An Assessment of Groundwater Resources in Salalah Wellfield Protection Zones

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DEDICATION

I would like to dedicate this work to Sayida Fatima Al- Zahra' - the daughter of Prophet Mohammad (pbuh), who has been a continuous source of inspiration to me.

Also, this research is dedicated to each and every member of my large and largely supportive and encouraging family, starting from my parents who really have deeply influenced my life success and their prayers and encouragements which helped me to accomplish this study and ending with the youngest member of the family who have given me their support.

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ABSTRACT

The Sultanate of Oman has seen a rapid development over the past three decades. As a result, water demand has risen in line with the development and improved standard of living. Many of the freshwater production wellfields are located in rapidly developing areas, where land values are high and frequent requests are received from landowners for various development activities. To protect the limited groundwater resources, Wellfield Protection Zones (WPZs) legislations were implemented in the Sultanate. The objective was to protect groundwater destined for the wellfields from contamination, over abstraction, saline water intrusion and adverse land development.

This study aims to determine whether groundwater in the Salalah wellfield protection zone is contaminated from existing development projects and whether the groundwater is of acceptable quality for drinking. Investigation of groundwater levels and salinity levels were part of the study. To achieve the aims of the study, a combination of collation, analysis of piezometric data and water quality data for Salalah wellfield protection zones were undertaken. A survey of existing development in red zone (the most critical zone) was done.

The study concludes that the net discharge from the production wells do not significantly caused changes in water levels in the aquifer. Water levels in the monitoring wells in the red and orange zones rose by 1.71m due to their location directly under the area of front of Jabel Al- Qara. Water levels declined by 0.13 m in the area where the large farms are located. Water quality parameters remained stable and comply with the Omani standards for drinking water. For example, Calcium level was 132 mg/l. Magnesium, Chloride, Sulfate, Nitrate and Fluoride some times approached the highest desirable levels but did not exceed them. They were at 27, 248, 42, 28 and 0.30 mg/l respectively. Trace metals, hydrocarbon concentration were within Omani drinking standards and no Coliform or E.Coli bacteria were detected in all of the groundwater samples. On the other hand, salinity in some monitoring wells increased marginally from 980 µS/cm in 1996 to 1100 µS/cm in 2004 in fresh groundwater zone. Whereas it increased from 4400 µS/cm in 1996 to 5000 µS/cm in 2004 in some wells in brackish groundwater zone. Increase in salinity was observed from 5000 µS/cm in 1996 to reach to 11000 µS/cm in 2004 in some wells in the closest part to the coastline. The increases in salinity may due to agricultural return flow, mixing of saline water from the deeper part of the aquifer or direct saline water intrusion from the area especially in the wells closest to the coastline.

The study recommends adoption of best management practices for Salalah WPZ and other WPZs in the Sultanate.

الخلاصة

شهدت السلطنة في الآونة الأخيرة كغيرها من بعض دول آسيا الوسطى، نموًا مضطردًا في عدد السكان واكبه نموًا وتطورًا هائلاً في التنمية الزراعية والاجتماعية والاقتصادية، وقد نجم عن ذلك ازدياد في الطلب على المياه لأغراض الشرب والاستخدامات الصناعية والزراعية، مما أدى إلى استنزاف المياه من الخزانات الجوفية التي تعتبر من أهم مقومات التنمية في السلطنة.

ولضمان حماية المياه الجوفية من التلوث والاستنزاف وتغلغل مياه البحر، قامت السلطنة بإنشاء مناطق حماية لحقول آبار إمدادات المياه في مختلف المناطق ، وتم إصدار القرارات و اللوائح والقوانين المنظمة للتنمية والأنشطة والمشاريع المختلفة والواقعة داخل نطاقات حقول الآبار.

هدفت هذه الدراسة إلى معرفة ما إن كان حقل آبار إمدادات المياه بصلالة، والذي يمد السكان بمياه الشرب والاستخدامات المختلفة قد تأثر بالملوثات من مختلف الأنشطة حوله، و معرفة ما إن كانت نوعية المياه الجوفية في هذا الحقل صالحة للشرب.

ولتحقيق أهداف هذه الدراسة فقد تم جمع بيانات مختلفة عن مستويات المياه لأبار المراقبة في هذا الحقل ونسب الملوحة فيها، وكذلك تم حصر جميع المنشآت الواقعة داخل النطاق الأحمر لحقل آبار إمدادات المياه بصلالة وسعادة و معرفة نوعية المياه الجوفية التي تمد السكان بالمياه للاستخدامات المختلفة.

ومن أهم النتائج التي توصلت إليها هذه الدراسة، هي أن مستويات المياه لابار المراقبة في النطاق الأحمر والبرتقالي لحوض إمدادات المياه بصلالة متذبذبة ، فهي من جهة تكون مرتفعة بحوالي ١٫٠٧م بسبب وقوع بعض الآبار اسفل جبل القارة مباشرة، في حين إن بعض المستويات تكون منخفضة بحوالي ٠٫١٣ م وذلك بسبب قرب هذه الآبار من المزارع الكبيرة التي تستهلك نسب ضخمة من المياه الجوفية لري مزروعاتها. كما أشارت الدراسة إن استهلاك المياه الجوفية من الآبار الإنتاجية لا تؤثر سلبا على مستويات المياه لآبار المراقبة القريبة منها ، وان نوعية المياه الجوفية فيها صالحة للشرب ، فقد لوحظ إن جميع تراكيز العناصر الكيميائية والهيدروكربونية لم تتجاوز الحدود المسموحة لمياه الشرب العمانية. فعلى سبيل المثال ، كان تركيز عنصر الكالسيوم في بعض الآبار حوالي ١٣٢ملغم/ لتر في حين كان تركيز كل من المغنيسيوم والكلور والكبريتات والنيترات والفلور هو ٢٧ ، ٢٤٨ ، ٤٢ ، ٢٨ ، ٠٫٣ ملغم/ لتر على التوالي ، كما لم تشر التحاليل البكتريولوجية عن وجود أي نوع من أنواع البكتريا في عينات مياه الشرب من تلك الآبار. من جهة أخرى ، لوحظ أن نسب الملوحة لمعظم آبار المراقبة و الواقعة في النطاق الأحمر لحوض إمدادات المياه بصلالة قد تزايدت بعض الشيء ، ففي سنة ١٩٩٦م سجلت بعض الآبار مستوى الملوحة فيها بحوالي ٩٨٠ ميكروسيمنز/ سم وارتفعت مستوياتها الى حوالي ١١٠٠ ميكروسيمنز/ سم في سنة ٢٠٠٤م، وكذا الحال في منطقة المياه الضحلة حيث ارتفعت مستويات الملوحة في بعض الآبار من ٤٤٠٠ ميكروسيمنز/ سم في سنة ١٩٩٦م إلى ٥٠٠٠ ميكروسيمنز/ سم في سنة ٢٠٠٤م ، اما بالنسبة الى منطقة الشريط الساحلي فقد سجلت مستويات الملوحة لابار المراقبة فيها إلى اكثر من ٥٠٠٠ ميكروسيمنز/ سم في سنة ١٩٩٦م حيث بلغت ١١٠٠ ميكروسمنز/ سم في سنة ٢٠٠٤م ، ولعل سبب ارتفاع مستويات الملوحة خلال فترة الدراسة يعود إلي كثرة الأنشطة الزراعية التي تقوم بها المزارع المنتشرة في النطاق الأحمر لحوض صلالة خاصة مما يؤدي إلى إنتاج مياه شديدة الملوحة إلى الحوض مباشرة او قد يعود سبب ازدياد الملوحة إلي التذبذبات الحاصلة للخزانات الجوفية أثناء الفترة الموسمية للأمطار (موسم الخريف) والفترات الأخرى وربما إلى التغلغل الملحي المباشر للآبار الواقعة على طول حدود الشريط الساحلي.

وعلى ضوء نتائج هذه الدراسة تم اقتراح تطبيق اللوائح والضوابط المثلى لإدارة حقل آبار إمدادات المياه بصلالة وباقي حقول الآبار في مختلف مناطق السلطنة.

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LIST OF ABBREVIATIONS

Above msl	Above mean sea level
ANOCOVA	Analysis of Covariance
Ca	Calcium
Cd	Cadmium
Cl	Chloride
Co	Cobalt
Cr	Chromium
Cu	Copper
EC	Electrical Conductivity
E	Ethyl Benzene
F	Fluoride
Fe	Iron
GC- MS	Gas Chromatography-Mass Spectrophotometer
Hg	Mercury
IC	Ion Chromatography
ICP	Inductively Coupled Plasma
km^2	Square kilometers
m^2/d	Square meters per day
Mm^3/year	Million cubic meters per year
Mn	Manganese
Mo	Molybdenum

MPN/100ml	Most probable number per 100ml
MSGD	Minister of State and Governor of Dhofar
Ni	Nickel
Pb	Lead
ppb	Part per billion
ppm	Part per million
T	Toluene
Vn	Vanadium
Z	Xylene
Zn	Zinc

CHAPTER 1
INTRODUCTION

1.1 General

The Sultanate of Oman lies in the arid region of the world with irregular and scant rainfall. The water demand is mostly dependent on groundwater resources for domestic, municipal, agricultural and commercial purposes.

In the last three decades, Oman has seen an unprecedented development. A rapid increase in population and the accelerated increase in industrial and commercial development in the country resulted in an increase in water demand and increased waste generation. This exerted a heavy load on groundwater supplies, leading to water deficiency, resulting in lowering groundwater table and seawater intrusion in coastal areas.

On the other hand, most soils in Oman are of low organic contents with high infiltration capacities; which favors rapid movement of surface applied chemicals and fertilizers to groundwater (Al-Shoukri, 2002). Because of that, a number of groundwater pollution incidents, originating from leakage of underground storage tanks and seepage of leachates from mine tailings, have been reported. Agricultural developments utilizing inorganic fertilizers and pesticides are also a major concern for groundwater pollution.

Increasing demand upon municipal wellfields, coupled with rapid infrastructure development and agricultural expansions, have emphasized the need to protect municipal wellfields by implementing the Wellfield Protection Zones (WPZs) legislation.

1.2 The Need for Wellfield Protection

In Oman groundwater is critical because water supply is predominantly dependant on it. The available fresh water is very limited and relies only on the rainfall. Over-utilization of groundwater to meet the increase in water demand is threatening water quantity as well.

Water quality could deteriorate due to contamination from domestic, agricultural and industrial waste. Also, water quality is being threatened by seawater intrusion, considering that, in Oman, soil layer above the aquifers is relatively thin or absent in most areas (MRMEWR, 2002). The nature of soil reflects the aquifer properties or the characteristics of the groundwater table, and the velocity of flow of groundwater determines the vulnerability of the aquifer to pollution (WHO, 1984).

The most vulnerable strata in Oman are the uncemented coarse wadi gravels in active wadi channels and fractured limestone (MRMEWR, 2002). It is possible that the fractures in the rocks provide migration pathways of pollutants (HMR, 2004) and this is posing a great threat to human health. Therefore, both water quality and quantity should be protected if future generations are to continue accessing water from the wellfields.

Protection of groundwater quality from the impact of human activities is a high priority for land use planners and water resources managers. This situation has arisen because:

- Groundwater moves slowly through the ground and so the impact of human activities lasts for a relatively long time,
- Groundwater may be difficult to clean, even when the source of pollution is removed, and
- Unlike surface water, where flow is in defined channels, groundwater is present everywhere.

Therefore, regulations have been issued requiring that pollution must be prevented as part of the sustainable groundwater quality management.

1.3 An Overview of the Wellfield Protection Zones

A wellfield is a group of production boreholes located close to each other within a reasonable distance, located in the same catchment, and supplying domestic water to a town or village. These wellfields are drilled and operated by the Ministry of Housing, Electricity and Water, the principal exceptions being Sohar water services provided by Diwan of the Royal Court and the Dhofar region, where water services are provided by the office of the Minister of State and Governor of Dhofar (MSGD). The management and protection of the wellfields is the responsibility of the Ministry of Regional Municipalities, Environment & Water Resources (MRME & WR). These wellfields are increasingly required to produce more water to satisfy demand, stretching their capacities and sometimes leading to over abstraction. Also, it is recognized that the need for water to be protected from pollution has to be balanced by the need for land/urban development. This poses a technically and politically challenging problem as management aspects of wellfield protection involve a wide range of factors requiring structural and non-structural ways of managing water resources. The aims of wellfield protection are to prevent any pollution reaching groundwater and to save the resources from over abstraction.

The zoning of the wellfields is based on travel time of potential pollutants to reach groundwater, basic hydrologic data and the direction of groundwater flow (Stott House & Road, 1992). They were categorized according to the distance from the site to the first upper production well of the wellfield (Al-Riyami, 1996). The most important aspect of wellfield management considered is the development of optimum operating policies. A total of four zones in the Sultanate of Oman, are used for the protection of wellfields:

The red zone: is the area immediately surrounding the municipal wellfield, in which pumping from other wells, or any release of contaminants, has an immediate and measurable effect on the quantity or the quality on the groundwater. The time for any particle to contaminate groundwater takes only one year.

The orange zone: is the outer zone and the main recharge area to the well field in which the travel time for any particle to contaminate groundwater takes 10 years,

The yellow zone: is the remainder of catchments upstream of the wellfield.

The blue zone: is an area downstream of the wellfield up to the coast, in which excessive pumping is likely to cause saline water intrusion.

This study deals with the hydrological and water quality assessment for Salalah wellfield protection zones, which were promulgated by the former Ministerial Decree No. MD 45/88. Then it was replaced by Ministerial Decree No MD 196/2001 due to the reviewing of protection plan, and finally to MD 308/2001 on 14 November 2001, due to new addition of Wadi Darbat wellfield protection zones to the Article (1) of the Minsterial Decree No MD 196/2001.

1.4 Objectives of the Study

The Salalah water supply wellfield is the largest developed source of fresh water in the Southern Region of Oman. As such, it must be protected as a valuable national resource. One of the main constraints is the over consumption of freshwater and intrusion of saline water. More water is being consumed by the domestic uses and rapid agricultural development.

The main objectives of this study were:

1. To determine whether groundwater in the Salalah wellfield protection zones is contaminated from existing development projects.
2. To evaluate whether groundwater in the Salalah wellfield is of acceptable quality for drinking.

