipitation at all.

For the environmental impact assessment of the FzS the average monthly precipitation was calculated for two measuring stations close to the port over a period of 20 years (1984-2004). It showed that while most precipitation falls during the winter months of November through March, there is a lack of a strong seasonal pattern (Five Oceans LLC., 2010). This demonstrates the irregularity of precipitation patterns in the study area.

Station	ID	Elev	Average Monthly rainfall for 20 Years (1985-2004)												
		m asl	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Liwa	DN516027AF	10	28.4	43.6	26.1	16.1	7.1	0.0	65.3	2.7	0.4	99.0	11.5	27.5	111.1
Majis	DN603661AF	2	26.3	47.5	28.2	10.3	5.4	0.0	13.3	1.8	2.2	35.5	8.5	21.0	101.0

Table 3.1.2; Average Monthly Rainfall (Five Oceans LLC., 2010)

3.1.4. Wadi flow

When precipitation does occur large amounts of water come to run off. This is due to the intensity of the rainfall events, which cause the infiltration capacity of the soil to be exceeded. It is estimated that 40% of precipitations ends up being discharged into the ocean through the wadis (HMR Consultants, LEA Associates South Asia Pvt. Ltd, Perkins+Will, 2010). Another large chunk of that is expected to evaporate due to the high temperatures and potential evaporation. Potential yearly evaporation exceeds annual precipitation levels by far. It has been calculated to be 2855 mm/year.

Two dams have been built in wadi streams in the project area. They are located in Wadi Hilti (constructed in 1989) and Wadi Al-Jizi (constructed in 1985). These dams have been built with a dual purpose. They serve as flood protection dams as well as retention dams that aim to decrease the loss of precious fresh water by allowing it a longer time to infiltrate into the soil. Wadi Al-Jizi dam has been constructed further upsteam, where the channel is less branched out and deeper. This allows for a smaller length of the dam but requires a much greater height as compared to the dam in Wadi Hilti which is much longer and less high. The locations of the dams can be found in Figures 3.1.5 and 3.1.6 shows a picture of both dams.

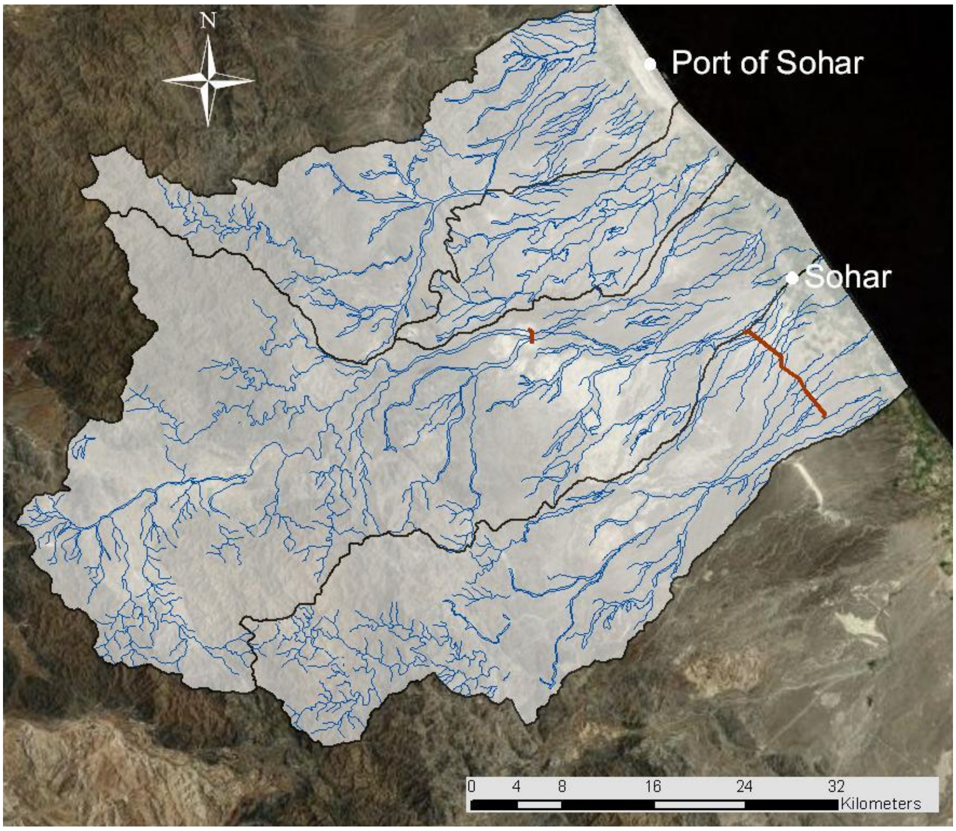


Fig. 3.1.5; Location of the two dams in the study area

Fig. 3.1.6; Wadi Al Jizi Dam (left), Wadi Hilti dam (right)

3.1.5 Groundwater

The main aquifers of the study area are phreatic and reside in alluvial deposits described in Section 3.1.2. Differing levels of cementation of this alluvium combined with the presence of rocky outcrops make the hydraulic conductivity and saturated thickness of the aquifer hard to estimate. In general, hydraulic conductivity of alluvium is relatively high to presence of coarse sands and gravel. Conductivity values ranging between 25 and 450 m/d have been measured. The general direction of groundwater flow is towards the coast (HMR Consultants, LEA Associates South Asia Pvt. Ltd, Perkins+Will, 2010).

A record of groundwater depth in meters below ground level (m bgl) from more than 100 wells has been processed to be able to view the changes in groundwater depth over time. All maps, made in 5 year intervals, are presented in the page below (Fig 3.1.6). They show and alarming rate of depletion of this aquifer on which so many inhabitants of the area rely. In 1985 there were still significant areas of the study area where the water table was reached between 5,5 to 10 m bgl. In 2009 such areas were no longer present, and in large areas the water table seems to have dropped about 15 meters over these 25 years.

The maps also allow for some analysis of the effectiveness of the recharge dams in the study area. Upstream of wadi Al-Hilti dam, the water table seemed to rise in the years after its construction in 1985. However, its effectiveness dropped after the water table upstream of the dam started to drop again. The effect on the water table of Wadi Al-Jizi dam, constructed in 1989, is harder to read of these maps. The retention of water behind Wadi Al-Jizi dam seems to have had little influence on the overall pattern of a declining water table.

3.1.6 Seawater Intrusion

High groundwater salinity levels have been a persistent problem in the coastal aquifers of Oman for some decades now. Judging from the severe rate of depletion of the groundwater one would expect similar problems in the Sohar area. Electrical conductivity measurements in a significant number of wells in the study area allowed for the preparation of maps depicting EC levels in the aquifer in 1995, 1997, 2000 and 2005 and can be found in figure

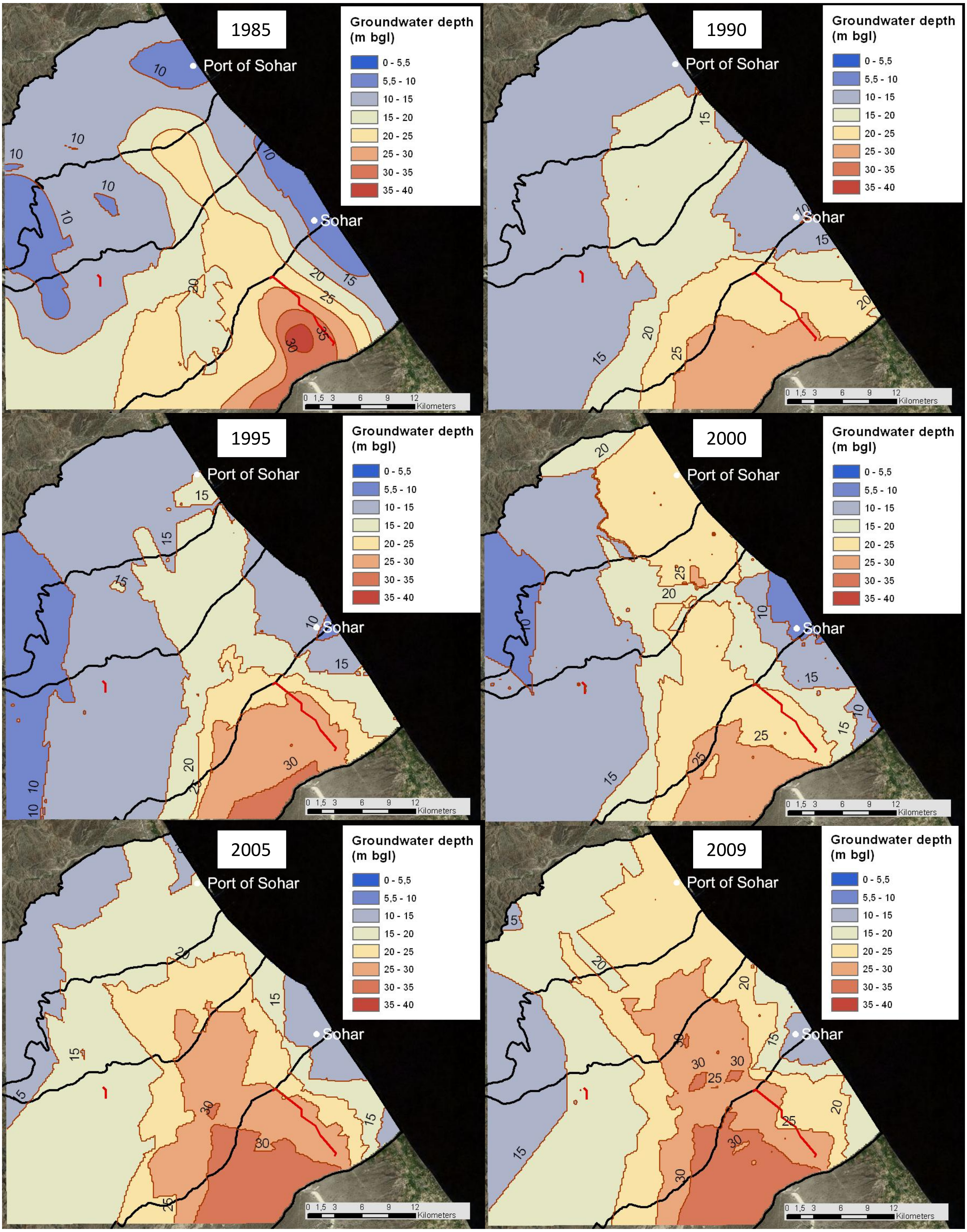


Fig. 3.1.7; Groundwater depths from 1985 to 2009 in m bgl

3.1.8. These pictures indeed show gradually increasing salinity levels along the coastline. The most notable increase of salinity is visible in Wadi Bani Umar Al Gharbi in the vicinity of the Port of Sohar. These findings are counterintuitive as groundwater extraction is usually assumed to be largely for agricultural purposes. The general consensus was therefore that the port would cause a decrease in the amount of water extracted and therefore the underlying groundwater would be less prone to seawater intrusion.

Wadi Al-Jizi and Wadi Hilti experienced the least amount of salinity increase. Nevertheless over a time period of only 10 years large areas experienced and increased electrical conductivity level of more than 1000 $\mu S/cm$. This can be seen as a worrying trend and evidence of a skewed water balance.