Specific Objectives include:

1. Identification of potential sources of pollution in the red zone of the wellfield area.
2. Investigate whether groundwater levels are falling due to groundwater pumping.
3. Determine groundwater quality of production wells in the Salalah Wellfield Protection Zone.
4. Discuss solutions, providing recommendations for management of water resources in the Salalah wellfied protection zones.

1.5 Scope of the Project

A four-step methodology was adopted to achieve the objectives of this study. First, a detailed literature review was carried out to gather the background information. However, some difficulties were faced in searching the literature. Second, water level, abstraction, rainfall and salinity data were collected from the database of the MRME&WR and from the office of the Minister of State and Governor of Dhofar. This was done by meeting with several departments and directors of these offices. Third, sampling procedures for major chemical ions, hydrocarbon and microbiological analysis were selected and samples were collected and analyzed accordingly. Finally, on the basis of the data collected for this study, several types of statistical analysis were performed, for example the analysis of Covariance using Data Desk program, Hill plot and Surfer analysis.

CHAPTER 2
LITERATURE REVIEW

2.1 Management of Water Resources Protection in the Southern Region in the Sultanate

Several studies were conducted to provide the framework for actions that protect groundwater in Southern region of the Sultanate of Oman. Some of them are discussed below:

John Taylor & Sons (1979)

The aim of this study was to find a new source of fresh water supply at Salalah town that comply with the WHO water quality standards. The findings showed that saline water from the coastal zone and brackish water from the east and the west of Salalah plain may intrude due to the over abstraction needed for domestic water and for agriculture activities, which exist near the wellfield area. Samples from wellfield area were collected and compared with WHO standards. The results showed no deterioration of water quality. The study suggested to relocate big farms from the wellfield area, and also suggested making protection zones around the wellfield area and to set regulations to protect groundwater from any pollution. The study recommended monitoring water quality regularly and building desalination plants for alternative resources.

WS Atkins international (1989)

This study discussed many topics under spectral development section including agriculture, livestocks, fisheries, oil, minerals, industries and services for the southern region, discussing also spatial development of population, settlement planning, utilities, transportation and environment conservation. Finally this report discussed support inputs including water resources and human resource development, mentioning accelerated development, where there is a danger of overutilizing of water resources. Therefore, the main conclusions were that the southern region needs to proceed cautiously in its water resources development. It suggests continuing monitoring of the water table and saline intrusion on the Salalah plain; investigating possible water resources development using a mathematical hydrological model, providing licenses of new boreholes with implementing legislations.

Dames and Moore International (1991)

The master plan study was prepared for the protection and development of the water recourses of Salalah and for the provision of water supply and wastewater disposal infrastructure needed for the rapidly growing city. The study suggested several alternatives to protect ground water from over abstraction. These alternatives were assessed in terms of their technical, economic, social and environmental viability. The alternatives include desalination and new water resources, relocation of some activities, aquifer recharge with reclaimed water, blending of reclaimed water with new water resources.

Dames and Moore International (1993)

The purpose of this study was to evaluate the environmental impacts of the project and to identify appropriate measures and monitoring programmes. This study represented the first phase of the implementation of Water and Wastewater Master plan for Salalah. It was reported that fresh water supply is in the form of an unconfined fresh water aquifer, which serves as the source of water for potable and other uses. However, the aquifer is being over abstracted, resulting in the interface of seawater and brackish water. Therefore, the Master plan for Salalah was prepared; to protect and develop effectively the water resources of Salalah and to, provide an adequate water supply and wastewater treatment. It was concluded that, major benefits will result from the implementation of Salalah Wastewater Project and best measures will be developed to minimize the adverse impacts.

Entec Europe limited (1998)

The main objective of this study was to determine ways of maintaining development activities whilst minimizing risks to wadi Adai, Al Khowd in Muscat and the Dhofar Governorate Municipal in Salalah. However, due to the continued rise in population and expanding demand for land and water, reviewing of the wellfield protection zones policies were conducted. The study recommend that all existing developments should adopt best practices to reduce the risk of pollution of the aquifers, groundwater should be controlled, a program of public awareness and training should be considered, monitoring of water quality in the wellfields should be carried out and finally relocation of some modern farms.

Binnie &Partners Ltd (1999)

This study presents an integrated catchment management plan for Salalah water assessment area. Its purposes were to consider how to protect both existing and future sources from contamination, to discuss measures to promote the efficient use of water and to consider ways in which demand may have to be managed when supplies are limited. It recommended relocating agriculture activities near wellfield area and implementing national actions programs such as introducing domestic/ municipal and agriculture water tariff.

HMR (2004)

The aim of the study was to review the acceptability of the current wastewater recharge scheme. The review followed a series of studies conducted during 1990s, which identified the alternatives for the augmentation of groundwater resources and prevention of saline water intrusion. The study made some important recommendations. First the effluent qualities should meet the drinking water standards at the point of injection. Second, injected wastewater should remain for at least one year in the ground and distributed in the potable water supply system. Next, a minimum separation distance of 600m should be maintained between extraction wells and injected wells. Finally, the monitoring wells should be provided to detect the influence of the groundwater recharge.

GEO-Resources Consulting (2005)

The aim of this study was to provide a quantitative understanding the Salalah water resources, formulating an appropriate water resources development and allocation plan for the future (up to 2020). This study used a groundwater model to evaluate historical and future water resources development scenarios in addition to the assessment of management options in relation to the water resources of Salalah Region. The study concluded that there was a significant reduction in the groundwater quality along the coast. It recommended applying the best water practices management, removing large farms near wellfields, and expanding wastewater re- injection scheme.

2.2 Protection of Groundwater

Good water management is the key to solving most water problems. Viessman and Hammer (1985) discussed surface and groundwater management and protection in terms of quantity and quality. The topics discussed some problems, which originated from various kinds of activities on water resources. The pollution from non-point sources or diffuse sources discussed by Novotny and Chesters (1981) mentioned plannings and management of this type of pollution on water quality included conservation practices, modeling techniques, management practices. Barcecona et al. (1988) discussed measures that can be taken to ensure protection of the natural groundwater resource. Many specific contaminated sites of groundwater were investigated. The measures which are taken by U.S EPA to protect surface and groundwater have been discussed by Barcelona (1990) in order to make reliable predictions about the response of contamination to various corrective measures. Meredith et al. (1992) provided a method to delineate wellfield zones and the characteristics of each zone. They also reported the ways in which pollutants can reach groundwater. In order to use scientific methods for groundwater protection planning, Flockhart et al. (1993) examined three test cases in their research using GIS (geographic information system). They concluded that this technique supports regulatory and land acquisition decisions for setting a public water supply. In order to protect water resources in the various countries, many of the agencies provided regulations and legislation to reduce water pollution. The Federal Ministry for the Environment, (1993) in Germany enforced and initiated a large number of measures to improve the quality of water.

The study, which was conducted by Al-Harthy (1995) on Wadi Maawil area in Al-Batinah region in the Sultanate, showed that the aquifer is unconfined and is vulnerable to contamination. The aim of the study was to use GIS to collate diverse spatial data, produce a GIS model which emulates the decision making process in formulating WPZ and build an on- line interface that will allow queries of the GIS model for protection planning and management. The study concluded by using a GIS model in which all the relevant information for aquifer protection can be integrated in a geographically referenced framework for assisting decision-making. GIS system can be also used to monitor changes in water quality. In his thesis, Bait-Ishaq (1995) aimed to use GIS and remote sensing for spatial analysis to identify the relationships between changing water level, water quality and land use in Al Batinah Region. The study concluded that due to the excessive well pumping, particularly near the coast, the groundwater levels declined and more fresh water was replaced by seawater. Recommendations were made for implementing sufficient management measures to save groundwater. Al Riamy (1996) on Wadi Adai aquifer potential and future use, reported the importance of zoning the wellfield in order to develop a protection mechanisms for Muscat water resources. Wellfield protection is one management strategy to protect major aquifers from pollution. The efforts of the Sultanate as a case study in delineation protection zones and associated regulations were discussed by Al-Shoukri (2002).

2.3 Groundwater Quality

It is essential to protect groundwater resources against overexploitation, resulting from human activities and pollution. Therefore, the resources should be protected and managed. Some studies have been reviewed for this purpose.

The problem of saline intrusion in the unconfined aquifer in Al Batinah region in Oman was discussed by Stanger (1985). The problem was due to agricultural expansion, which existed near the coast and consumed a lot of freshwater. The increase in urban and industrial water demand is another reason for salinity problem. The article recommended implementing water conservation measures and appropriate management. Zinger and Michael (1993) and Ellis et al. (1993) described the status and trends in the water quality for surface water and groundwater separately of the study area in USA. The article provided understanding of the natural and human factors affecting water quality through considering the characteristics of hydrologic, geologic, water and land use. A comprehensive and practical advice on designing and setting up monitoring programs was given by Chapman (1996) in order to obtain valid data for water quality assessment in all types of freshwater bodies. A discussion of hydrological processes concerned with the means of entry, distribution and self purification of pollutants in surface and ground water were also conducted in addition the effects of such pollutants on the health of human beings.

The subjects of the document by Wiley & Sons (1997) concerned on the impact of drinking water parameters on public health and conducted a reliable drinking water sampling and monitoring. The Quality of the groundwater samples has been assessed by comparison with the Omani standards No 8 for Drinking Water issued by Ministry of Commercial and Industry (MCI) (1998). Martinez.& Bocanegra (2002) discussed the problem of water quality deterioration in Mardel Plata in the Argentine near Atlantic coast. They found that human activities lead to salinity interface with freshwater.

2.4 Water Resources in the Sultanate of Oman

In order to gain a broad overview of the Southern Region water resources, studies which were conducted by consultants with the help of various ministries. PAWR (1983) summarized data and information on water resources of the sultanate. The descriptions were based on data collected and reports prepared by the Public

Authority for Water Resources, by numerous consultants and government agencies. Some of the important references of geological maps and their detail explanations of the geological status in all regions of the Sultanate, were prepared by Platel et al. (1992). These studies were issued by the former Ministry of Petroleum and Minerals (MPM). The former Ministry of Water Resources provided a report on the management of water resources in Salalah plain and Jabel Al Qara (MWR, 1995), which presented some measures to asses groundwater resources in the Southern Region such as utilizing of Khawrs, enhancing recharge in the Jabel Al Qara and others.

Mott Macdonald (1999) in the master plan for the ground water pollution protection study in the Sultanate of Oman, covered many topics. Some of them covered the areas with large change in ground water characteristics including Salalah and Batinah plain of the Sultanate. It was stated that the problem of over abstraction of ground water leads to the intrusion of saline water, unless serious action is taken to overcome this problem. The study recommended implementing groundwater policies to ensure preventing pollution. The other important topic of this study was concerned with the areas where contamination can easily cause loss of exploitable ground water. This topic discussed the requirement of special protection for all public water supply wellfields that exploit good quality groundwater. It also discussed wellfield protection guidelines that define policies aimed at controlling development in the Wellfield Protection Zone (WPZ). It recommended reviewing the protection regulations of Salalah and Muscat wellfields. MRME &WR (2004) provides some details about hydrology and groundwater status of all regions in the Sultanate.

CHAPTER 3
THE STUDY AREA AND WATER RESOURCES

3.1 Location

Salalah is the major regional center in the Dhofar region of Oman. It is situated on the southern coast of Oman and lies between latitudes 16° 55′ and 18° 00′ and longitude of 54 ° 00′ to 55 ° 30′ (Platel et al., 1992). The area is bounded by Saudi Arabia to the northwest, by the Republic of Yemen to the southwest, and by the Arabian Sea to the southeast. The estimated expansion of the population including Saada from 161,993 individuals in 2003 (MNE, 2003) to an estimated 294,000 individuals in 2020 (Entec, 1998) will require a major increase in housing and in land for industrial, commercial and general urban uses.

The region can be divided into three main areas as shown in (Figure 1):

- The Salalah coastal plain which extends to about 10 Km from the coast.
- The Jabel Qara, a mountain range, which borders the plain and extends along the southern coast of Oman.
- The Nejd, a flat arid area that lies inland of the Jabel Qara, sloping gently to the north.

3.2 Hydrogeology and Geology

The Salalah plain extends for around 800 km^2 (PAWR, 1983) and is underlined by limestone of the Taqa Formation, with a mostly thin covering of wadi alluvium and calcarenite (MRME&WR, 2004). The groundwater is contained in the alluvium and the limestone. It is related to the fissured and Karstic zones of the uppermost member of the Taqah formation (HMR, 2004). In the Salalah Plain, it was suggested that the alluvial deposits could also act as an unconfined aquifer. In general, the hydrogeological characteristics of the aquifer are complex (MRME&WR, 2004).

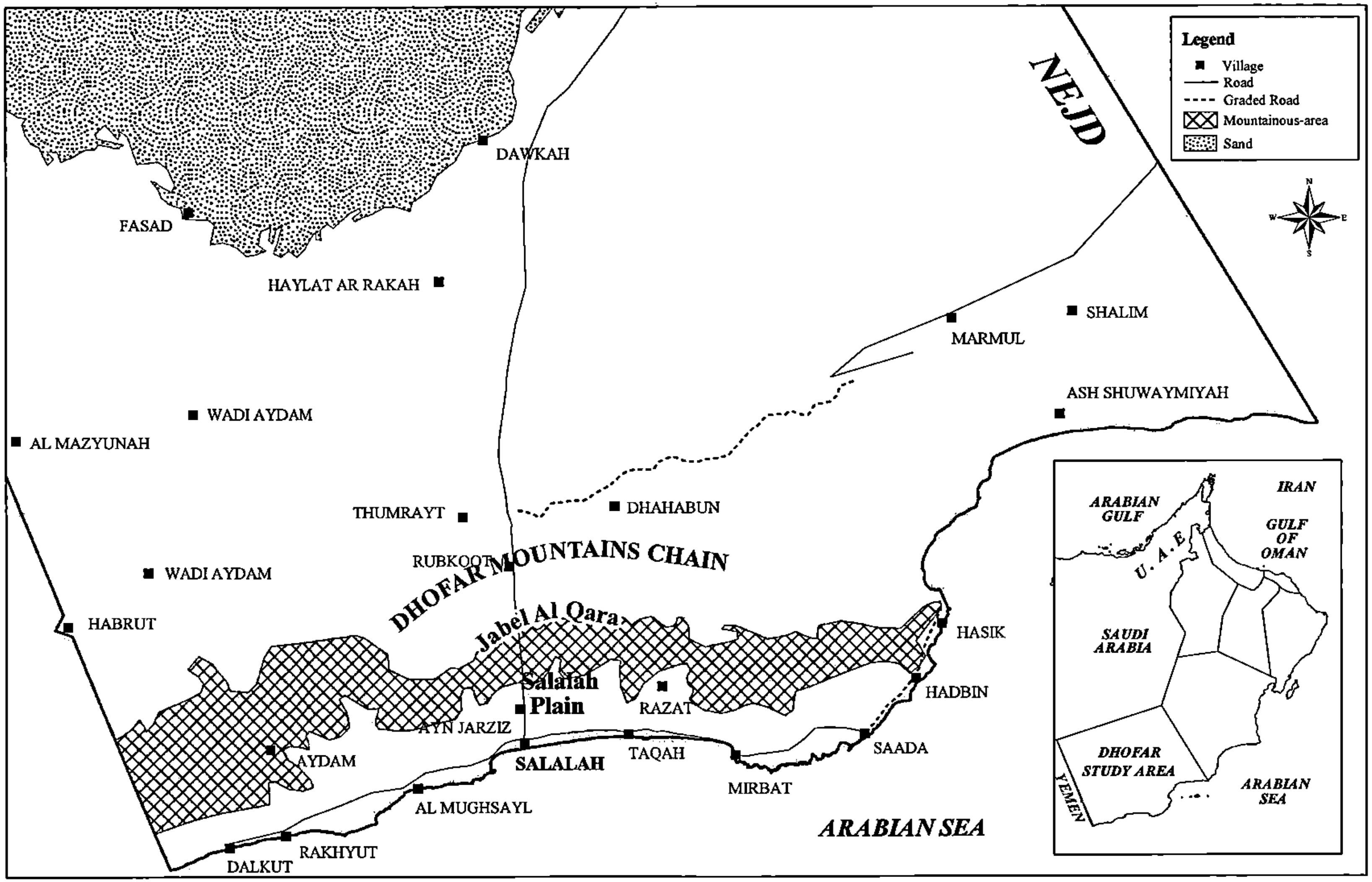


Figure 1. Location of the study area

Platel et al. (1992) states that the Salalah plain is a specific geological domain, corresponding to an extensive subsided block bounded by major normal faults brought the Um Er Radhuma (UER) and Dammam Formation next to younger rocks of the Adawnib Formation. The Salalah plain is unique because it consists of the only known deposits of limestone in the area, which is organized into three groups, Fars, Hadramaut and Dhofar Groups.

3.3 Hydrology

The Salalah plain area has a very different climate from the rest of the country. It is characterized by high humidity and low potential evaporation during the winter, and a cooler summer that is dominated by the Kharif (Monsoon) season between June and August with much of the rain falling on the southern slopes of Jabel Qara. Heavy rainfall may occur in any season during rare cyclonic storms resulting in surface floods.

MWR (1995) reported that much of the freshwater in the Salalah plain come from subsurface flow of wadis from the Jabel al Qara. These are Wadi Jarziz, Wadi Sahalnwt, Wadi Razat and Wadi Hamran and to a lesser extent rainfall infiltration and surface floods on the plain, also contribute to freshwater supply.

3.4 Water Resources of the Study Area

Salalah plain depends on groundwater for its water resources, which originates from a tongue of fresh groundwater that extends through the center of the plain to the coastal margin (MRME&WR, 2004). The quantity of groundwater available in the wellfield is limited by the natural groundwater recharge. The recharge of groundwater comes principally from the Garziz, Nahiz and Sahalnawt drainage areas (Pendleton, 1986).

In the early of 1970s, Salalah town was supplied by water from a larger supplier of Umm al Ghawarif wellfield (Entec, 1998). But this was replaced with two wellfields located to the north of the town on the coastal plain that underlies the western part of Salalah plain and the eastern developed area of the city. Salalah wellfield was constructed in 1982, with 10 production wells at that time, but due to the expansion of the population and increasing water demand, Saada wellfield was constructed in 1986 with 3 production wells (Mott Macdonald, 1999). Recently one more well was dug in each of these wellfields. The total volume of water abstracted from the two wellfields in 2004 was around 9.5 Mm3/year (HMR, 2004).

As discussed earlier, four protection zones delineate all wellfields. The Salalah wellfield as shown in (Figure 2), consists of two wellfields Salalah and Saada. The red zone, which surrounds the production wells for both Salalah and Saada wellfields, extends along an area of about 50 km^2. The outer orange zone extends along an area of about 200 km^2, the recharge to this zone comes from wadi Naheez, Wadi Sahlanout and wadi Garziz, the inflow from these wadis. The yellow zone has an area of about 400 km^2, and finally the blue zone extends along 100 km^2 of Salalah plain.

3. 4.1 Aquifer Properties

The two wellfields are located in Karstic limestone of the Baleed Formation (HMR, 2004) which is the main aquifer on Salalah plain. The fresh water aquifer is recharged during the Monsoon (Khareef) season. During this season, part of the precipitation reaching the groundwater in the Jabel percolates through the Umm er Rhaduma limestones formation and flows out into the plain (COWL Consultant, 1992). The through flow from the Jabel to Salalah plain was estimated by steady state model of about 55 Mm^3/year (GEO-Resources, 2005). Further water supply for the area comes from perennial springs, which issue from the edge of the Jabel Qara. Ellis et al. (1993) reported that the recharging to the aquifer can occur by several different processes:

- Infiltration of direct rainfall,
- Infiltration of excess applied irrigation water,
- From springs at the foot of the mountain area,
- Infiltration of surface water,
- Subsurface flow from the mountain area.

Depth to the water table extends to about 70-90 m near the front of the jabel (PAWR, 1983). The transmissivity of the Baleed member aquifer is very high due to its Karstic nature; four-days pumping tests in the Salalah wellfields gave tranmissivities of 1100 to 150,000 m^2/d. Storage coefficients from these tests ranged from 0.007 to 0.01(Taylor&Sons, 1979). In the northern Salalah plain pumping tests gave tranmissivities from 198 to 5472 m^2/d and the storage coefficients of $6.5x10^{-6}$ to $6x10^{-2}$ (Entec, 1998).

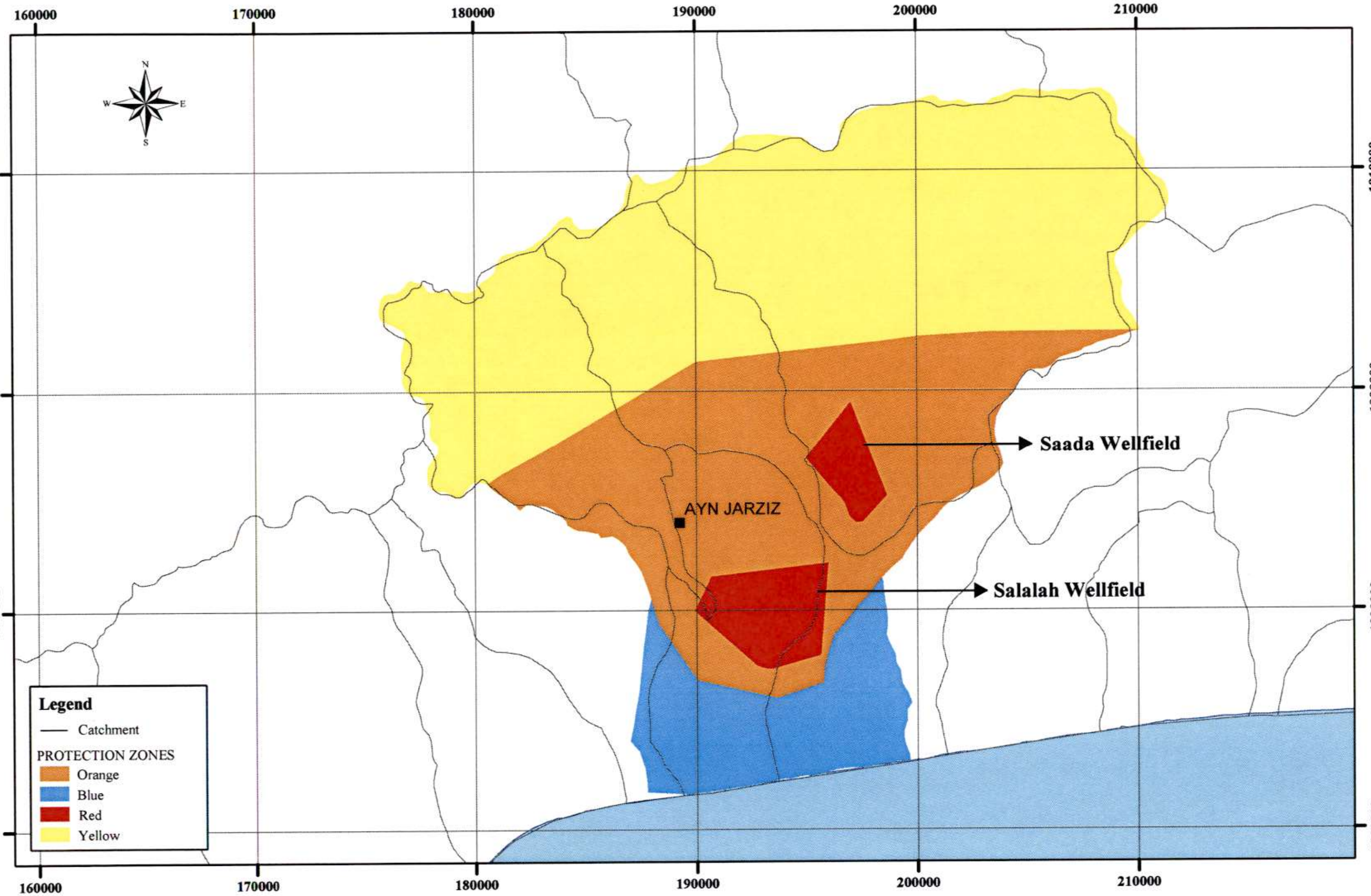


Figure 2. Salalah wellfield protection zones

CHAPTER 4
DATA COLLECTION AND ANALYSIS

4.1 General

Data for the present study were collected in the red, orange and blue zones of the wellfield, from 1996 to 2004. These data are stored in the Environmental Database of the Ministry of Regional Municipalities Environment and Water Resources (MRME&WR) and the office of the Minister of State and Governor of Dhofar. The data covered the whole study area, and data accuracy was verified by reviewing previous studies.

4.2 Inventory of Pollution Sources

In the areas around the public water supply wellfield, there is concern that existing developments within the wellfields may be causing contamination of the groundwater. Contamination can occur either as point sources, such as from the landfilling of waste or diffuse use of chemicals, such as fertilizers and pesticides.

4.2.1 Groundwater Contamination by Pollutants

Some serious pollutants can be detected in groundwater. Nitrogen and some toxic metals (Cadmium, Mercury, Copper and Zinc) are examples of pollutants that can contaminate groundwater in quantities above acceptable levels (Novotny & Chesters, 1981). Organic matter, phosphate and pathogenic microorganisms are immobile in most soil and groundwater, and are usually absent unless considerable leaching from contaminated surface occurs (Novotny & Chesters, 1981).

4.2.2 Pathways of pollutants through the aquifer

Groundwater contamination mostly occurs in recharged area (Novotny & Chesters, 1981) through fractures in the rocks or as leachate from soil. Barcelona (1990) reported the pathway of contaminates to reach groundwater. This can be summarized as follows:

- Passage through the unsaturated zone, in such processes as volatilization, ion exchange, adsorption, oxidation and biodegradation.
- Passage through the saturated zone by ion exchange, adsorption, dilution, dispersion, oxidation, biodegradation and precipitation.
- Arrival at groundwater sources.

In Salalah catchment, the plain is covered by clayey to loamy soils (MAF, 1990). When soils are rich in clay and organic matters, sorption and biodegradation of contamination can occur (Entec, 1998). As discussed earlier in section 3.2 the nature of Salalah plain is considered to be fissured; as such many types of contamination can reach groundwater. (i.e, bacteria and pathogens, fertilizers and pesticides. This also applies to waste produce around industrial facilities, leakage from above and underground petroleum storage tanks and by leakage from underground septic tanks.

In order to detect pollution sources, which are considered to contaminate groundwater resources, a survey of existing activities was carried out in the red zone of Salalah (WPZ) in early months of 2004. The aim behind the survey was to classify and identify the pollution sources and to map such updated sites of the area.

4.2.3 Potential Groundwater Contamination Sites

At the study site, several contamination sites were reported as shown in (Figure 3). The southeast part of the Salalah Wellfield belongs to Jarziz Farm Company, and is developed as an area of fodder crops. Included in this area is an Agricultural Research station or the Ministry of Agriculture and Fisheries (MAF) research Farm. To the north of the agricultural area, is an area of a workshop and a cement and block factory. The remaining area contains a few cattle and private farms and some small housing.

There are no developments at Saada Wellfield, apart from the Sahalnawt Dam just east of the wellfield. Saada pumping station and residential area lie right in its center.

4.2.4 Contaminant Survey

The MAF agricultural research station and the Jarziz Farm use potential pollutants such as pesticides, herbicides, fertilizers and manure from livestock, the manure is stored as powder and later mixed with water for distribution, both farms have labour camp associated with them, which have septic tanks. In the Jarziz Farm, organophosphorous pesticides are used when required on the crop. The Slaughterhouse and dairy waste are taken away from the site in tankers and disposed at permeated disposal sites. The Cement and Block factory has been in existence now for several years it has fuel storage tanks, a small labour camp and a private well. The workshop has underground fuel storage tanks, which were installed a long time ago, waste oil and water are kept in an underground concrete tank and then removed together with sewage from the septic tanks by tankers for disposal off site.