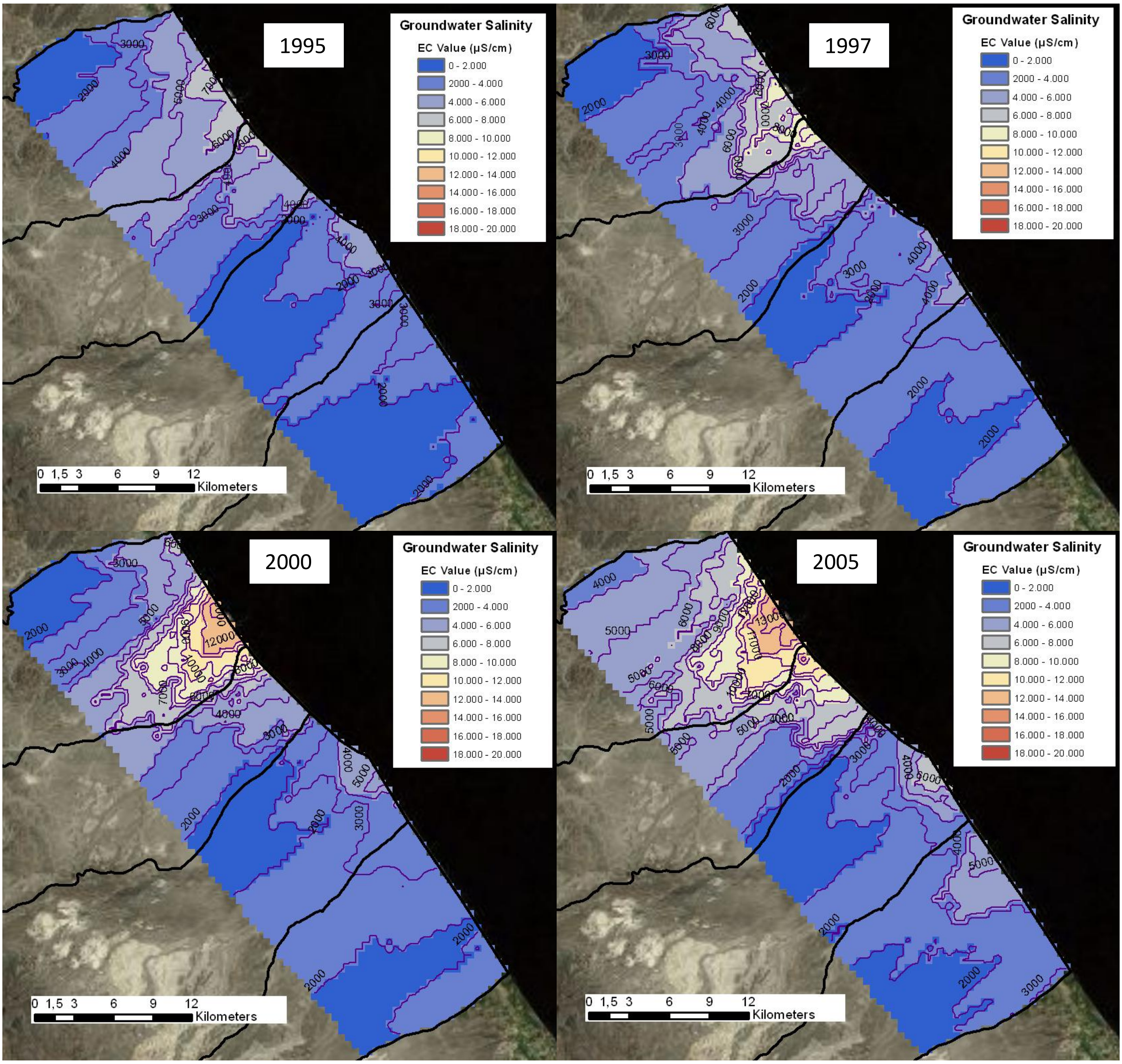


Fig. 3.1.8; Electrical conductivity levels of the groundwater in the study area

3.2 Water Balance

3.2.1 Catchment specific

Average water table depth has been calculated for all wells in each catchment on a yearly basis. Looking at the fluctuation of the water table over time allows for estimations of the change in storage over the duration of the data series as well as careful predictions for future groundwater fluctuations. This was done for each separate catchment such that assessments can be made of where the declining water table is most alarming. This enables water management strategies that aim to mitigate this threat to be more specific.

Figure 3.2.1 shows annual average water table fluctuations in wadi hilti. On average, from 1982 until 2009 the water table in all wells in Wadi Hilti declined by 3 cm/year. This implies a loss of about $18 \cdot 10^6$ $[m^3]$ per year. On top of that this decline shows a negative trend, meaning that the process of declining water table accelerated during this period. The results of the other catchments are summarized in Table 3.2.1. The graphs for the other three catchments can be found in Appendix V.

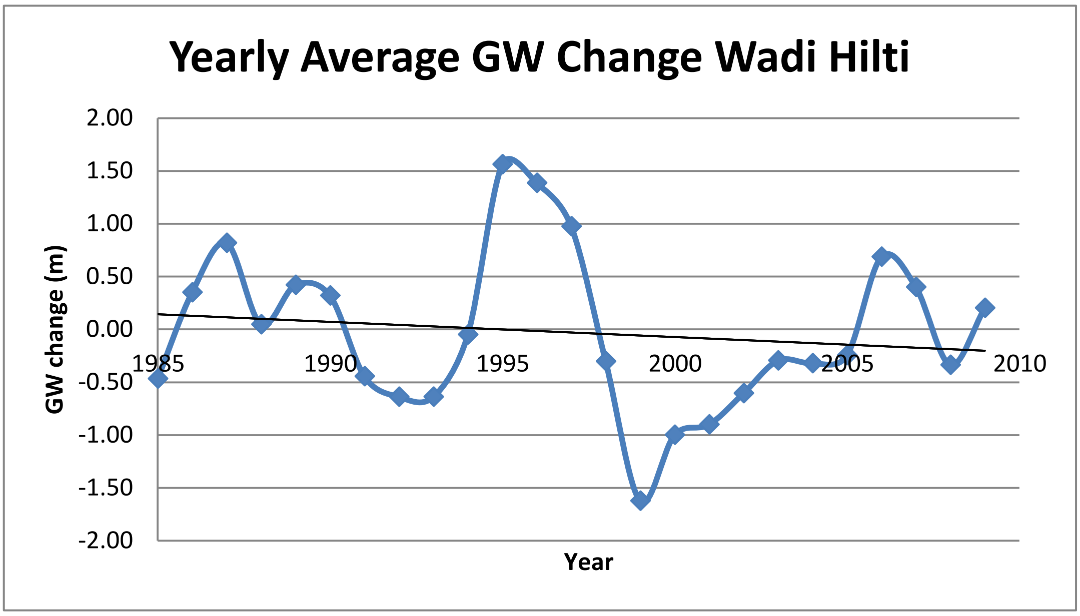


Fig. 3.2.1; Water table fluctuations in Wadi Hilti

	Area (km^2)	Average Yearly GW change (m)	Yearly Change in Storage (m^3)	Trend
Wadi Bani Umar	480	0.01	$4.8 \cdot 10^6$	Decelerating
Wadi Suq	211	-0.11	$-23 \cdot 10^6$	Accelerating
Wadi Hilti	648	-0.03	$-19 \cdot 10^6$	Accelerating
Wadi Al-Jizi	1151	-0.06	$-69 \cdot 10^6$	Accelerating

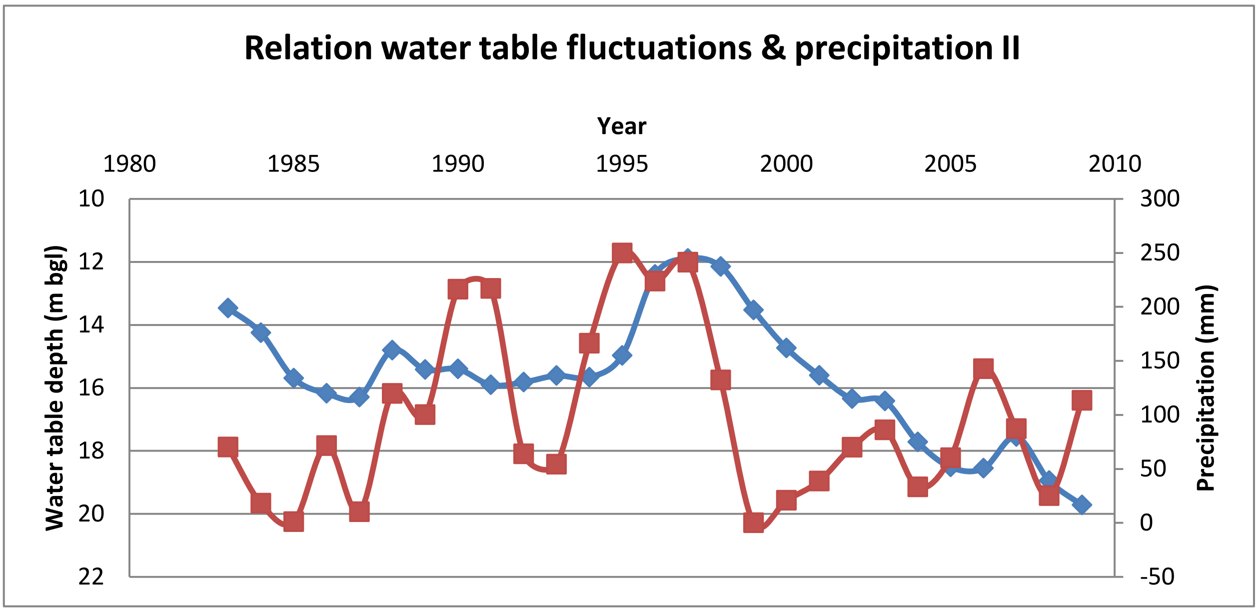
Table 3.2.1; Summary of water balances in all four catchments

Three of the four selected catchments show a yearly increase in the hight of the water table ranging from 3 to 11 cm per year. These 3 catchments also exhibit an accelerating trend in the rate of decrease. Wadi Bani Umar is the only exception in that it displays a minute increase in yearly water table depth of 1 cm per year. This finding contradicts the previously shown maps which clearly show a decreasing water level in Bani Umar as well as significant seawater intrusion. The reason for this might be the that only five wells had a significantly long and continuous measurement record of water table depth causing high uncertainty in the estimation of the water balance. Since the maps were made using wells outside of the project area as well they might give a more realistic view of the changing water table levels in Wadi Bani Umar. In all catchments fluctuations in water table depth are large. Wadi Al-Jizi exhibits the largest fluctuations. In 1995 the water levels recorded its highest annual rise (recharge) of 4 meters. The largest decrease of the water table in Wadi Al Jizi was recorded in 1999 when the average water level recorded in the wells dropped around 2,5 meters.

3.2.2 Total study area

Amongst all wells in the study the yearly average change in the water table was -0.05 m. Multiplying this with the total area of 2490 km^2 gives an approximation of the annual loss in storage of the aquifer. This was calculated to be $107 \cdot 10^6\ m^3$. This is a significant loss of storage which requires major changes in water management in order to achieve sustainability in water resources. Figure 3.2.2 shows the annual average water table depth over the entire study area.

The graph also shows the average yearly precipitation. The graph seems to indicate a clear correlation between years with high rainfall and a rising water table. This is to be expected as rainfall is the only source of recharge in the study area. Since the climate in Oman is hard to predict and many years of extreme drought could be followed by years of relatively high precipitation it is extremely difficult to make accurate estimations of future groundwater levels. Such predictions would depend largely on ones estimation of future average precipitation.



3.2.2; Average water tabel depth and precipitation

3.3 Stakeholder Analysis

3.3.1 Stakeholder description

Sohar Industrial Port Company (SIPC)

The Sohar Industrial Port Company is the main stakeholder of the project area. SIPC, set up as a 50/50 joint venture between the Ministry of Transport and Communication (MoTC) and the Port of Rotterdam, is now approaching its 10 year anniversary. Since the first vessels docked in Sohar, the Port of Sohar has experienced a rapid growth rate under the management of the SIPC and this growth is expected to continue in the coming years.

The development of the Sohar region is inevitable linked to the success of the development of its port. This can also be said for the development of water management in the region. With its important position in study area the port can influence water availability in an important way. Potentially these could be beneficial to both the port as well as the inhabitants of the region. Besides Sohar's strategic location outside of the Strait of Hormuz, creating job opportunities in the Al-Batinah province played a major role in choosing Sohar as the location of this port. If the large amounts of industrial affluent can be harnessed for irrigation or to replenish the local aquifer directly this could aid in reversing the trend of seawater intrusion and thus help create better conditions for agriculture and more jobs in the agricultural sector.

Currently operations at the port are expected to have little effect on fresh water resources as the water used by companies in the port are largely obtained through desalination (Five Oceans LLC., 2010). Several groundwater wells are present but are installed for use in emergency situations only, in case the seawater intake falters. Nearly all industrial affluent is being discharged back into the sea where it was drawn from initially making the effect on the underlying aquifer minimal.

Freezone Sohar (FZS)

The Freezone Sohar is a newly established joint venture between the Government of Oman, the Port of Rotterdam in The Netherlands and SKIL Infrastructure in India. This industrial estate will provide a place for off shore businesses to establish themselves close to the port. The FZS is not yet operational, but the first phase of the project consisting of about 500 Ha of land is expected to be ready in the coming years. When the final stages of the FZS will come to fruition it will cover an area of about 4,500 Ha. Figure 3.1 shows the envisioned area which the FZS will occupy within what is referred to as the Greater Sohar Industrial Zone. In essence the FZS will be the landlord for any company wanting to establish itself in this industrial estate. As part of the landlord agreement it has to provide the tenants with any water related needs that they may have. Besides they are also responsible for the handling of discharged water as well as protecting the Freezone from damage by wadi flows.