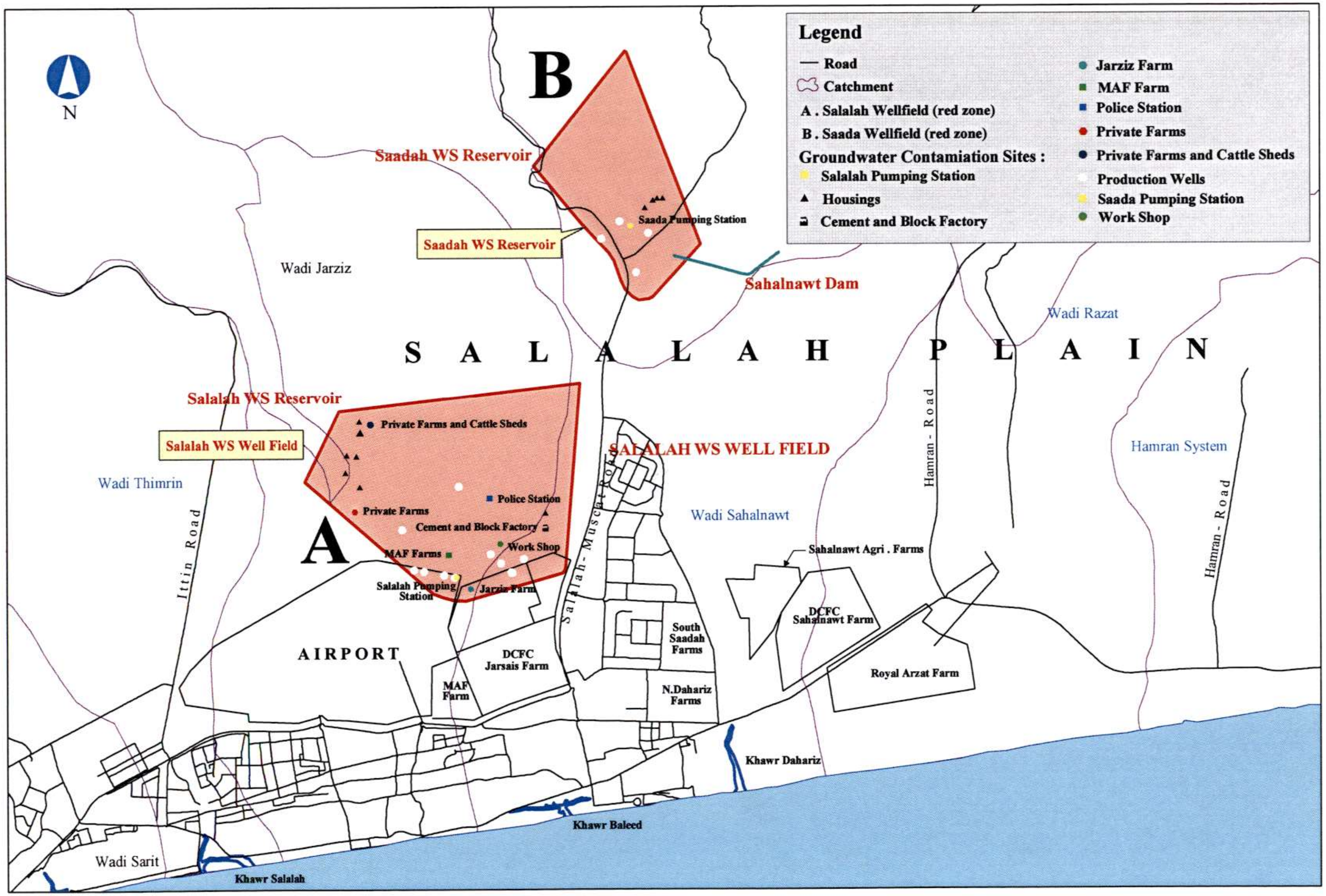


Figure 3. Potential contamination sources in red zones

A small number of housings are distributed in the red zone of Salalah and Saada, they have septic tanks for disposal of human wastes. The houses in red zone of Salalah have small shelters that are only occupied during the Khareef season (Monsoon) and are unlikely to have septic tanks. The private farms have their own private wells, they use natural and some times artificial fertilizers for growing crops; some of them have cattle sheds and the labour sites have septic tanks.

4.3 Groundwater Levels

The majority of the groundwater level data for the Salalah plain is in the vicinity of the wellfields. Several exploration boreholes were drilled along the Jabel front in 1983. There are no transient water level records available for most of the Jabel Qara (mostly in Yellow zone) because water levels have been stable (Entec, 1998). Bait Ishaq (1995) reported that groundwater level had remained fairly constant in the mountains area, because there has been no large increase in agricultural landuse in these areas.

In this study most of the water resources assessments are based on records extending from 1996 to 2004.

4.3.1 Water Levels in Front of Jabel Area

Historical monthly data of monitoring boreholes were obtained from the database of MRME &WR from 1996 to 2004. Twelve monitoring boreholes located in the red and orange zones in the area front of Jabel Qara were chosen randomly (Figure 4). The above boreholes were exported into Surfer Program (Figure 5) and EXCEL worksheet (Figure 6) in order to create the spatial and temporal variation for the above period.

In order to examine if water levels of the wells located in the front of Jabel area has changed over the period from 1996 to 2004, an analysis of Covariance was carried out using Data Desk program using (ά=0.05).

Regression analysis was used, to define the relationship between pumping of groundwater from the production wells and the water levels of the mentioned monitoring boreholes (Figure 7); this was done by using Hill plot analysis. The analysis was done by using average monthly change in water levels for each year of 12 monitoring boreholes (from 1996 to 2004) with monthly abstraction data for the same years (Appendix 1).

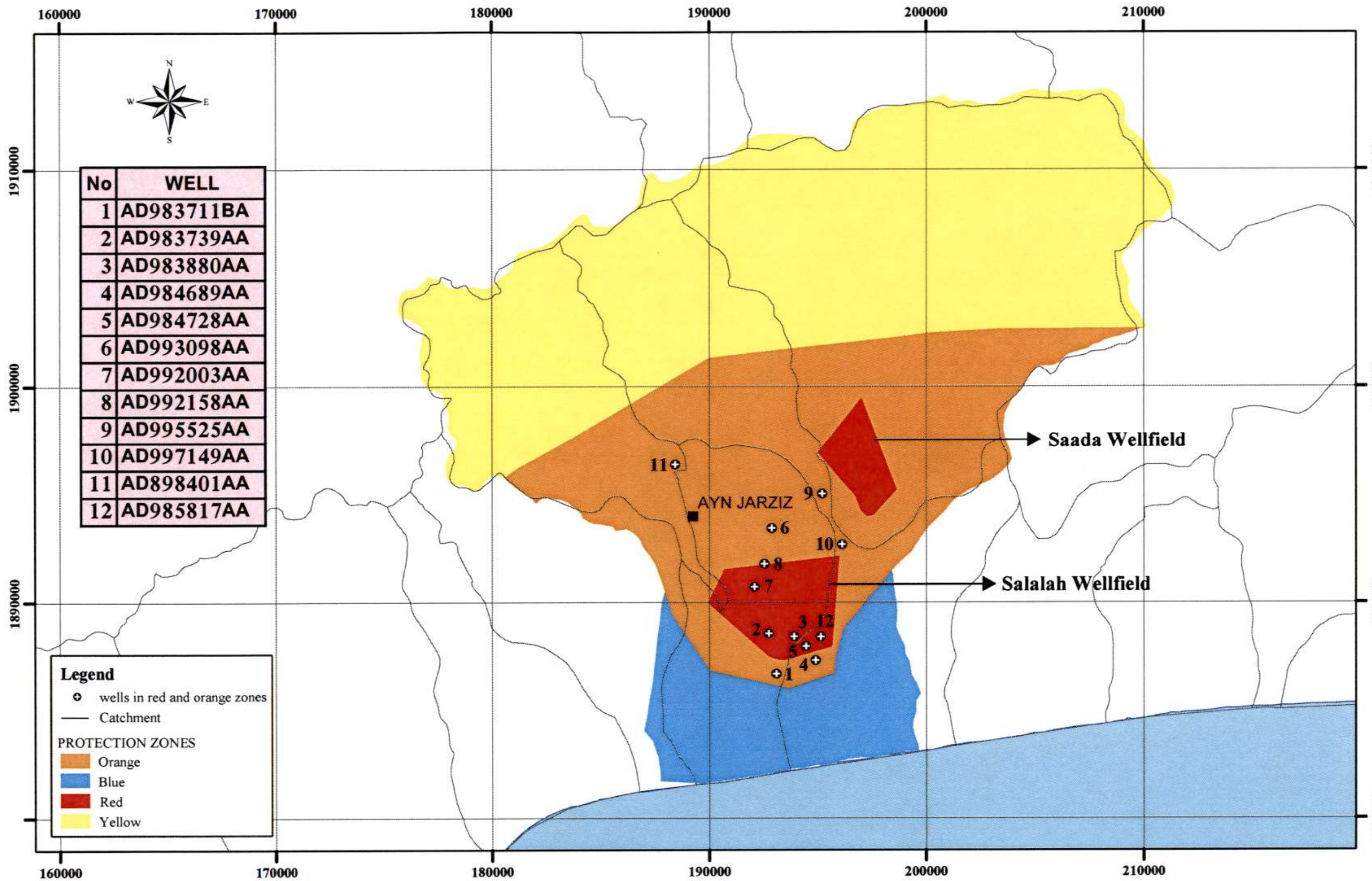


Figure 4. Monitoring wells in red and orange zones

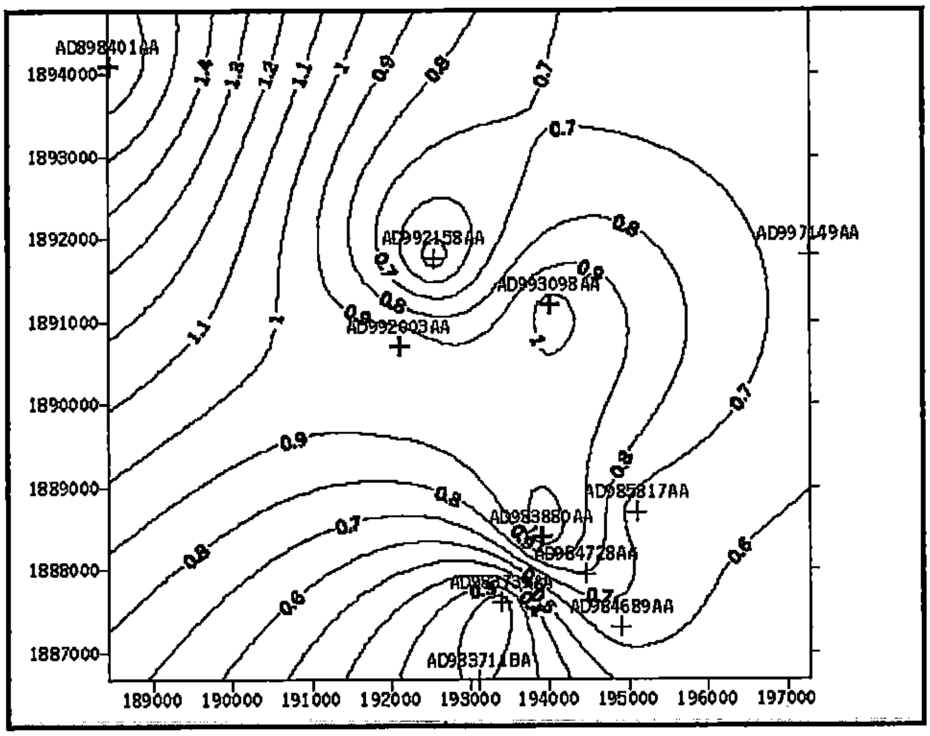
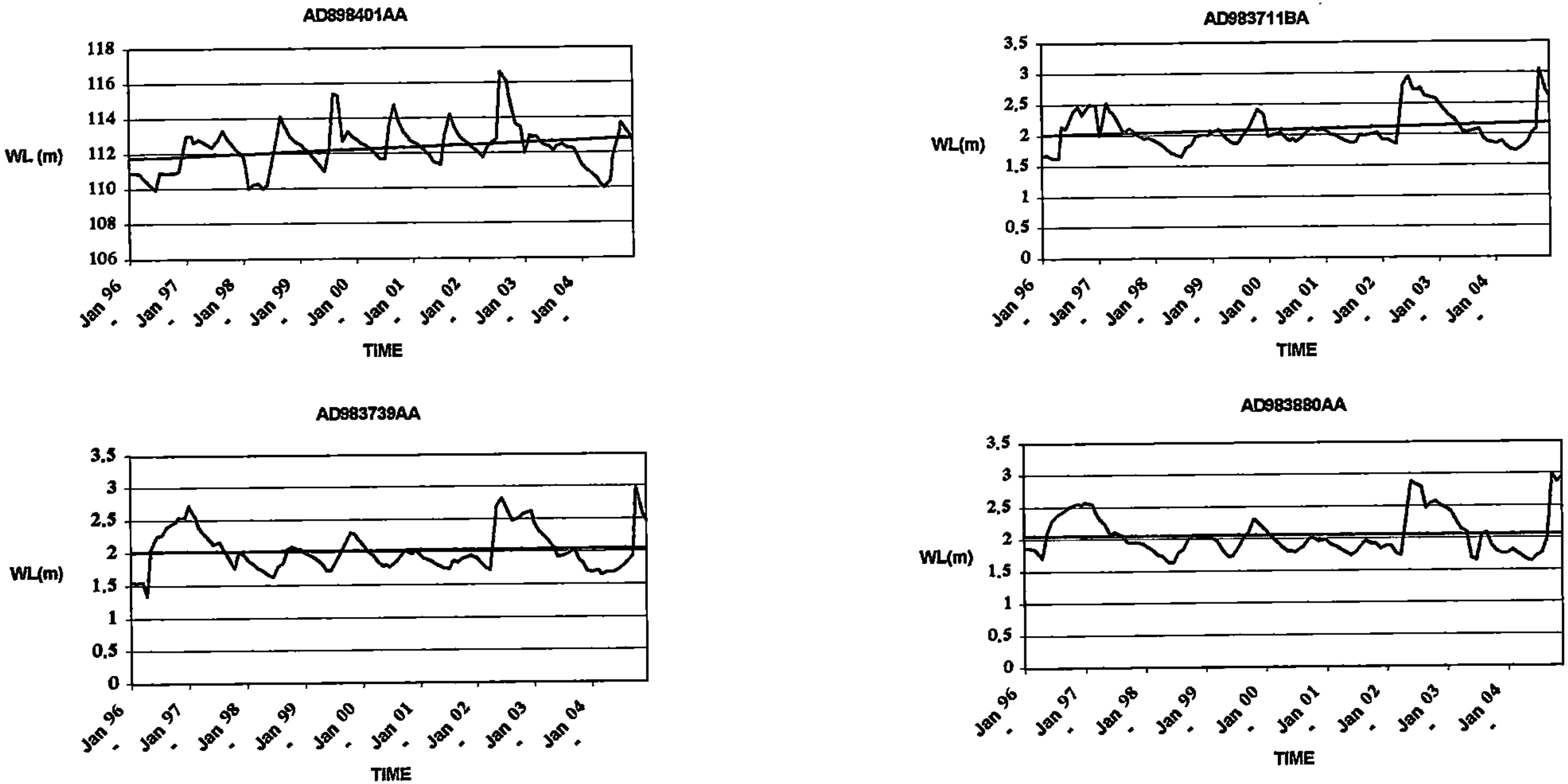


Figure 5. Spatial variation of rise in groundwater levels in red and orange zones between 1996 and 2004



Figur 6. Hydrographs of water level monitoring wells above msl in red and orange zones

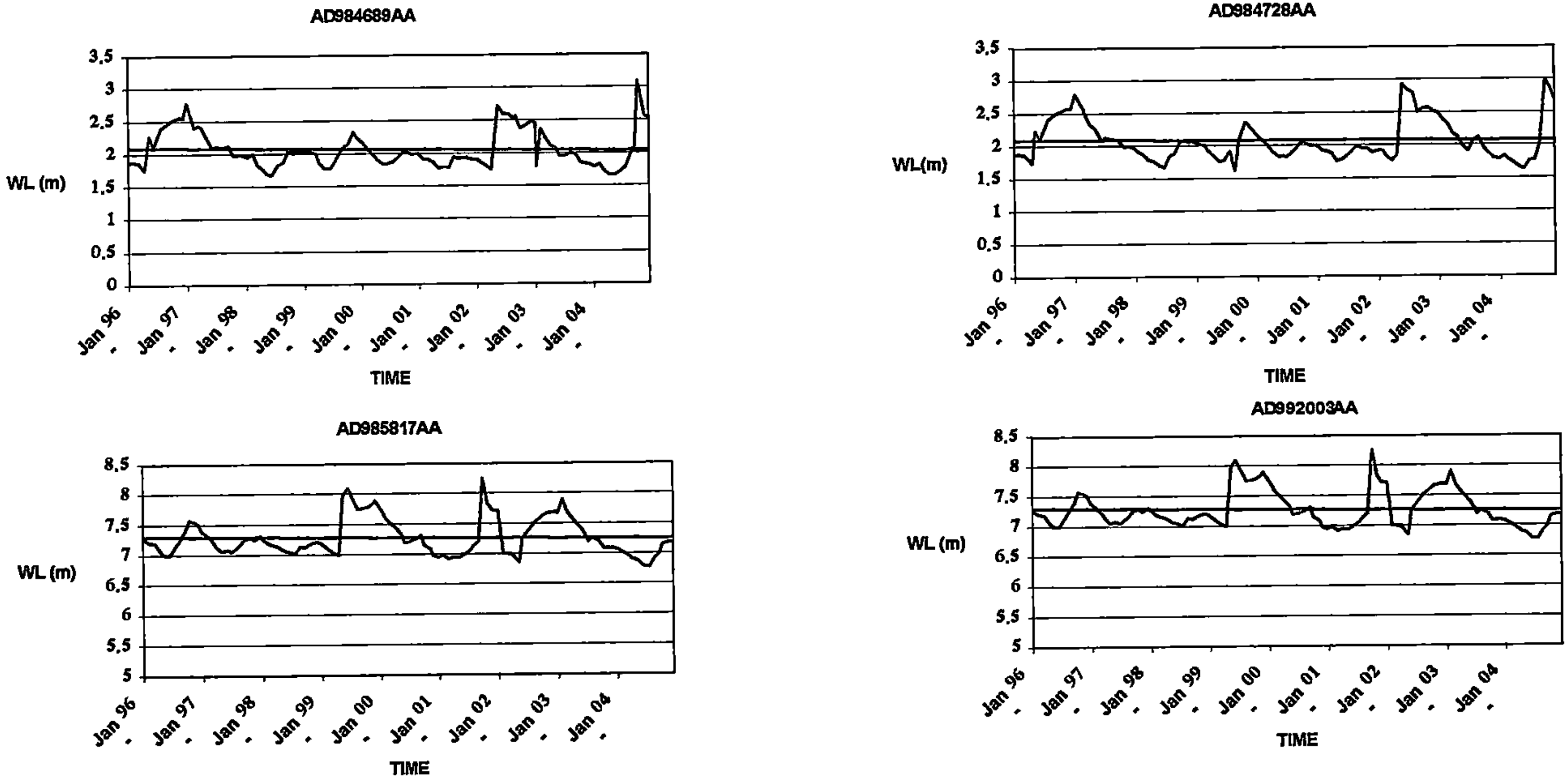


Figure 6. Hydrographs of water level monitoring wells above msl in red and orange zones (continued)

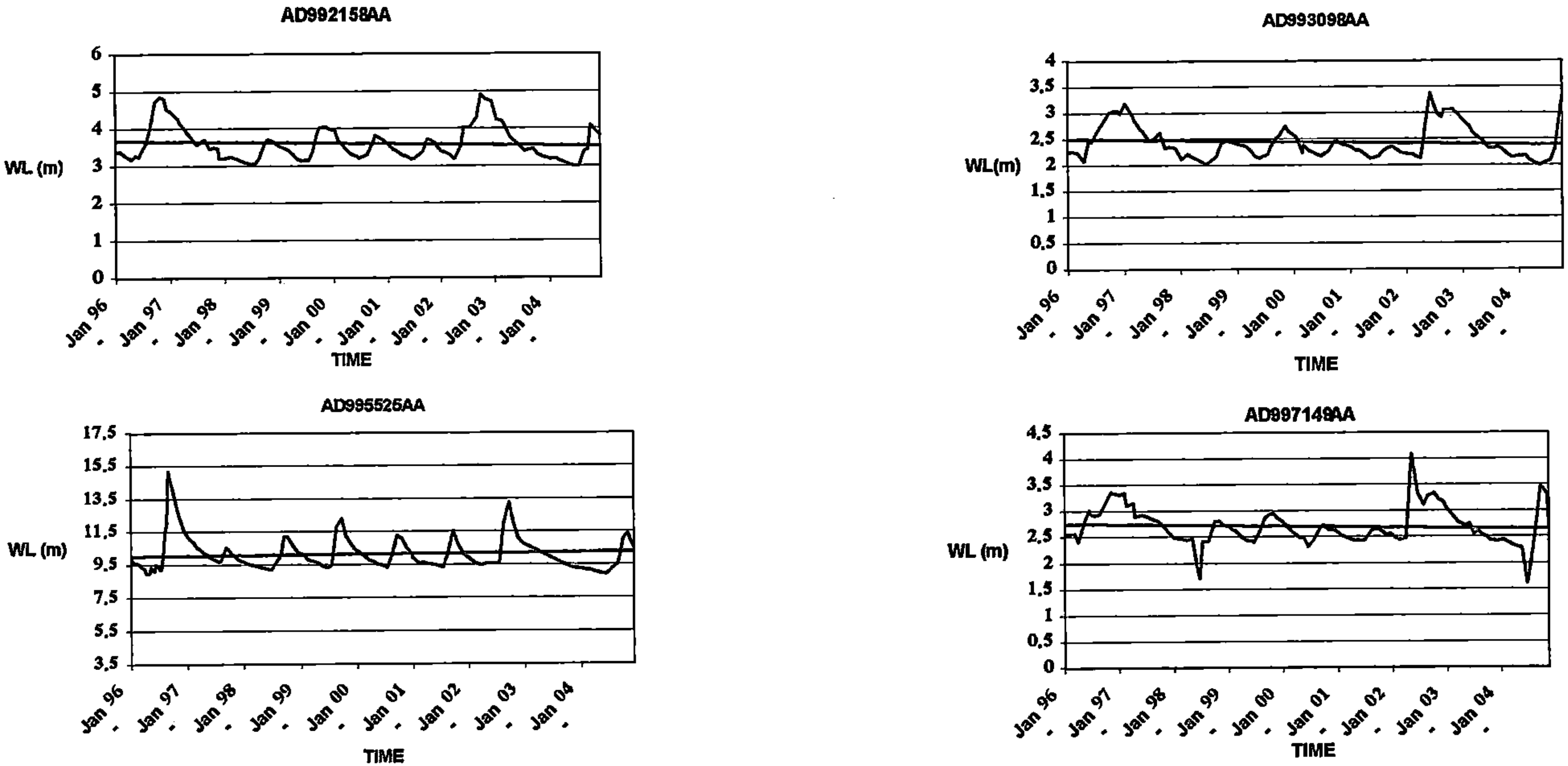


Figure 6. Hydrographs of water level monitoring wells above msl in red and orange zones (continued)

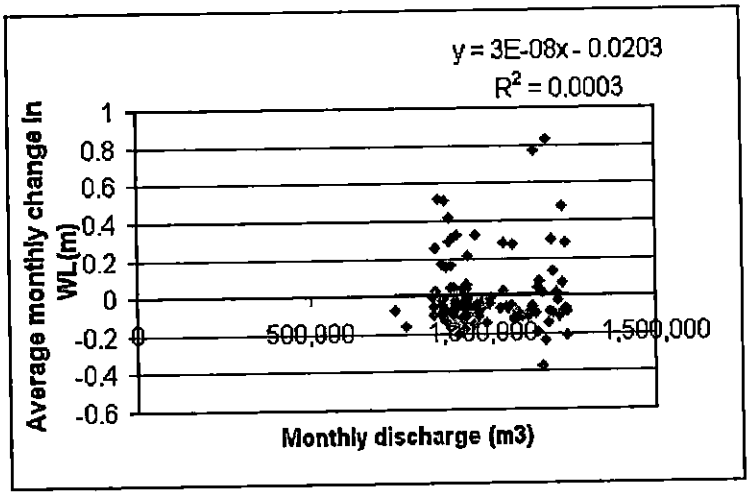


Figure 7. Relationship between the average monthly change in water levels (m) and monthly abstraction volume in cubic meter (1996-2004).

4.4 Water Quality Assessment

This involved the analysis of a large number of water quality parameters, which were conducted in the laboratories of both MRME & WR and MSGD (Minister of State and Governor of Dhofar). Three types of analysis as mentioned below were conducted twice, one in January 2005 and the other in April 2005, except the analysis for hydrocarbons, which was conducted only once. The water quality was checked against the Omani standards No 8 for Drinking Water issued by Ministry of Commercial and Industry (MCI) (1998) for Omani drinking water (Appendix 2), and compared with the historical data available in the database of MRME & WR (Appendix 3).

4.4.1 Major Ion Analysis

The major ions (Bicarbonate, Chlorides, Nitrates, Sulfates, Calcium, Sodium, Magnesium and Fluoride) in the water were analyzed at MRME & WR laboratories. The samples were collected in plastic containers, cooled using ice plate and finally analyzed by using IC for anions and ICP instruments for cations using the standard methods of Water and Wastewater,20^{th} Edition. The laboratory also analyzed pH, EC, total alkalinity, and total hardness using standard methods.

4.4.2 Trace Metal Analysis

Heavy metal analysis included analysis for Cadmium, Lead, Mercury, Copper, Zinc, Cobalt, Chromium, Vanadium, Manganese, Iron, Molybdenum and Nickel. The samples were collected, kept in glass containers in a cool box. They were then taken to the laboratory, where they were cooled using ice plate, digested to a transparent solution with nitric acid, and finally analyzed by ICP using the standard methods of Water and Wastewater,20^{th} Edition.

4.4.3 Hydrocarbon Analysis

BTEX (Benzene, Toluene, Ethyl Benzene and Xylene) analysis was also conducted in the laboratories of MRME & WR. Only four groundwater samples of four production wells were analyzed in order to compare the results with the results of Entec (1998), which did analysis of the same production wells (TP3, TP6, TP8, S1). Groundwater samples for BTEX were collected in glass bottles of 250 ml and were analyzed by GCS using the standard methods of EPA 524.2 and 624.

4.4.4 Bacteriological Analysis

Bacteriological analyses were carried out in the laboratory of the MSGD, and were analyzed within 24 hours from sampling. Bacteriological tests included the test for total Faecal Coliformes and *Eschiritchia coli* (E-coli). All the groundwater samples were collected in preserved glass bottles. IDEX Quantity Test was used to identify the presence and the concentration of these two types of bacteria. The results were expressed in most probable number per 100ml of water (MPN/100ml).

4.4.5 Quality Assurance and Accuracy of Analytical Analyses

For calibration purposes, standards were purchased from reputed international suppliers (BDH Spectrosol grade and Restek Corporation) for major ions and BTEX analysis. Actual calibration was done using three replicate measurements. The MRME & WR laboratory where analysis was done is under the Aquacheck (UK) proficiency-testing program.

The detection limits for each parameter of major ions and trace metals are shown in Table 1 and Table 2 respectively:

Table 1. Detection limits for major ions

	EC	Ca	Mg	Cl	NO3-N	SO4	F	Na	K
Detection limits (ppm)	0.5μS/cm	0.5	0.5	0.02	0.05	1	0.02	1	0.2

Table 2. Detection limits for trace metals

	Fe	Mn	Cu	Cd	Hg	Ni	Pb	Cr	V	Co	Zn
Detection limits (ppb)	0.4	0.06	0.2	0.3	0.005	1.2	5	0.3	0.05	0.8	0.02

The method of detection limits specified for the BTEX analysis is ranged from 0.02 to 0.05 µg/l.