An elaborate environmental impact assessment has been conducted for the FZS. It showed that, much like in the port, actual groundwater extraction in both the construction as well as the operational phases will be close to non-existent. However, the Freezone will alter the water balance slightly for its development adversely affects the infiltration capacity in the area. The large increase in hard surface areas (it is estimated that around 95% of the FZS will consist of impervious areas (Five Oceans LLC., 2010)) means more rainfall will come to run off rather than infiltrate. Since rainfall events in Sohar are limited to infrequent but intense events, of which large quantities of rainwater come to run off already, the effect on water quantities in the underlying aquifer will likely be small, especially at the scale of the study area.

One of the future aims of the Freezone is to develop an agricultural cluster. With this cluster the Freezone is trying to take into account the culture and background of the people in the Al-Batinah region. Al-Batinah has traditionally been the agricultural hart of Oman and thus such an agricultural cluster would fit neatly into this tradition. However, in order to sustain this cluster farming in the region has to be up scaled to a more industrial level. Whether this is achievable will depend on being able to supply farmers with enough water to run large scale farms at competitive prices. “The high costs of irrigation will not provide the farmers with products that can compete at global price levels (Master Plan North Batinah Region 2025, 2007)”. It is therefore in the interest of the Freezone and by extension the Port of Sohar to support initiatives aiming to increase water availability in North-Batinah.

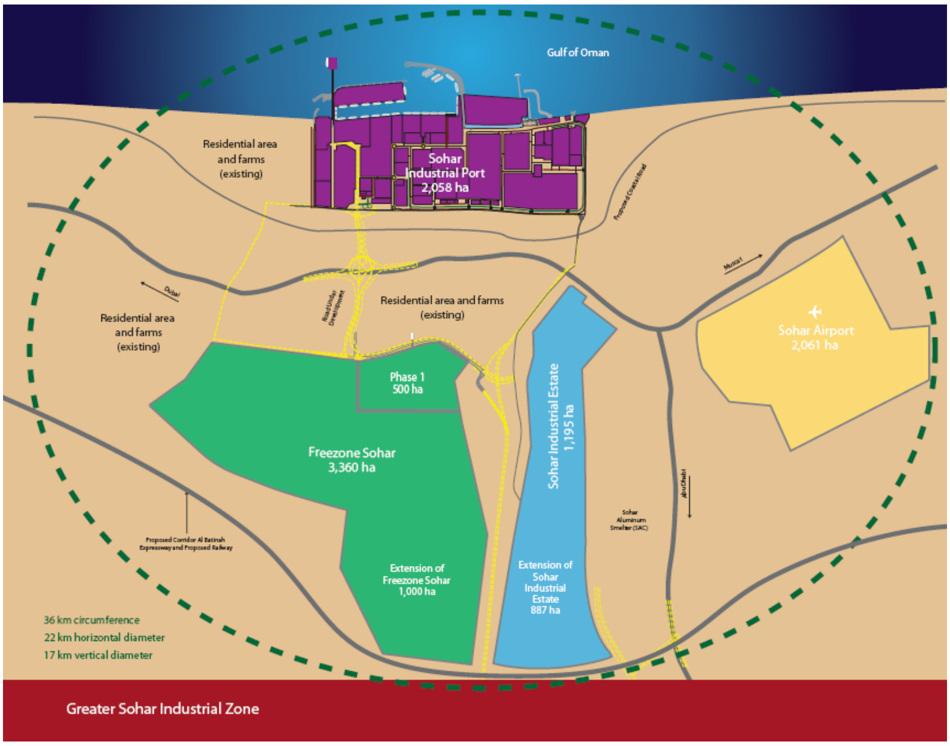


Fig. 3.3.5 Greater Sohar Industrial Zone (Master Plan North Batinah Region 2025, 2007)

Ministry of Regional Municipalities and Water Resources (MRMWR)

The MRMWR is the main governmental stakeholder dealing with the management of water resources. It operates an extensive monitoring system which is used to collect data on all aspects of water resources including wadi flows, meteorology, groundwater levels and salinity, falaj data and dam storage. The data gained in this manner is widely used in Oman for research relating to water resources and flood risks by both the Ministry itself as well as external groups studying water resources in Oman.

Insights gained from such research are important factors in the Ministry's decision making processes. The ministry's water resources department's vision is defined on its website and compromises three main goals;

- Supplying sources of potable water and creating balance between water utilization and renewable resources.
- Enhancing water resources and protecting them against depletion and pollution and rationing water consumption.
- Establishing water preservation principles and increasing awareness on the importance of rationing water use.

Majis Industrial Services Company (MISC)

MISC is a government owned water utilities supplier in the PoS. Established in 2006, Majis' initial task was to operate the seawater intake and chlorination facility in the PoS. This facility is now used to satisfy customers throughout the port in their cooling and process water demands. Since then their portfolio has gradually expanded as MISC is aiming to not only deliver cooling and process water but also potable water. A new desalination plant is currently being constructed and expected to be finished within two years which will allow MISC to produce potable water rather than rely on external suppliers. On top of that facilities are already in place that allow for the centralized collection of sanitary waste water and in the future also industrial affluent.

These facilities are at various stages of their installation and some are still running well below their full capacity. The treatment plant for industrial affluent will have a capacity of 10000 m^3/d and the domestic sewage treatment plant has a capacity of 3000 m^3/d, yet no more than a 1000 m^3/d of that is actually being used. One of the reasons for this is that several large companies were already active in the port before Majis started to offer their services. This meant that these companies had to arrange the treatment of their sanitary and industrial waste by themselves and since they now have all the appropriate treatment facilities in place they do not require the services that MISC offers or will offer in the future.

Currently the amounts of waste water being treated by Majis are not of the quantity that they can be really significant in influencing water resources in the study area. About 300 m^3/d of treated sanitary waste water is being used for landscaping within the port. However, MISC is also expanding to the FZS. If they can manage be there from the start and make sure all tenants of the FZS make use of their services their waste water flows could increase significantly during the next decade. Such large amounts of treated waste water are a potential source for irrigation and landscaping in the project area and could positively influence the water balance.

Sohar Development Office (SDO)

The Sohar Development Office uses a network of pipelines totaling 853.213 km in length (2009) to supply water to the citizens and industries in the of wilayet Sohar (which does not include the PoS and the FZS). It also charges money for this service, charging different fees for the water depending on the type of customer and the amount consumed.

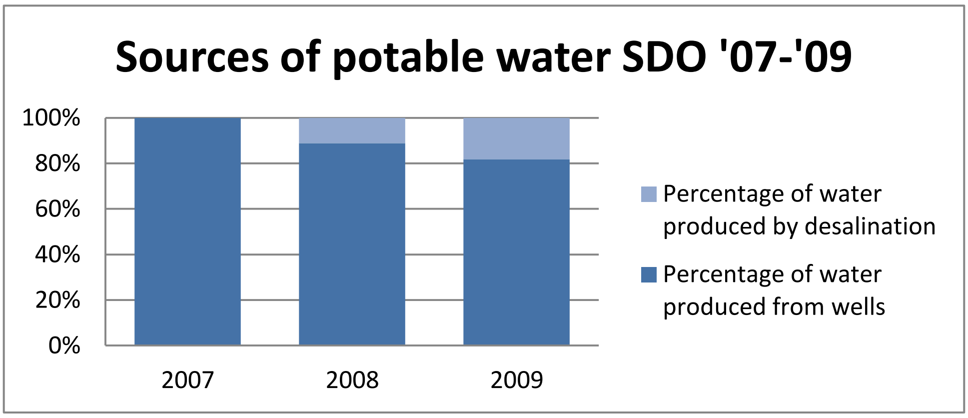
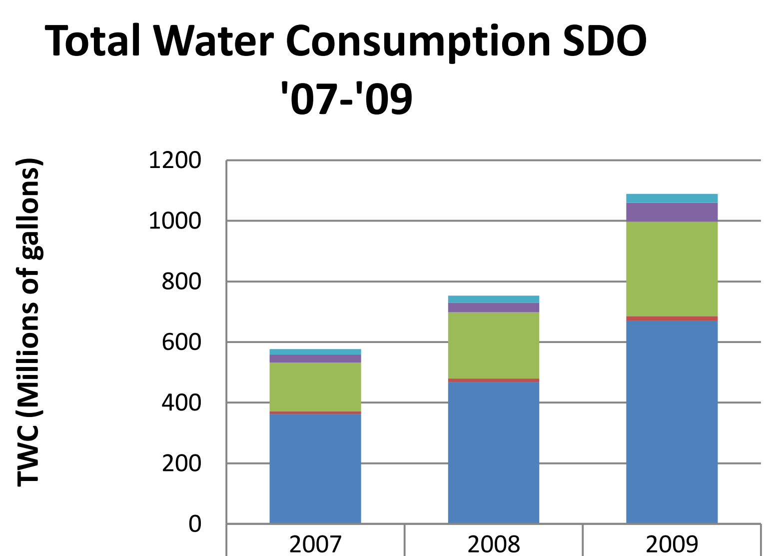


Fig. 3.3.6 Percantage of water produced by desalination versus production from wells (Data: SDO)



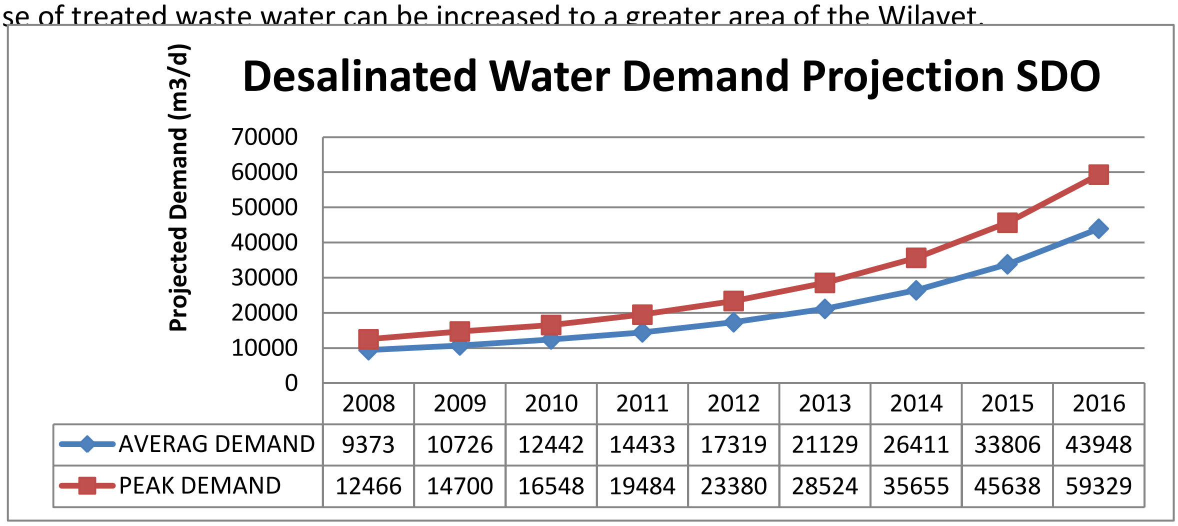
	2007	2008	2009
Government Mosques	18.7	22.5	30.2
Commercial	26.1	31.7	61.5
Governmental	160	219.5	312
Industrial	9.8	11.3	15.2
Residential	362.6	467.8	670.1

Fig. 3.3.3 Total water consumption in the wilayet of Sohar (Data: SDO)

Until 2008, the SDO depended fully on groundwater as the only source for potable water. In 2008 a new desalination plant was commissioned which is currently operational.

Certain areas now receive water from the GW wells, some from the desalination plant and some receive mixed water. The groundwater wells used by SDO draw water mainly from the aquifers in the foothills of the mountains upstream of the wadis within the project area. Figure 3.3.2 shows the actual percentage of water that has been drawn from these wells versus that which has been desalinated. In all likelihood the short trend shown in Figure 3.3.2 will continue. This dependence of the SDO on groundwater wells cannot continue for much longer and therefore it will have to rely more and more on desalinated water as evidence by the projections of future desalinated water demand (Figure 3.3.4). The increasing demand from the Sohar area, which is also shown by the steeply increasing production numbers
(Figure 3.3.3), has led to an ever decreasing groundwater table in the aquifer where the 10 wells belonging to the SDO draw from. The SDO thus has a strong influence on water availability and a potential to alter it. At the same time it would also benefit from improved water availability.

Besides supplying potable water the SDO also handles the sewage system of Sohar and the surrounding villages. The water treated here is used for irrigation, but for landscaping purposes only. The size of the network, which does not cover a great enough area, is currently the limiting factor in the reuse process. The amount of treated water available is not limiting. Work is currently on the way to develop this network such that the use of treated waste water can be increased to a greater area of the Wilayet.



	2008	2009	2010	2011	2012	2013	2014	2015	2016
AVERAG DEMAND	9373	10726	12442	14433	17319	21129	26411	33806	43948
PEAK DEMAND	12466	14700	16548	19484	23380	28524	35655	45638	59329

Fig. 7.3.4 Water Demand Projection for the Wilayet of Sohar (SDO)

Public Authority of Electricity and Water (PAEW)

The Public Authority of Electricity and water (PAEW) is a governmental institution which operates at the national level. It is tasked with the production of water and supply of water to citizens and industries throughout Oman. For this purpose they use desalination plants as well as specific well fields, although desalinated water takes up the vast majority of their production. This implies that they own nearly all water related infrastructure in Oman including desalination plants and supply networks. However, in the Wilayet of Sohar the PAEW has relegated these duties to the Sohar Development Office and as such they are more influential in the Sohar area.

The interest of the PAEW in the sustainability of water resources revolves around maintaining the aquifer below the Al-Batinah plain as a strategic reserve. In terms of size and proximity to the surface this aquifer is unique in Oman and therefore they would like to see extraction from the aquifer itself minimized such that it can be relied upon in case of emergencies at the desalination plants.

Supreme Committee for Town Planning (SCTP)

The Supreme Committee for Town Planning is a committee in which all ministers of the Omani government have a seat. In the SCTP the concerns of the ministries are assembled in order to determine the best course for the future development of Oman in terms of spatial planning. Long term land use development is decided upon in the SCTP and resulting plans for the development of future land use are therefore binding. For the Al Batinah province this has resulted in the 'Comprehensive Master Plan for Al Batinah Coastal Area'.

The Al-Batinah province is estimated to contain nearly 53% of the total agricultural land in the Sultanate (Comprehensive Master Plan for Al Batinah Coastal Area) and the Omani government is aiming for an even larger contribution of the agricultural sector to its GDP. To achieve this water resources management and spatial planning will play an integral role in this province which is the most suitable province for agricultural development.

Ministry of Environment and Climate Affairs (MECA)

The position of MECA in water management is limited to conducting studies and writing reports about pollution of groundwater, as the only surface water present in Oman is seawater which does not fall within the scope of this study. The MECA does not actually implement any physical measures themselves and rely fully on the ministry of finance for the financing of any of their proposals.

MECA has been responsible for extensive monitoring programs, focused especially on the pollution in Wadi Suq, which has ultimately been used to write the large comprehensive JICA (Japan international Cooperation Agency) report. This report is now considered *the* main reference for any groundwater related research in the Sohar mining area, which is an important part of the project area.

Allready in 1996, when the Ministries of Water Resources and Environment were still combined, a proposal for the remediation and treatment of groundwater in Wadi Suq has been made. Several phases of this proposal have indeed been executed and as a result it now appears that the increase of pollutants coming from the mining area has ceased. Figures 3.3.5 and 3.3.6 show the details from a well several kilometers downstream of the location of Oman Mining Company (OMCO).

Fig. 3.3.5 The location of well KM 14

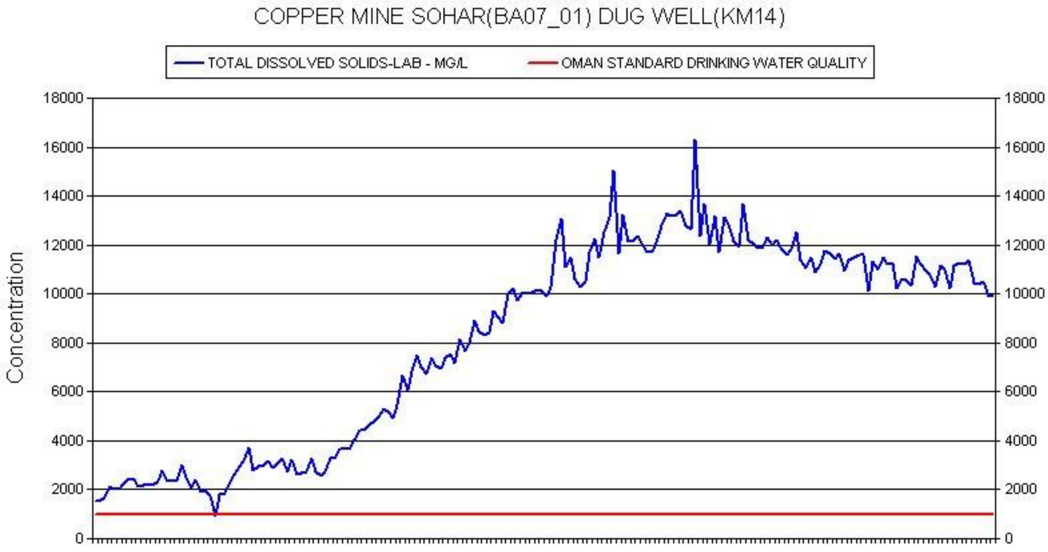


Fig. 3.3.5 Trend of groundwater pollution at well KM 14 from 1984 to 2004, compared with standard drinking water quality (red line) (MECA)

On a larger scale MECA is also concerned with the trend of seawater intrusion in the Al-Batinah province and would encourage initiatives that aim to halt or revert this trend.

Sohar Environmental Unit (SEU)

The Sohar Environmental Unit is a recently formed branch of the ministry of environment. Its jurisdiction is strictly limited to the Port and the Freezone Sohar. Within these boundaries it handles requests for environmental permits. Companies looking to establish themselves in the Freezone or the Port of Sohar require these permits for e.g. discharging waste water into the sea and causing emissions. Once these permits have been granted the SEU is also the institution responsible for overseeing whether the guidelines are being adhered to. It does this by executing inspections. Since groundwater extraction has been minimal in the port the SEU has until had little involvement in water management.

Ministry of Agriculture and Forests (MOAF)

The Ministry of agriculture (MOAF) is involved in water management through irrigation. Their influence in water management is considerable, as the MOAF offers a range of services and subsidies to farmers that would like to start using modern irrigation techniques rather than the out-dated flood irrigation techniques that are still commonplace in Oman. These services are offered in the hope that the agriculture sector, which still relies heavily on groundwater for irrigation, will become more sustainable and durable. Failure to do so could lead to farmers having to use more desalinated water for irrigation which would drive up the costs of farming produce considerably. The services that are offered by the MOAF include;

- Free consultancy
- Free design for new irrigation set-up
- Free instructions of how to the new irrigation system
- Subsidies that cover the purchase of the equipment

Besides stimulating a change towards a more modern agricultural sector the MOAF also conducts research at their own research facility. Vital research regarding irrigation and infiltration in local soil types as well as tests with irrigation using treated waste water are conducted here. On top of that the MOAF conducts an agricultural census which quantifies the agricultural sector in Oman. This census includes data on the number and size of farms, type of crop/livestock and irrigation types.

Al-Batinah Farmers Society (ABFS)

The Al-Batinah Farmers Society is an association of farmers which aim to improve the region's agricultural sector. The society is mainly concerned with the commercial aspects of farming in Al-Batinah. Their goal is to make farming more profitable through improved marketing of and quality of the produce. Greater water availability could aid in this process by opening up opportunities for larger scale farms which are generally more competitive.

Ministry of National Economy (MONE)

The MONE's role in water management is limited. One of MONE's tasks is "carrying out a substantial transformation in the structure of the national economy by developing a multiplicity of income sources, instead of depending mainly on a depletable source like oil in order to achieve economic balance and sustainable growth" http://www.moneoman.gov.om). This is referred to as the diversification of the Omani Economy. Water resources management could play an important role in this process by supporting sectors of the economy such as agriculture and tourism.

MONE also aims "To participate in formulation of long term strategic objectives of economic and social development that are consistent with available resources and potentials of economic sectors and various planning regions." This requires a thorough understanding and mapping of water resources as well as projections of future water resources. Economic development comes with a greater dependency on water resources and therefore has to be taken into account in order to optimize water management.

3.3.2 *Location*

The stakeholders interviewed during this study can be classified into two groups; one that operates at the local/regional scale and others operating at a national scale. Figure 3.1 shows a map of the PoS and the FZS. These lie approximately seven kilometers apart on either side of the main road running parallel to the coastline. Figure 3.2 shows the PoS and the FZS in relation to SDO, whose sphere of influence lies just southeast of the port and entails the entire wilayet of Sohar, up to the gate of Sohar in the south-east. Besides these stakeholders, the other local stakeholders that were interviewed are MISC and the SEU, which are both exclusively active in the port and aim to take their services to the Freezone as well.

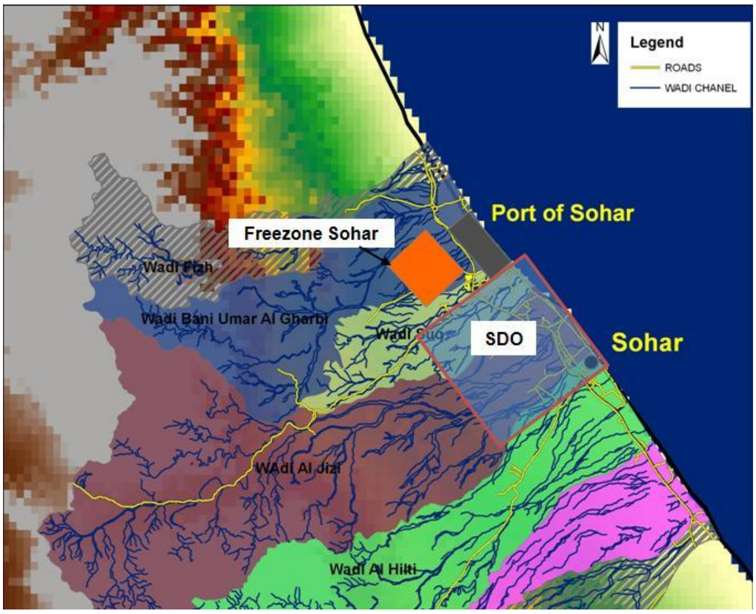


Fig. 3.7 The location of some of the local stakeholders in the study area

Other stakeholders are active on the national level, and as such their interests and influence cover the entire project area. The PAEW is the exception, which has relegated a large part of their duties within the Wilayet of Sohar to the SDO.

3.3.3 *Mandate/Authority*

Sohar Industrial Port Company/Freezone Sohar

Being the landlords of respectively a port and a industrial estate, any tenant will have to adhere to an agreement with the landlord when wishing to settle in either of these industrial areas. This agreement will include certain incentives but also some obligations. Obligations that relate to water management include that companies will undergo an initial environmental permitting phase and afterwards will be subject to monitoring obligations (Five Oceans LLC., 2010) imposed by the SEU, implying that companies cannot simply extract or discharge water.

Majis Industrial Services Company

The mandate carried by MISC has grown since the year of its conception. Initially it was to supply only seawater to companies but now it offers or plans to offer much more services including; chlorinated seawater, process water, potable water en waste water treatment. However, one of the main issues for MISC is that they do not have the authority (and nor does the SIPC) to force tenants in the port to make use of their services.

Ministry of Regional Municipalities and Water Resources
The MRMWR's objective in relation to water resources is too maintain/restore balanced water resources. This is done through research, regulations and physical measures.

Physical measures include the construction of recharge dams and the maintenance of the Aflaj system. The Aflaj system is still an inspiring example of sustainable water management and its continued use in Oman contributes to preserving its water resources.

Regulations also play a vital role in preserving water resources by protecting them from pollution or over extraction. Regulations are generally enforced through Royal Decree's. An important decree is Royal Decree No. (114/2001) promulgating Environmental Protection and Pollution Control Law. Among other issues, this law imposes strict rules and regulations for discharging waste water. "No hazardous waste or substances or other environmental pollutants shall be discharged in Wadis, watercourses, groundwater recharge areas, rainwater and flood drainage systems or aflaj and their channels. It is also not allowed to use or discharge untreated wastewater in the above-mentioned places."

Sohar Development Office
The mandate of the SDO is to provide the inhabitants of the wilayet of Sohar with potable water. Through determining the prices of potable water careful use of this precious resource can be stimulated, as it does by raising the cost of water once the threshold of 5000 gallons has been exceeded.

Public Authority of Electricity and Water
The PAEW will have a similar mandate to that of the SDO's water department in the wilayet of Sohar. Its mandate is to make sure that inhabitants of Oman will be satisfied in their demands for water.