4.4.6 Saline Water Intrusion

The distribution of groundwater salinity, expressed as Electrical Conductivity (EC) was also studied. The main area of freshwater occurs in the central area of the plain (around the wellfields) and its EC is less than 1000 µS/cm. Elsewhere on the plain the groundwater is typically brackish, the EC ranging from 2000 to 5000 µS/cm. In an area in Salalah plain near the coast, groundwater is non-potable and has EC above 5000 µS/cm (Dames & Moore, 1993).

Earlier and recent studies observed that the main existing potable waters are being exploited by both urban (9.5 Mm^3/year) and irrigated agricultural sector (40.4 Mm^3/year) (HMR, 2004) which are of two types: the small scale private sector farms in agriculture strip paralleling the coast and large scale modern farms in the area of front of Jabel and near the red zone (fresh water zone). The over abstraction of fresh groundwater results in degradation of the resources through saline and brackish water intrusion from the coastal and adjacent brackish water areas.

In order to examine whether the salinity (µS/cm) has changed during the study period (1996 to 2004) with the distance from the sea (in km), ANOCOVA analysis using Data Desk program was conducted using (ά=0.05). Wells were divided into three groups: 7 to 9 km from the coast (freshwater), 3 to 5 km from the coast (brackish water) and 0.5 to 1 km close to the coast. The salinity monitored wells and their closest water level wells in each part are shown in (Figures 8-10). In order to identify salinity variation EXCEL program was used to plot them. The closest water levels to salinity-monitored wells were plotted as shown in (Appendix 4), but unfortunately data from only one well in the closest part to the coast was obtained.

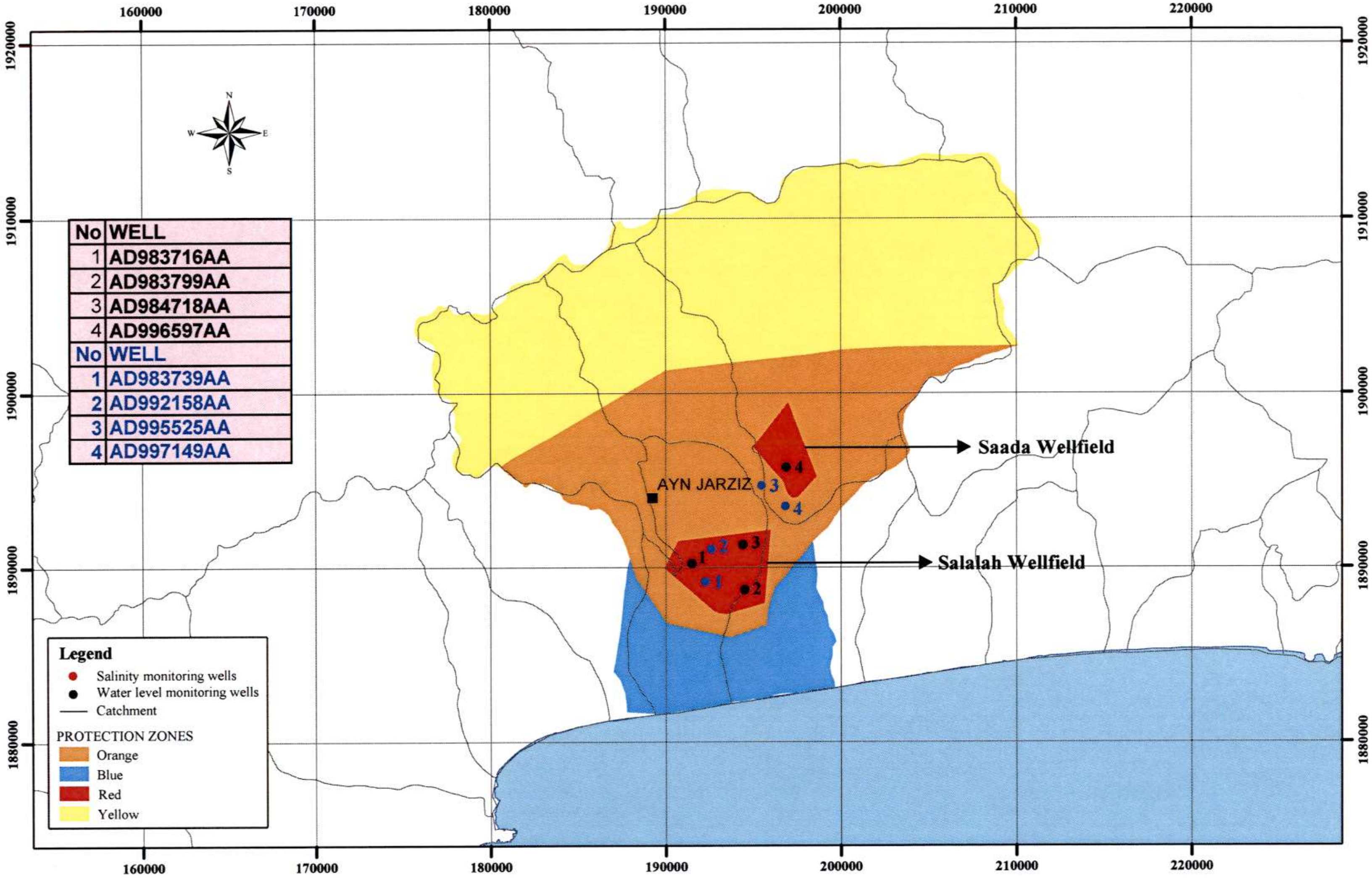


Figure 8. Salinity and water level monitoring wells 7 - 9 km from the coastline

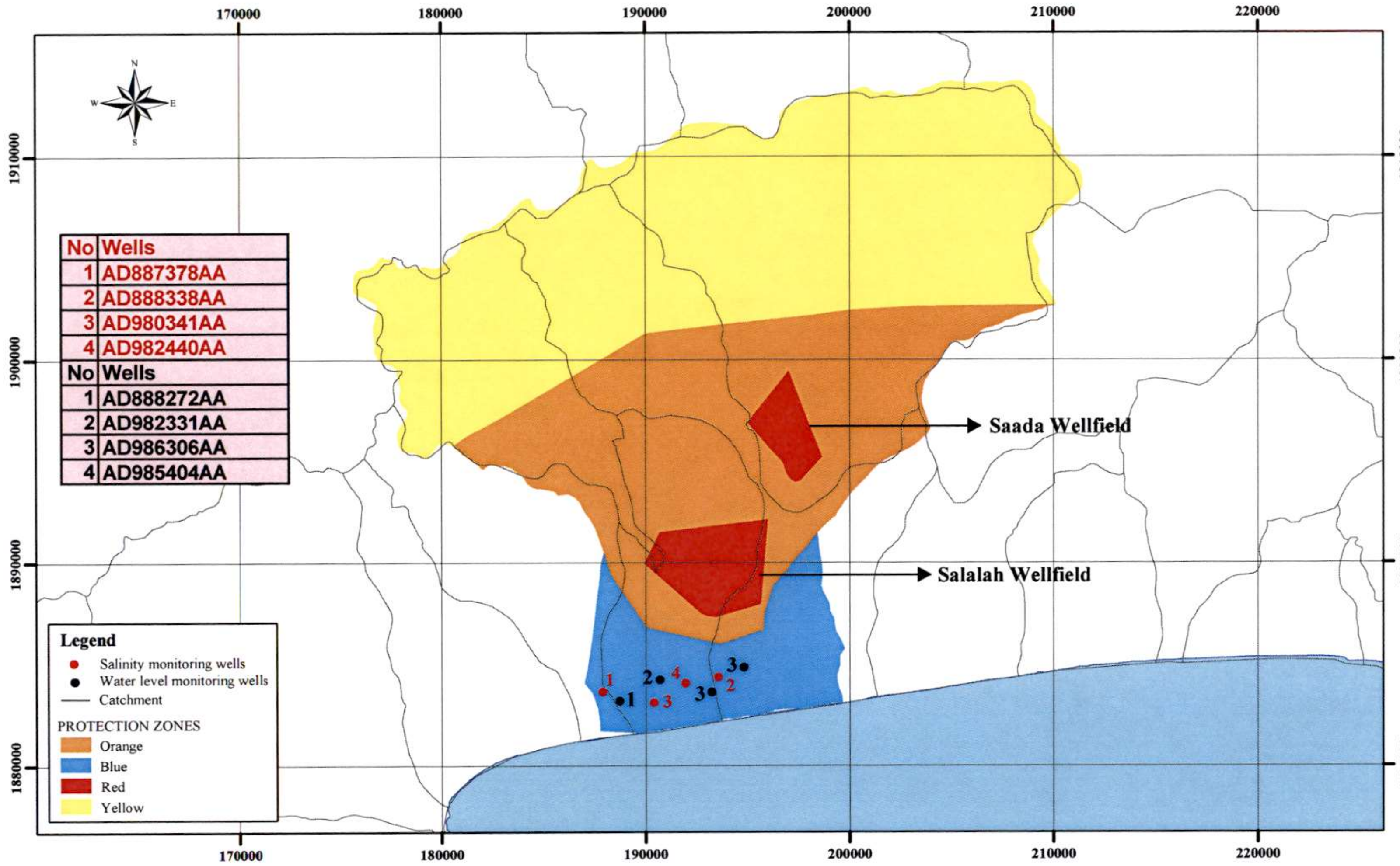


Figure 9. Salinity and water level monitoring wells 3 - 5 km from the coastline

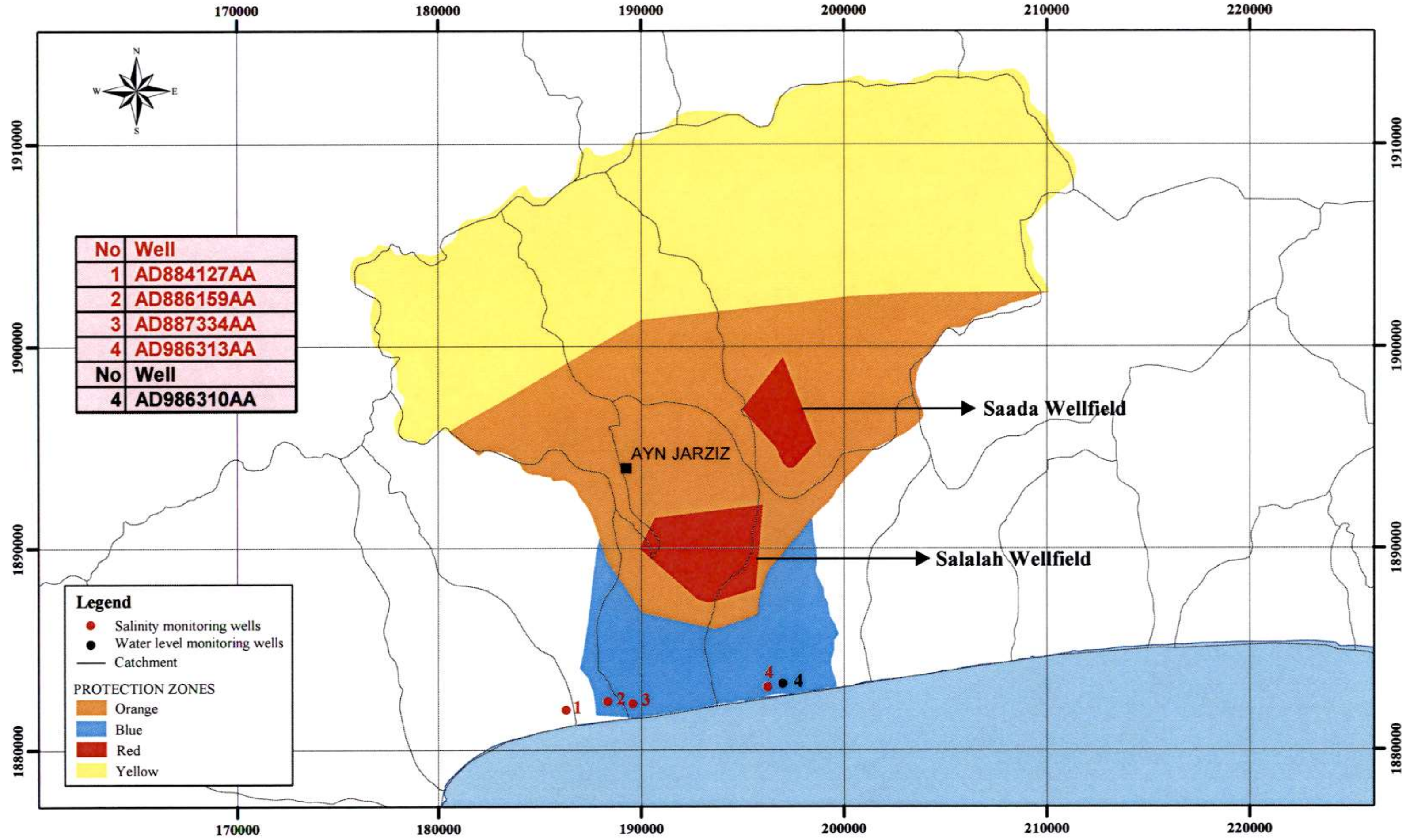


Figure 10. Salinity and water level monitoring wells 0.5 -1 km from the coastline

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

From the analyzed and evaluated piezometric and hydrochemical data which were obtained, the layout of results and discussion can now be developed.

5.2 Inventory of Pollution Sources

The activities with potential to impact groundwater in the red zone of Salalah (WPZ) includes residential, agricultural and industrial. The most important groundwater pollutants arising from housings and domestic water use are nutrients, chemicals (e.g. fats, soaps, detergents solvents, disinfectants, grease) and pathogens (bacteria and viruses) principally from disposal of septic tank and greywater.

Agricultural activities may cause rise in nitrate and phosphorus concentration of the groundwater due to the extensive use of fertilizers. Salinity problems, on the other hand, may rise from pumping groundwater for irrigation purposes, resulting in accumulation of salts in the soil, thus reduction of plants ability to extract water from soil.

Industrial activities, which include the workshop for vehicle repairs and cement and block factory, maybe classified as point sources of pollutants entering groundwater like hydrocarbons such as Benzene, Toluene, Ethyl Benzene and Xylene, in addition to heavy metals such as Zinc and Cadmium.

Many agencies and countries list underground storage tanks, septic tanks, agricultural activities, municipal landfills and abandoned hazardous waste sites as major threats to groundwater (Entec, 1998). The Federal Ministry for Environment in

Germany (1993) listed pollution sources, which affected their surface, and groundwater sources, and their regulations and legislations to the relevant activities in order to protect them. In Oman, MRME & WR introduced an activity matrix to all wellfields to show the level of acceptance for different activities in different zones and their regulations. The activity matrix is shown in (Appendix 5) while the best practices for the prevention of pollution are shown in (Appendix 6).

5.3 Groundwater Levels

When excessive pumping takes place, the natural balance will be disturbed and groundwater levels will change. This study shows no evidence to suggest that there is a significant effect of over pumping from wellfields on water levels in the area of front of the Jabel.

5.3.1 Water Levels in Front of Jabel Area

According to the graph of spatial variation (Figure 5) in both red and orange zones (front of the Jabel), it is observed that there is rising and falling in water levels in the aquifer. This is not uniform: it rose by 1.71 m in well No AD898401AA due to location of the well directly in front of Jabel area, where the groundwater flow is high, and fell by 0.13 m in well No AD983739AA due to it's location, where big farms are located and much pumping occur.

The hydrographs of monitoring wells (Figure 6) showed that there is an indication of sharp fluctuations in water levels during the study period from January 1996 to December 2004. They increased in periods of June, July and August, and decreased in other months. However, their trend lines showed stability in most of the wells, this fact improves our statistical analysis of Covariance as shown in Table 3 below:

Table 3: Analysis of Covariance on water levels of 12 monitoring wells in red and orange zones.

Source	df	Sum of Squares	Mean Square	F-ratio	Probability
Time	1	0.0374978	0.0374978	0.11538	0.7342
Well	11	287391	26126.5	80394	0.0001
Time*Well	11	19.0277	1.72979	5.3227	0.0001

As shown in the above table, there was no significant change of water levels for all monitoring wells during the time of the study period ($p>0.05$). However, the same conclusion can be reached as shown in Table 4 below, if two wells AD898401AA and AD995525AA are not included in the same analysis due to their large seasonal fluctuation of water level that affecting the condition of homoscedasticity (equal variance) for ANOVA:

Table 4: Analysis of Covariance on water levels of 10 monitoring wells in front of Jabel area.

Source	df	Sum of Squares	Mean Square	F-ratio	Probability
Time	1	0.125268	0.125268	1.0605	0.3033
Well	9	632.776	70.3084	595.24	<0.0001
Time*Well	9	0.774872	0.0860968	0.72891	0.6827

The regression analysis (Figure 7) showed no significant relationship between the average monthly change in water levels and monthly abstraction volume.

Therefore, it can be concluded that, the discharge (abstraction) data from production wells and the average monthly change in water levels, do not show any clear relationship. However, the rising of water levels may occur from other factors such as direct rain falling, irrigation return and maybe from artificial recharge to the aquifer.

It was observed by John & Taylor (1997), that the structure, topography and climatology of the Jabel front area indicated that the Salalah plain is recharged by rainfall from the mountains. The volume of groundwater, which intercepted in the front area of the Jabel was calculated using the Surfer program as 75500 m^3/year to 49.04 m^3/year (according to highest and lowest value of Storage Coefficient). The reading from Alobe rainfall gauge as shown below in (Figure 11), which is located in the central part of the aquifer, was plotted against the average monthly change in water levels. The result of the plotting is shown in (Figure 12):

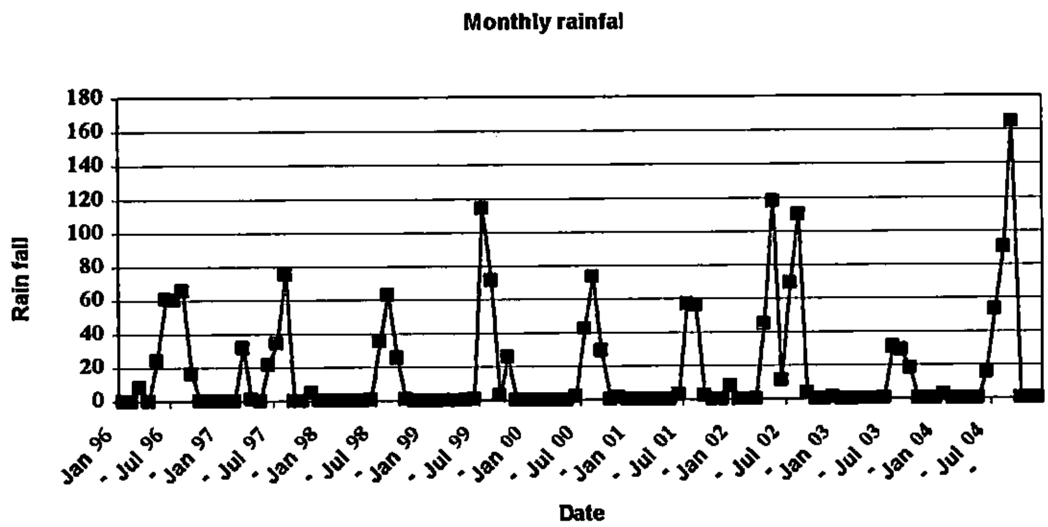


Figure 11. Alobe monthly rainfall gauge readings

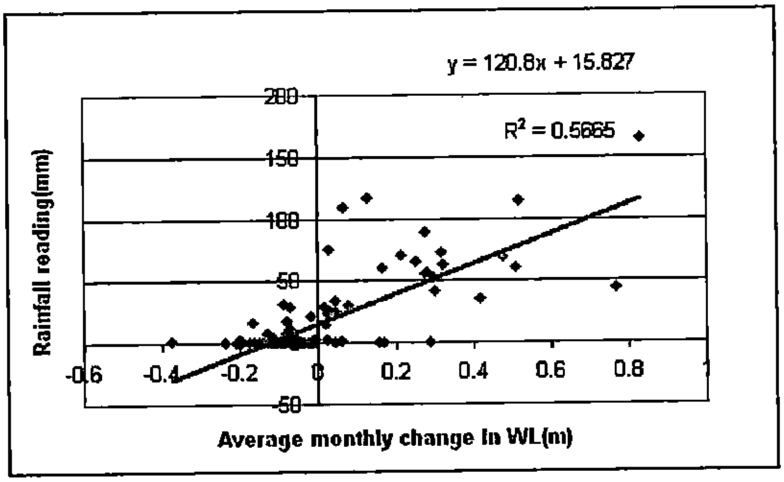


Figure 12. Relationship between monthly change in water levels (m) and monthly rainfall (mm).

The figure above shows that total rainfall explains about 56% of the observed variability in the average monthly change in water level.

In summary, the rise in the groundwater levels at different times was due to the Monson season that occurs annually between late June to September, which is in line with conclusion by Dames & Moore (1991) and Entec (1998). Also, the hydrographs showed that the rises in May /1996, May/ 2002 and in September/ 2004 were due to the cyclonic event that occurs every 7 or 10 years, usually in March, April or May (Binnie & Partners, 1999). On the other hand, the decline of the water levels at the different times was due to the absence of rainfall, especially in January and February in all years. The Alobe rainfall gauge read 0 (mm) for these two months. The other reason for the declining water levels could be due to agricultural activities as the large modern farms, which are located near the fresh water zones that abstract groundwater from their own private wells. These are recharged by nearby wadis and springs. This conclusion is in line with all mentioned previous studies on the management of the Southern Region.

5.4 Water Quality Assessment

The aquifer of Salalah plain is largely unconfined, and it is prone to be polluted from surface sources. Therefore, current water quality conditions were measured in Salalah (WPZ) in order to detect any changes and trends during the study period.

5.4.1 Major Ions

Mineral salts of low pollution potential are the most common constituents found in groundwater due to the local geologic, climatic and geographical conditions (Novotny and Chesters, 1981). If they are found in large amounts they may cause problems for human health. Dezuane (1997) outlined some problems to human health, which are caused by large contents of some salts: Nitrite may result in the potential formation of carcinogenic effects, diarrhea and dehydration can be caused by high content of Sulfate; Sodium causes cardiac, renal and circulatory disease. Kidney or bladder stones may be suspected in high content of Calcium, Magnesium and Chlorides concentration.

The results of major ion analysis are shown below in Table 5:

Table 5. Chemical ion analysis in mg/l of Salalah and Saada wellfields Jan/2005

Well	ECµS/cm	TDS	PH	TH	Ca	Mg	ALK	CL	NO3	SO4	F	Na	HCO3	K
TP2	946	630	7.74	396	111	27	212	168	20	39	0.28	20	240	0.40
TP3	969	646	7.88	376	107	26	220	207	18	42	0.30	21	242	0.40
TP4	974	649	7.76	352	99	25	208	184	22	40	0.27	20	250	0.40
TP5	1021	681	7.77	353	94	29	212	186	18	40	0.22	27	260	0.40
TP6	783	522	7.77	338	95	24	192	141	20	34	0.24	18	200	0.54
TP7	936	624	7.69	301	80	24	128	200	29	40	0.28	18	215	0.36
TP8	1259	839	7.60	420	120	29	216	248	26	41	0.30	18	251	0.36
TP9	1103	735	7.68	412	124	25	224	217	22	42	0.26	23	254	0.46
TP10	1286	857	7.55	456	142	24	208	248	27	39	0.22	22	245	0.44
TP11	882	588	7.54	396	112	28	116	149	22	35	0.26	20	250	0.40
TP12	746	497	7.54	317	91	21	240	108	20	38	.023	20	256	0.40
Saada1	839	559	7.67	371	105	26	200	129	26	32	0.28	17	263	0.34
Saada2	765	510	7.70	240	68	17	132	172	27	42	0.24	15	266	0.30
Saada3	756	504	7.95	252	73	17	110	139	28	40	0.26	15	260	0.30
Saada4	807	538	7.65	234	68	15	111	145	25	42	0.27	16	265	0.30

17-April /2005

Well	ECµS/cm	TDS	PH	TH	Ca	Mg	ALK	CL	NO3	SO4	F	Na	HCO3	K
TP2	966	500	7.64	305	89	20	196	150	17.2	38	0.2	61	240	0.86
TP3	1004	529	7.47	319	94	20	197	162	16.7	48	0.5	63	240	1.8
TP4	960	513	7.42	304	90	19	207	154	17.2	41	0.3	61	252	1.7
TP5	1008	504	7.64	311	91	20	216	150	0.5	38	0.3	66	264	1.9
TP6	767	401	7.42	245	70	17	170	104	22.4	33	0.4	46	207	1.7
TP7	922	478	7.20	299	86	20	174	147	22.0	35	0.2	56	212	2.2
TP8	1182	616	7.14	357	102	25	204	196	31.7	58	0.3	74	249	2.1
TP9	1086	540	7.40	327	92	23	210	151	26	47	0.2	67	256	1.9
TP10	1199	626	7.22	363	103	25	203	201	33	58	0.4	50	247	1.6
TP11	852	448	7.19	282	84	17	209	114	16.3	34	0.4	20	255	0.40
TP12	744	392	7.24	257	75	16	207	80	16.3	34	0.5	39	253	1.5
Saada1	824	441	7.19	300	92	17	217	98	19.8	35	0.3	41	265	1.3
Saada2	738	396	7.11	288	90	15	217	70	19.4	33	0.2	32	265	1.2
Saada3	724	384	7.19	274	84	15	216	67	18.5	30	0.3	32	264	1.2
Saada4	771	412	7.71	286	88	16	220	80	18.9	33	0.4	37	268	1.3

***TDS= Total Dissolved Solids, TH=Total Hardness, ALK=Alkalinity**

As shown in the above tables:

- Calcium levels were at or marginally above the highest desirable levels but were far below maximum permissible levels.

- Magnesium concentrations were well below the highest desirable levels, as are Sulfate, Nitrate and Fluoride levels.

- Chloride levels approached highest desirable level concentrations but did not exceed them; and

-Bicarbonate levels were very high. As such groundwater in Salalah and Saada wellfields is generally of the bicarbonate type. This observation is in line with conclusion of John Taylor & Sons (1979) that groundwater in Salalah plain is of Bicarbonate type, being associated with limestone formation, in which it reflects the chemical nature of the rocks through which it travel. Martinez and Bocanegra (2002), in a case study in Argentina reported that groundwater type in the study unit is commonly dominated by HCO_3^- ions because the addition of the large amounts of CO_2 from root zone and calcite if present is dissolved. However, this may cause high alkalinity. The HCO_3^- ions present carcinogenic and may also cause the corrosion of the pipes through which municipal water passes. Therefore, there is a need to examine trace or heavy metals in water.

5.4.2 Trace Metals

Trace elements are usually found in trace quantities. However, the level of these elements rose with the increase of industrialization and urbanization (Novotny and Chesters, 1981). Viessman and Hammer (1985) stated that the effects of some trace metals were exceeding the acceptable range. Iron and Manganese are not desirable, because they cause corrosion in distribution systems of water. Mercury can be converted into nerve poisoning compounds. Cadmium is replaced by Calcium in bones, and other trace metals are carcinogenic if found above acceptable limits, such as Arsenic, and Chromium. Table 6 shows the analytical results of these metals in the monitored wells:

Table 6. Trace metals analysis in mg/l of Salalah and Saada wellfields Jan/2005

Well	Fe	Mn	Cu	Cd	Hg	Ni	Zn	Pb	Cr	Vn	Co	Mo
TP2	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP3	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP4	<0.05	0.081	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP5	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP6	<0.05	<0.05	<0.01	0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP7	<0.05	0.051	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP8	<0.05	0.083	<0.01	<0.005	<0.001	0.02	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP9	<0.05	0.057	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP10	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP11	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP12	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada1	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada2	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada3	0.063	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada4	0.063	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01

17-April /2005

Well	Fe	Mn	Cu	Cd	Hg	Ni	Zn	Pb	Cr	Vn	Co	Mo
TP2	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP3	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP4	<0.05	<0.05	0.02	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP5	0.06	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP6	<0.05	<0.05	<0.01	0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP7	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP8	<0.05	<0.05	0.12	<0.005	<0.001	0.02	0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP9	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP10	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	0.02	<0.01	<0.01	0.01	<0.01	<0.01
TP11	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
TP12	<0.05	<0.05	0.02	<0.005	<0.001	0.01	0.04	<0.01	<0.01	0.01	<0.01	<0.01
Saada1	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	0.07	<0.01	<0.01	0.01	<0.01	<0.01
Saada2	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada3	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Saada4	<0.05	<0.05	<0.01	<0.005	<0.001	0.01	0.02	<0.01	<0.01	0.01	<0.01	<0.01

As seen above, the results were within the Omani Drinking water limits. Therefore, the water for all mentioned parameters is acceptable for drinking and is not likely to cause any significant effects to public health.