Supreme Committee for Town Planning
SCTP is an important authority which can approve or disapprove proposals for land use changes and thereby steer the direction of future land use and by extension water availability.

Ministry of Environment and Climate Affairs
MECA has the responsibility of making sure Oman's waters are kept clean of pollution and its people respect environmental regulations. It achieves this through its extensive monitoring network. Since polluted water can mean a loss in water availability MECA is in important authority in the management of water resources.

Sohar Environmental Unit
The SEU is an essence a regulating authority within the PoS and the FZS. As described in

chapter 3.3.1, it is tasked with preventing pollution by handing out the permits and then supervising whether the rules are adhered to by monitoring.

Ministry of Agriculture and Forests

In essence the mandate carried by the MOAF is to improve the agriculture sector in Oman. It does this by aiding farmers to obtain the necessary tools and information for a successful and sustainable enterprise. It does not have the authority however to force farmers to, for example, use other irrigation methods or irrigate with treated waste water.

4. Conclusions

4.1 Current hydrogeological situation

Over extraction and saline intrusion of coastal aquifers are a common problem in Oman. The maps of groundwater depths and the water balances of the four wadi catchments in the study area have shown that the Sohar area are no exception to that trend. Over the whole of the study area the water table decreased in depth with 5 cm per year. Multiplied by the total area this corresponds with an average loss of fresh groundwater of 118 Mm^3 per year.

According to the water balance all but Wadi Bani Umar have experienced a decrease in the groundwater table. In these catchments this process has also accelerated over the years, which could indicate that the total amount of groundwater being extracted from the aquifers is still increasing. The results of the water balance in Wadi Bani Umar could be debated however, since there were only a few wells in this catchment with enough measurements to contribute to the water balance. A more realistic picture might be given in the map which is based on an interpolation between data measured at many more wells. The maps of water table depth do show a notable decrease of the water table in Wadi Bani Umar.

Salinity levels also increased significantly over the period of 1995 until 2005 (Appendix IV). This is further evidence of a skewed water balance in the study area. Surprisingly a large peak of high salinity levels in the groundwater under the port started to appear. In this area electrical conductivity levels reached values of more than 10.000 $\mu S/cm$. Such high values have a severe negative influence on the yield of agricultural produce and farmers will only be able to farm salt resistant plants when using such water for irrigation. The latests available measurements of salinity levels (2005) in wells close to the coast were commonly between 3000 to 6000. Plant types such as a lemon tree irrigated with this saline water would yield less than 50% off what lemon tree irrigated with fresh water would. (Grattan, 2002).

Recharge in the aquifers showed a strong correlation with rainfall events as years of large precipitation usually coincided with a sharp rise of the water table (Fig. 3.2.2.). This is likely due to the high infiltration capacity of the alluvial plains in which the aquifers are situated. The alluvial deposits in the study area consist of a mix of sand, silt and gravel with a relatively high conductivity and infiltration capacity. Despite the large infiltration capacity of the soil an estimated 40% of the total rainfall still comes to run off (HMR Consultants, LEA Associates South Asia Pvt. Ltd, Perkins+Will, 2010). This is partly due to the prevalence of short, intense rainfall events. During such an event precipitation will often exceed infiltration capacity leading to surface runoff. Precipitation that does not come to run off either evaporates or infiltrates the soil and will recharge the aquifer.

In a country where fresh water is seen as a precious natural resource any water that comes to discharge into the ocean is seen as a waste. In an attempt to capture parts of this runoff two dams have been constructed, one in Wadi Al-Jizi and one in Wadi Hilti. The maps of groundwater depth over time (Appendix III) give insight into the effectiveness of such dams. They show that at least Wadi Hilti dam had a positive effect on recharge in the years after its construction. However, this effect becomes less and less visible over time. The reason for the decreasing effectiveness of the dams with age could be because of sedimentation upstream of the dam. In Wadi Al-Jizi dam a sedimentary deposit of 2,5 meters deep has formed behind the dam, as figure 4.1 shows. Vertical conductivity is likely severely hampered by this sedimentary layer.

Fig. 4.1; Measuring stick behind Wadi Al-Jizi dam used to measure water levels retained by the dam after precipitation. Notice how the soil starts at 2,5 m rather than 0 meters.

4.2 Stakeholder Analysis

From the interviews conducted a number of common concerns relating to water resources management emerged, as well as a number of potential measures which are viewed as the most desirable. Three important question where in this way answered by all stakeholders. These three questions were;

1. Why it is necessary to intervene in water resources management
2. Why it would be beneficial to intervene in water availability management
3. What kind of intervention is both realizable and has the potential to significantly influence water availability.

Finding common ground in the answers to these questions was an essential part of the stakeholder investigation as proposals which have the support of the whole community are much more likely to succeed.

The most common answer to the first question was that all stakeholders recognized the dangers of past and current over extraction of the scarce water resources available and therefore the importance of practicing a more sustainable water management in the study area. This necessity of interfering in water availability is evidenced not only by the hydrological data showing significant amounts of groundwater depletion and seawater intrusion but at the same time by the ever increasing demands for water in the region (Data SDO). There was slight difference in the perceived urgency of measures. Some see interference in water management in order to maintain the aquifer underneath the Al Batinah Plain as a must while others envision the aquifer more as a strategic reserve, that should not be tapped unless in emergency. However, nobody would like to rely completely on desalinated water for both security and economic reasons and feel measures to save or replenish the aquifer are warranted.

Sustaining or reestablishing a healthy aquifer will allow farmers as well as the municipal water supplier SDO to use groundwater rather than other, more expensive options such as desalinated water. "The high costs of irrigation will not provide the farmers with products that can compete at global price levels. This means that intensified export-oriented agricultural projects are risky (Regional Masterplan 2025)". Ensuring a relatively cheap source of irrigation water will therefore create a stronger agricultural sector, which will be mutually beneficial to both the people of the region and the PoS and FZS, which are already the economic engines of the project area. The people will benefit as the growth of the agricultural sector and the industrial sectors will create more jobs and the PoS and the FZS will benefit economically as well by achieving their indirect goal of creating more job opportunities in the region.

The remaining question to be answered was how to achieve the goal of improving water management. In the view of all stakeholders the most untapped potential lies in (expanding) the reuse of industrial and domestic waste water. Because of the economic growth of the region both these flows are continuously increasing. MISC as well as the SDO have been planning to and are eager to expand the use of treated waste water but have encountered several obstacles in the way of large scale implementation. Three major obstacles were identified during the stakeholder investigation, yet the solutions were also presented.

The first obstacle is that treated waste water cannot yet be used for the irrigation of crops produced for human consumption due to concerns about its quality. This is a valid concern which holds especially for treated industrial affluent. At the same time the water can still be used for landscaping or for directly replenishing the aquifer at locations where it has been determined to be most urgent and safe until treatment methods are sufficient to guarantee the quality of treated water is suitable for irrigation.

The second obstacle is that even if farmers would be allowed to use this water for irrigation, it will cost more than installing a groundwater pump and therefore they will be unwilling to commit to treated water for irrigation. This obstacle can also be overcome by using the water for landscaping, directly replenishing the aquifer or by compensating/subsidizing farmers which adopt treated waste water for irrigation. Treated waste water could otherwise be used on farms which can no longer use groundwater due to seawater intrusion and therefore rely on external sources of water already.

Lastly, there is an infrastructural/organizational obstacle. As mentioned earlier in this chapter several important tenants at the port have installed their own water treatment facilities. Neither MISC nor the SIPC can force these companies to start using centralized treatment in the form of MISC unless a ruling is made by a higher authority that forces these companies to make use of Majis' treatment facilities. This has had the result that the treated water flow at MISC is currently too small for large scale applications. This could change if MISC manages to present at the FZS from the onset of the project. For the SDO their infrastructural obstacle is slightly different. They do have a significant flow of treated waste water available but still need a larger network in place which will enable them to deliver it to the areas where it is needed. SDO is currently working on expanding this network.

Another method of influencing water resources which has the support of many stakeholders is the construction of more recharge dams. The effectiveness of recharge dams is perceived differently among stakeholders but they are one of the few ways of harvesting at least part of the discharge from the unpredictable wadi flows into a reservoir from which recharge can occur. At the same time they serve the additional purpose of flood protection dams.

The final common suggestion among stakeholders for improved water management was a more integral approach to water management with more communication and cooperation between stakeholders. Due to rapid changes in infrastructure and land use as well as furthered knowledge relating to water availability and management it was felt to be a struggle at times to stay up to date with the latest developments. This can lead to missed opportunities for cooperation, which is vital for achieving the shared goal of all stakeholders; protecting the area's water resources from depletion and pollution.

5. Discussion

5.1 Towards sustainable water management

The Sohar area studied in this paper is economically essential to the country of Oman for two main reasons. The first is the presence of the Sohar Industrial Port. This rapidly growing port has quickly taken up a position among the major ports of the Gulf region. The other reason is that it is situated in the Al-Batinah province, which is the province most suitable for agriculture. The water balance in the underlying aquifer, on which this agricultural sector depends, has been disturbed for at least several decades now as was shown in this paper.

If sustainability in water resources is to be achieved it will have to come from a thorough understanding of the resources available as well as the demand for water resources from the local stakeholders. Until now the Omani government has tried to halt the negative trend mainly through the construction of recharge dams. While recharge dams can most certainly aid in achieving sustainability of water resources, their effectives on the long term is questionable and they will always be limited by the amount precipitation. Oman knows long periods of drought during which a recharge dam can do nothing to replenish the aquifers. Therefore the solution will have to come not only from measures that increase recharge but also from measures that decrease the demand. Several such measures have been discussed in this paper.

Perhaps most essentially measures have to be taken that limit the amount of groundwater used for irrigation. Either through the reuse of treated waste or by adopting advanced irrigation techniques this could be achieved. The presence of the Sohar Industrial Port and the increasing population in the study area have resulted in large amounts of waste water. As of yet the quantity (and quality) of treated water is not nearly enough to significantly alter the water balance. Yet in an area where fresh water resources are hard to come by and diminishing rapidly, the recycling of waste water will have to play a more important role if sustainability is to be achieved. Part of the solution will also have to come through increasing use of desalinated seawater. Already desalinated water is playing an increasingly large role in the study area. There are some drawbacks to the use of desalinated water, especially its cost, and none of the stakeholders in the area would like to depend completely on desalinated water.

Achieving sustainability of water resources in the Sohar area will not be an easy task, but one that has to be undertaken and will ultimately be in the best interest of all parties involved. Realizing that goal will require contributions from all parties and a multifaceted approach.

5.2 Methods & Further Research

The method of calculating the water balance in this paper was slightly unconventional. The more traditional method of summing up values such as evaporation, infiltration and discharge requires a much higher density of data and a more thorough understanding of the soil. Little is known in the study area about for example the rate of infiltration during precipitation events of differing intensities which is required for this approach. The method used in this paper was chosen as it relies solely on actual measurements rather than estimations of complex variables such as precipitation intensity, rainfall/runoff relationships and evaporation.

An issue with the chosen method was that the density of wells is very high near the coast but gradually decreases inland. To get a more accurate picture of water resources further offshore more wells are required in the mountains and the foothills. Nevertheless the plain is where nearly all agricultural activity takes place and it is where people live and thus it deserves priority.

The complex nature of the soils in the study area deserves priority if further research into this topic of this paper is to be done. The alluvial plains are the medium in which the groundwater travels but little is known about properties such as the depth of the layer and the different levels of cementation in the study area. As a result the depth and confining layers underneath the phreatic aquifer are little known.

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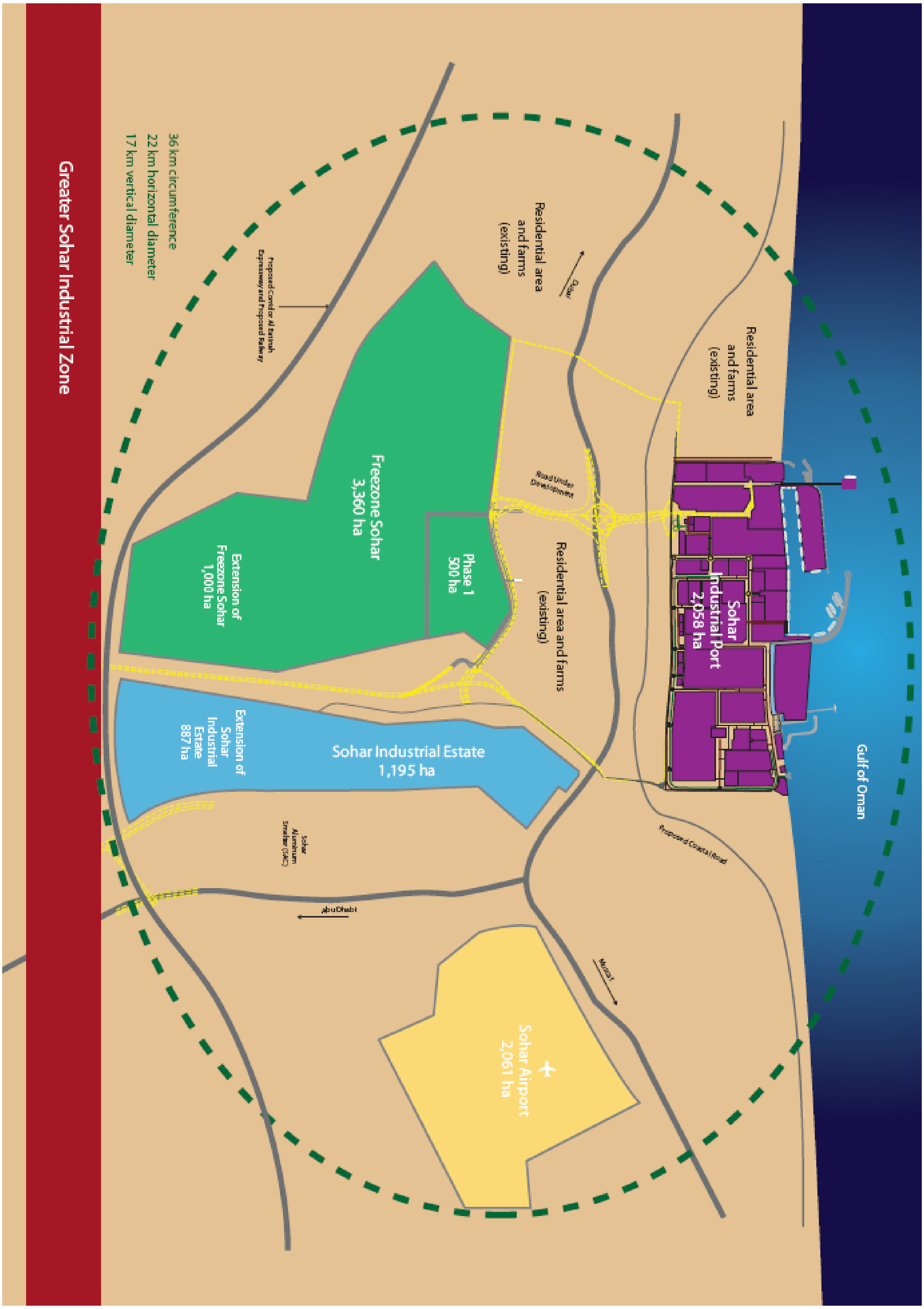
Appendix I: Map of the Greater Sohar Industrial Zone



Appendix II: Questionnaire for Stakeholder Interviews

Water Availability Management Study Sohar

Questionnaire for Stakeholders WAM Study Sohar

General questions

1. What is your position in WRM, how are you involved the WRM process within the Wilayets
2. What is your view on the current Water Resources Management situation in Sohar/relevant catchment area
3. How could water resources management be improved
4. Which organisational frameworks exist for your Stakeholder group, if any
5. Do you think you would benefit from an organisational framework for your Stakeholder group
6. Would you be interested in attending a work shop addressing water availability management in a broad perspective in the Sohar area

Project related

7. Which projects have you benefitted from most in recent years
8. What kind of WRM related projects would Sohar benefit from most in the coming 5/10/20 years
9. Which WRM related projects have been planned the coming 5/10/20 years
10. Would your stakeholder group be capable and willing to finance (part of) a major WRM related project
11. Would your stakeholder group encourage the construction of more dams for retention/flood protection/ground water recharge
12. Would your stakeholder group encourage reuse of treated waste water

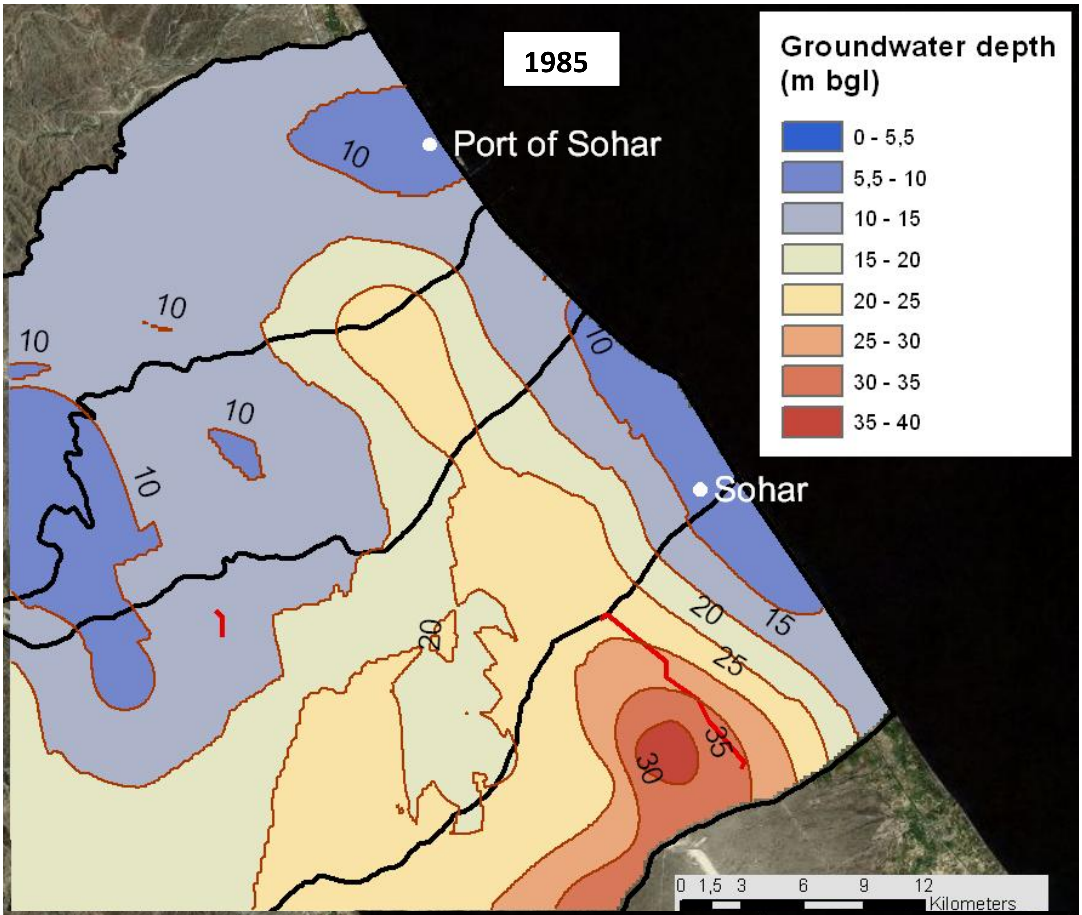
Threats

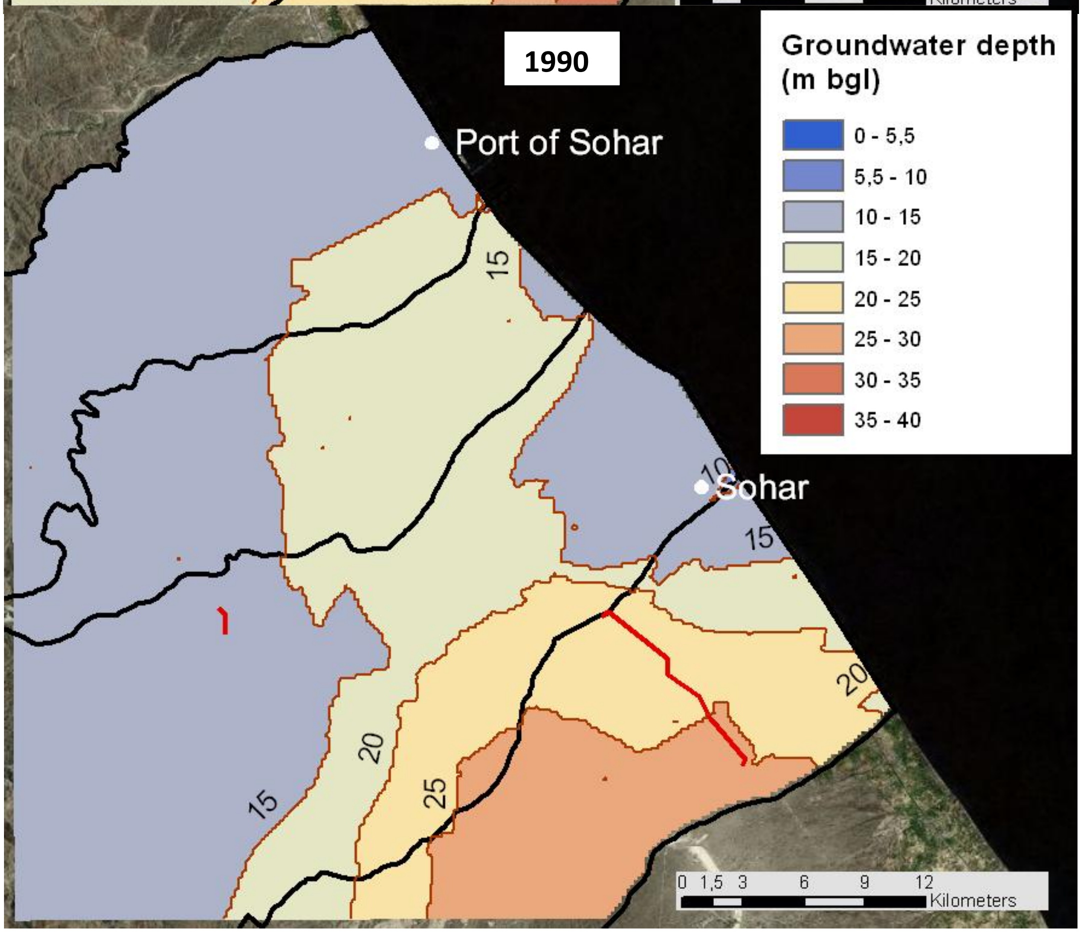
13. Which threats exist in Sohar/relevant catchment area
14. Is your stakeholder group confronted with any detrimental effects caused by salt water intrusion through ground water aquifers
15. Is your stakeholder group confronted with any detrimental effects caused by pollutants transported by surface or ground water

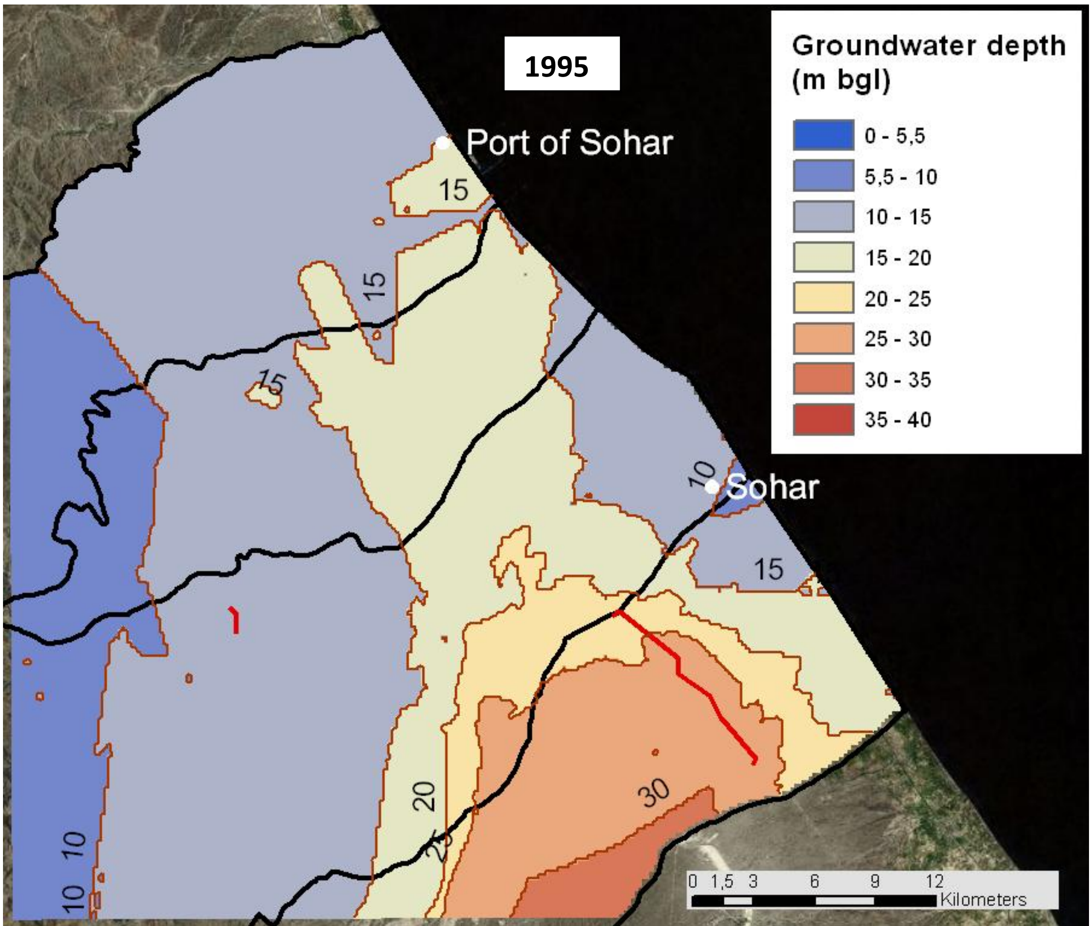
Data availability on:

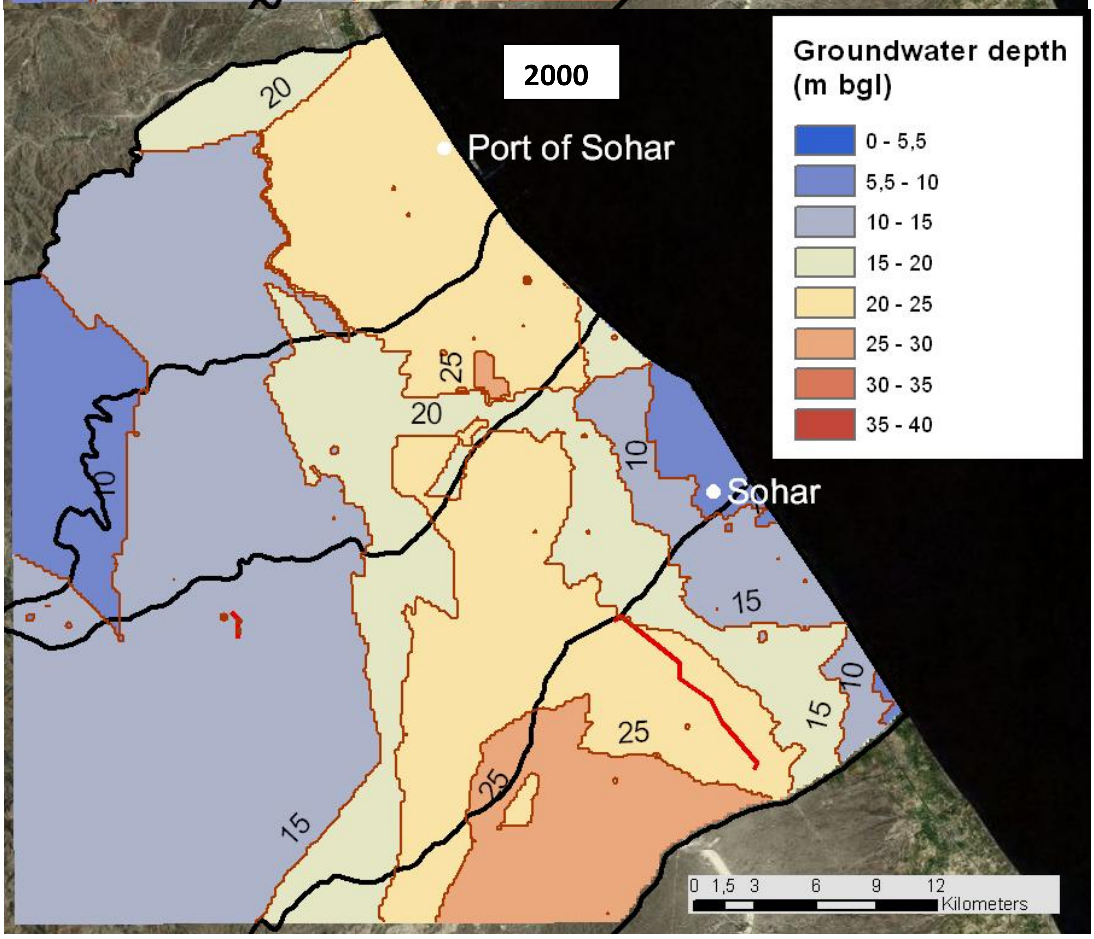
1. Water demand, water use, water production
2. Organisational structure
3. Projects ongoing within the WRM framework
4. Number of stakeholders within stakeholder group

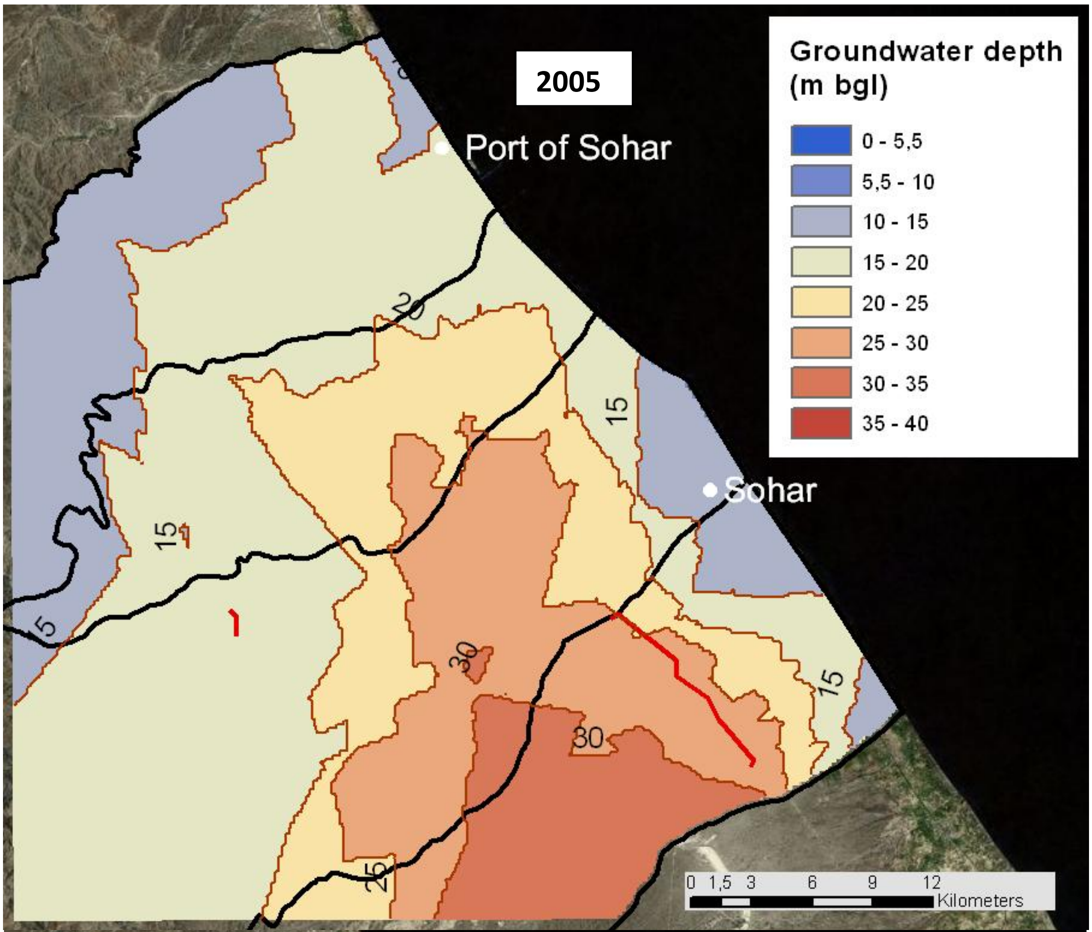
Appendix III: Groundwater depth '85, '90, '95, '00, '05, '09

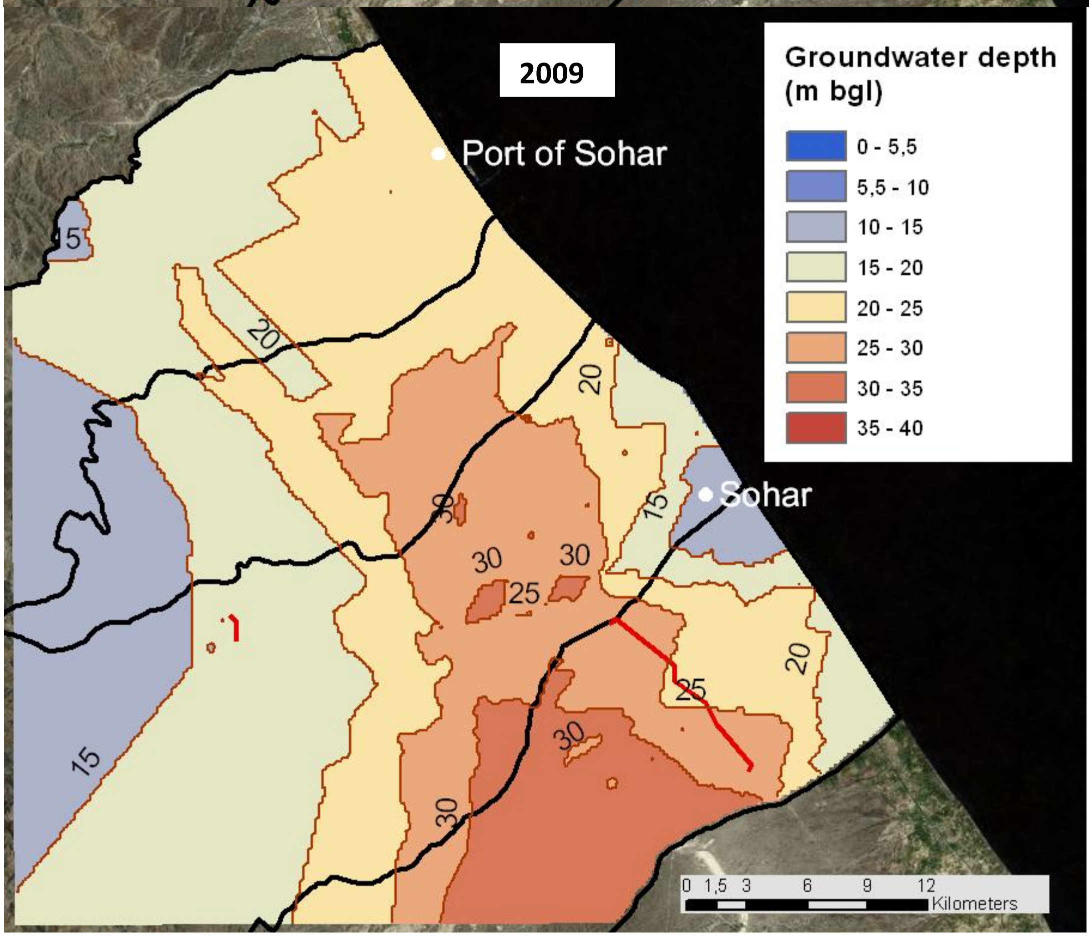




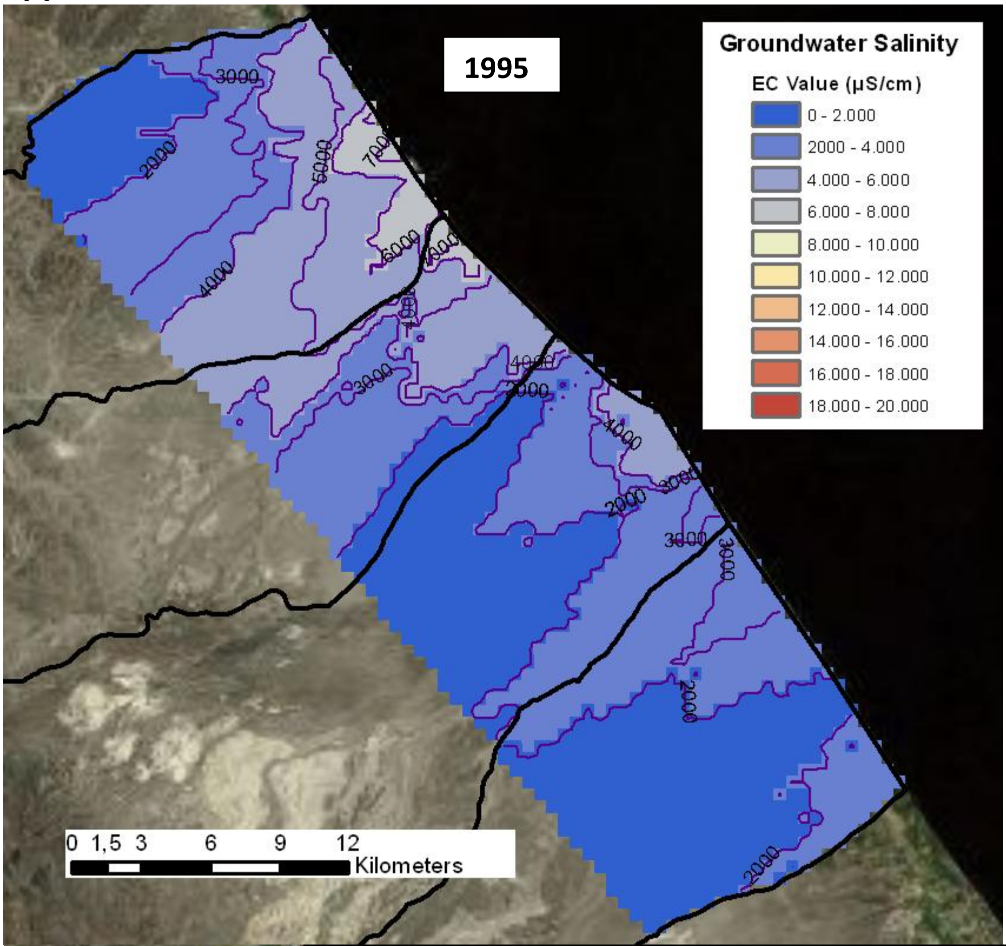

1995
Port of Sohar
Sohar
Groundwater depth (m bgl)
0 - 5,5
5,5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
0 1,5 3 6 9 12 Kilometers

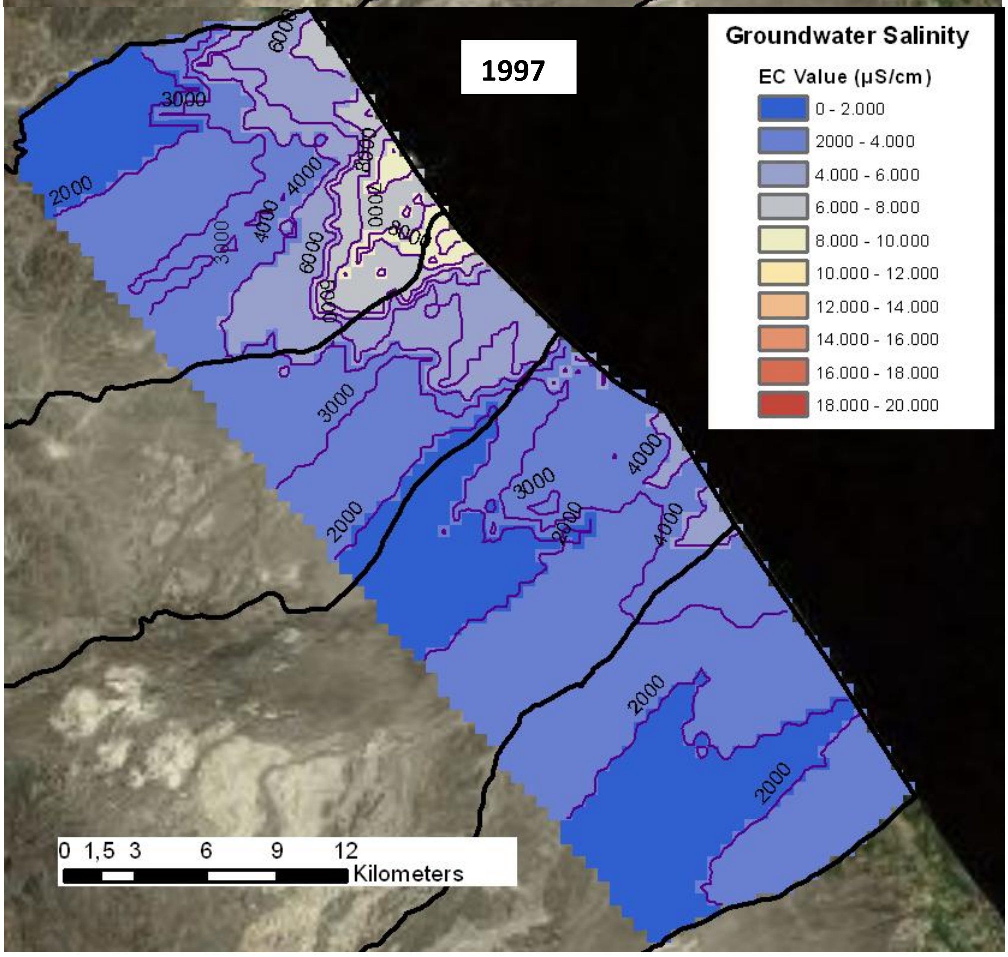

2000
Port of Sohar
Sohar
Groundwater depth (m bgl)
0 - 5,5
5,5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
0 1,5 3 6 9 12 Kilometers

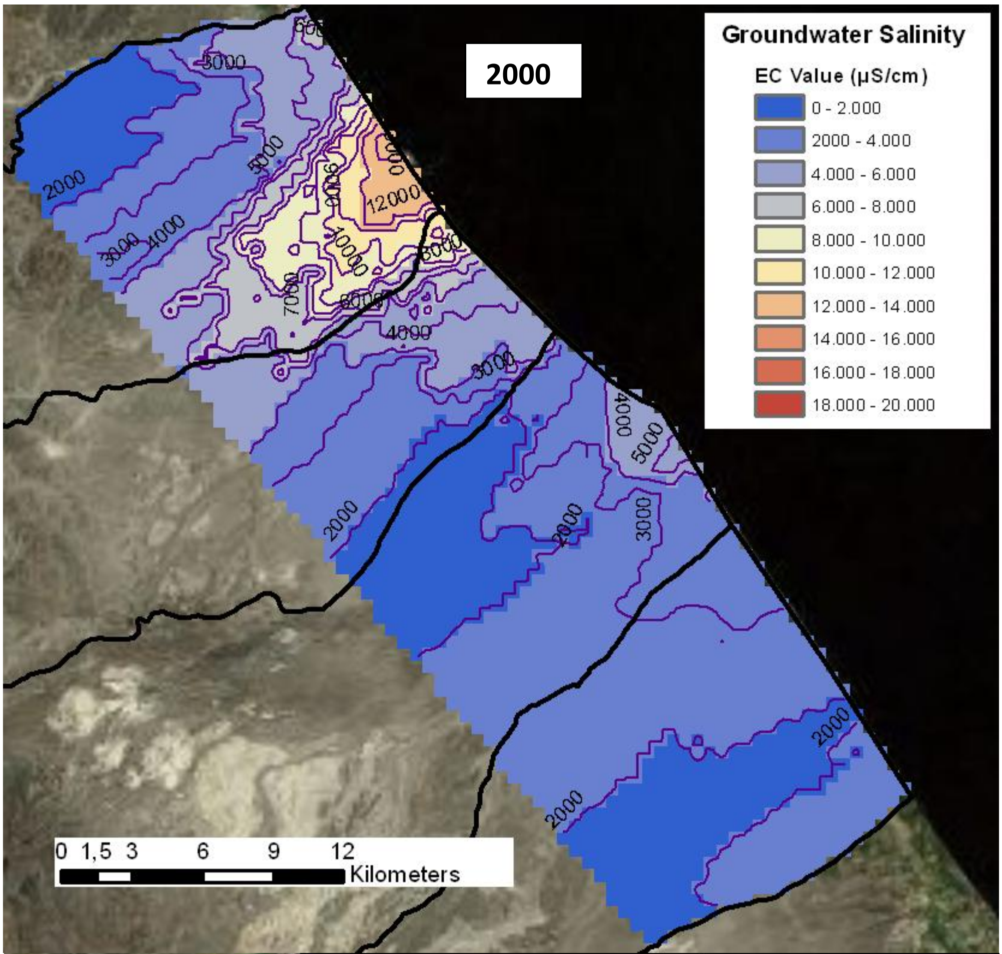

2005
Port of Sohar
Sohar
Groundwater depth (m bgl)
0 - 5,5
5,5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
20
15
15
15
15
30
30
25
0 1,5 3 6 9 12
Kilometers

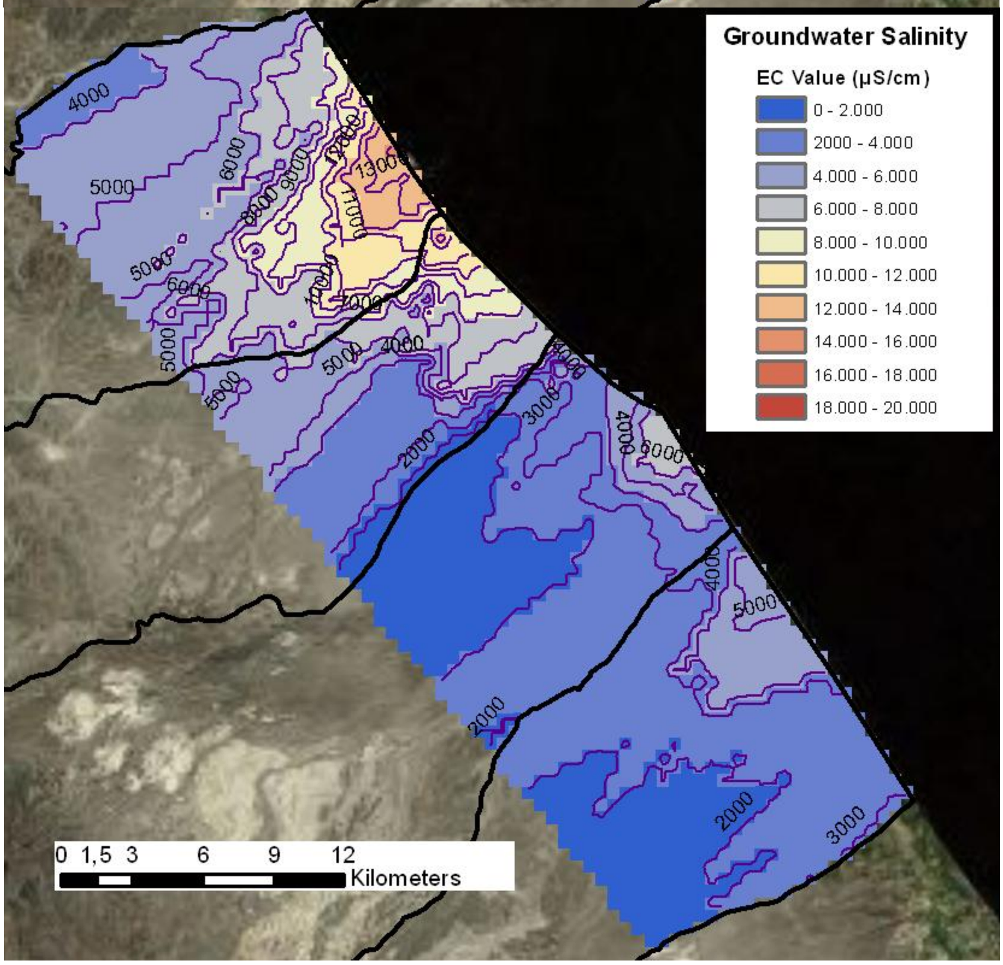

2009
Port of Sohar
Sohar
Groundwater depth (m bgl)
0 - 5,5
5,5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
15
20
20
15
30
30
30
25
25
20
30
30
15
0 1,5 3 6 9 12
Kilometers

Appendix IV: Seawater intrusion






2000
Groundwater Salinity
EC Value (µS/cm)
0 - 2.000
2000 - 4.000
4.000 - 6.000
6.000 - 8.000
8.000 - 10.000
10.000 - 12.000
12.000 - 14.000
14.000 - 16.000
16.000 - 18.000
18.000 - 20.000
0 1,5 3 6 9 12
Kilometers


Groundwater Salinity
EC Value (µS/cm)
0 - 2.000
2000 - 4.000
4.000 - 6.000
6.000 - 8.000
8.000 - 10.000
10.000 - 12.000
12.000 - 14.000
14.000 - 16.000
16.000 - 18.000
18.000 - 20.000
0 1,5 3 6 9 12
Kilometers

Appendix V: Yearly average water table fluctuations, catchment specific