5.4.3 Hydrocarbon

Oil is one of the most damaging forms of pollutants for human health. Therefore, monitoring the accumulation of these pollutants is vital for maintaining public health. Dezuane (1997) listed some toxic effects of petroleum hydrocarbons on human health such as damaging Kidney and Liver, causing anemia and leukemia. Also Benzene causes problems with the nervous system.

The results of hydrocarbon analysis show the following results as shown below in Table 7:

Table 7. Hydrocarbon analysis in µg/l
Jan/2005

Levels of BTEX (µg/l)				
Sample	Benzene	Toluene	Ethyl Benzene	Xylene
TP3	<0.05	<0.05	<0.05	<0.05
TP6	<0.05	<0.05	<0.05	<0.05
TP8	<0.05	<0.05	<0.05	<0.05
S1	<0.05	<0.05	<0.05	<0.05

The above results show the BTEX limits are within the standard limits of Omani drinking water.

5.4.4 Microbiology

Faecal coliform and *Eschiritchia coli* (E coli.) are two types of microorganisms, which, if present in drinking water, establishes pathway for transmission of diseases such as dysentery, cholera and typhoid (Viessman and Hammer, 1985).

Microbiological analysis of samples from the study area in the study period showed the absence of Faecal Coliforms, and *Eschiritchia* bacteria.

The results of all parameters except for trace metals and hydrocarbons were compared with historical available hydrochemical data in (Appendix 3), which showed similar results to the current results. Therefore, it is concluded that water quality for the all mentioned parameters has not changed over this period of time (1996-2004) and complied with Omani drinking water standards providing an acceptable supply for Salalah town, as long as present water quality patterns are maintained. This observation complies with John Taylor & Sons (1979), Dames & Moore (1993) and Entec (1998) on the absence of inorganic and heavy metals contamination in groundwater.

No historical data are available for trace metals and hydrocarbon, but it can be compared with analysis conducted by Entec (1998), which showed the absence of organic pollution, in Salalah Plain, which is in line with the observations of this study.

5.4.5 Saline Water Intrusion

The analysis by Data Desk program showed the following results:

Table 8: Analysis of Covariance on salinity monitoring wells

Source	df	Sum of Squares	Mean Square	F-ratio	Probability
Time	1	24.1584E6	24.1584E6	11.909	0.0006
Location	2	29.7383E6	14.8691E6	7.33	0.0007
Time*Location	2	31.4629E6	15.7315E6	7.7551	0.0004

As shown above in Table 8, there was a significant change of salinity over the time of the study period for the 3 groups of salinity monitoring wells ($p<0.05$). the Interaction existed also between the distance and the time.

Based on hydrograph analysis in (Figures 13-15), it can be concluded that there was a fluctuating trend of salinity of groundwater over the study period (1996-2004). However, the trend lines showed an increase in salinity due to the increase in the depth to water table of the wells near the front of Jabel area (7-9 km from the coasline) as mentioned in section 3. 4.1. The other reason for increasing the salinity in the red zone is maybe because of agriculture activities from the large farms there. Ellis et al. (1993) reported in a case study in USA where groundwater was used for irrigation, that solutes tend to concentrate in the irrigation water by evapotranspiration. Thus, the excess applied for irrigation water can result in the degradation of the quality of water in the upper parts of the aquifer.

The trend lines of brackish groundwater zone (3-5 km from the coastline) showed a gradual increase in two wells AD888338AA and AD980341AA. Salinity increased from 4400 μS/cm in January 1996 to 5000 μS/cm in December 2004 for the first well, while it increased from 2700 μS/cm to 3400 μS/cm for the second. This can be due to returns from irrigation water, which accumulates salt in soil and root zone (Entec, 1998). The other two wells showed a decrease of salinity due to the fissured and karst zones and also from high transmissivities as discussed in section (3.4.1) that this might lead to good quality of groundwater to accumulate through these zones. This observation is in line with Binnie & Partners (1999) that salinity decreases near the aquifer, which has high transmissivity. The other reason for decreasing salinity in this part is may due to the blending of saline water with freshwater as discussed in most of the mentioned studies.

An increase in salinity was shown in the trend lines of all hydrographs close to the coast (0.5-1 km from the coasline), see (Figure 15). In general as water moves from the recharge area toward the coastal parts, the water quality deteriorates as minerals are dissolved by water.

The above observations agree with Entec (1998) and GEO-Resources (2005) observations that the saline intrusion has occurred close to the coast and as far as 4.5 to 5 km from the sea, whereas the groundwater in the freshwater zone did not show any deterioration. This is due to the fact that wells which are located in the upper reaches of flow system are able to intercept a large recharge from the Jabel before it reaches the zones of the major agricultural abstraction in the central part and in the coastal belt (Dames & Moore, 1991). Huntzinger Ellis (1993) and Entec (1998) reported that fresh groundwater found in area of large tranmissivity values (as discussed in section 3.1.2) is not affected by salinity.

Recent studies have indicated that the saline intrusion has decreased compared to previous studies. GEO-Resources (2005) estimated that the average annual intrusion from the coast was 5.6 Mm^3/year (using steady state model) and the maximum was about 7 Mm^3 in 1994. The study by GEO-Resources (2005) suggested that the cyclonic events which occurred in May 1996, May 2002 and late September 2004 and the wastewater injection schemes along the coastal strip, resulted in reduced saline intrusion in that area and under the urban area due to reduction in the salt loads. The cyclonic precipitations are characterized by low intensity and long duration, and they cover a wide area (Barcecona et al., 1988). They probably have a major impact on natural recharge to groundwater, but they do not expect to reverse major increase in salinity (WS Atkins International, 1989).

GEO-Resources (2005) estimated by steady state model that the recharge to the aquifer by both rainfall and artificial recharge was 8.4 Mm^3/year. This can create a natural barrier for salt intrusion and thus decrease the salinity. Saline intrusion is included as part of the water balance. The outflow to the coast was estimated from the steady state model by GEO-Resources (2005) was 13.7 Mm^3/year.

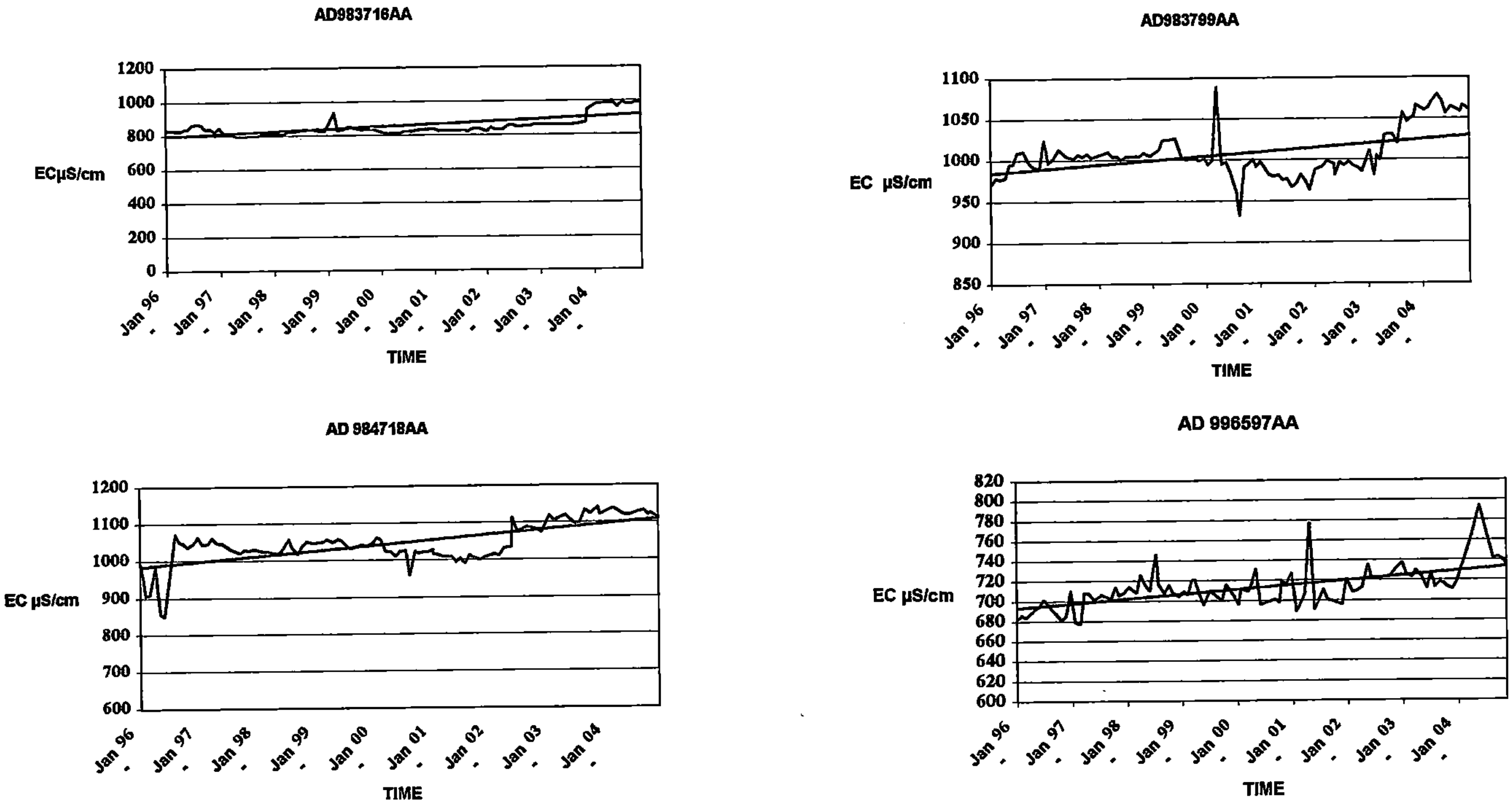


Figure 13. Hydrographs of salinity monitoring wells 7 to 9 km from the coastline

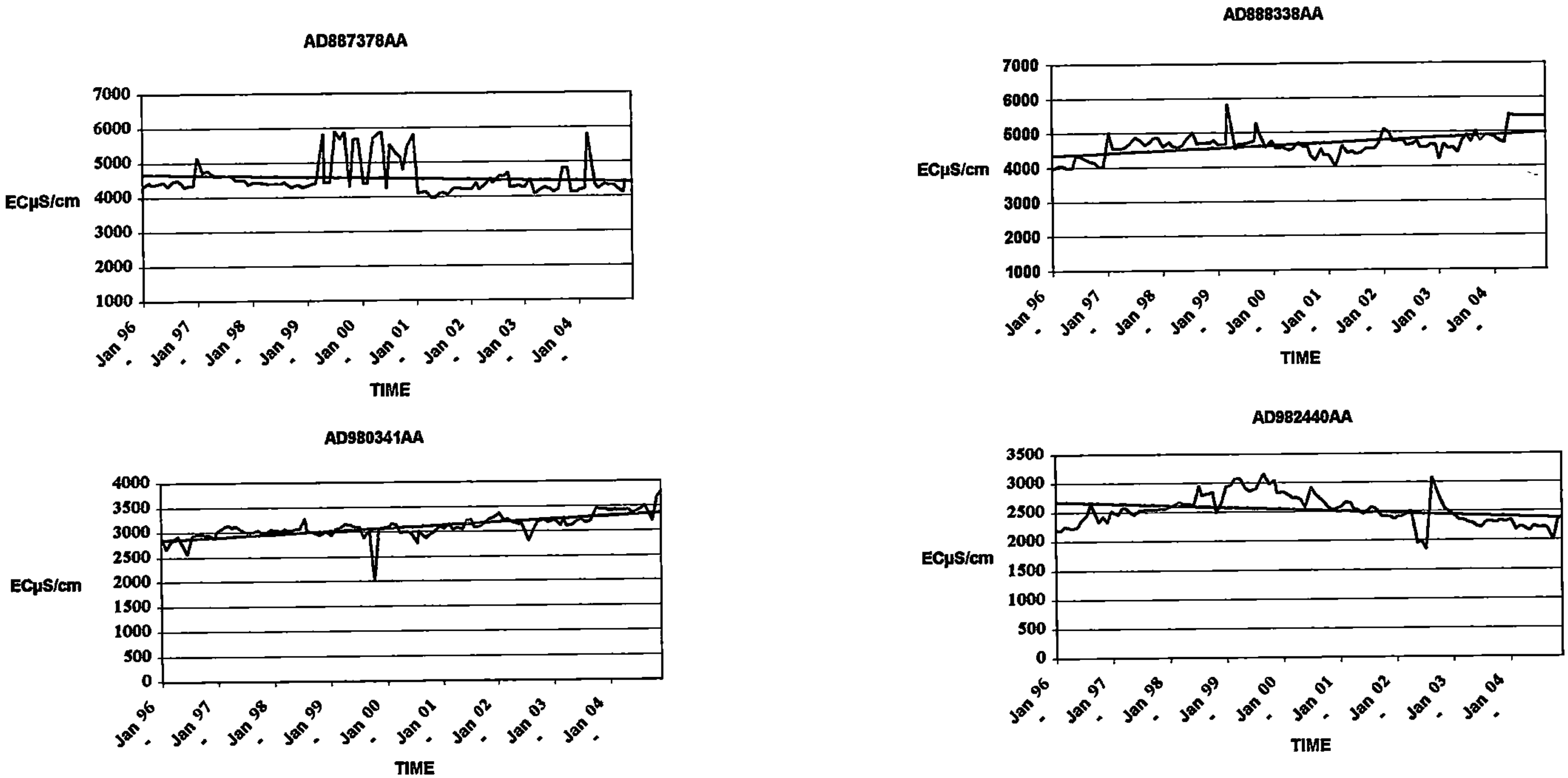


Figure 14. Hydrographs of salinity monitoring wells 3 to 5 km from the coastline

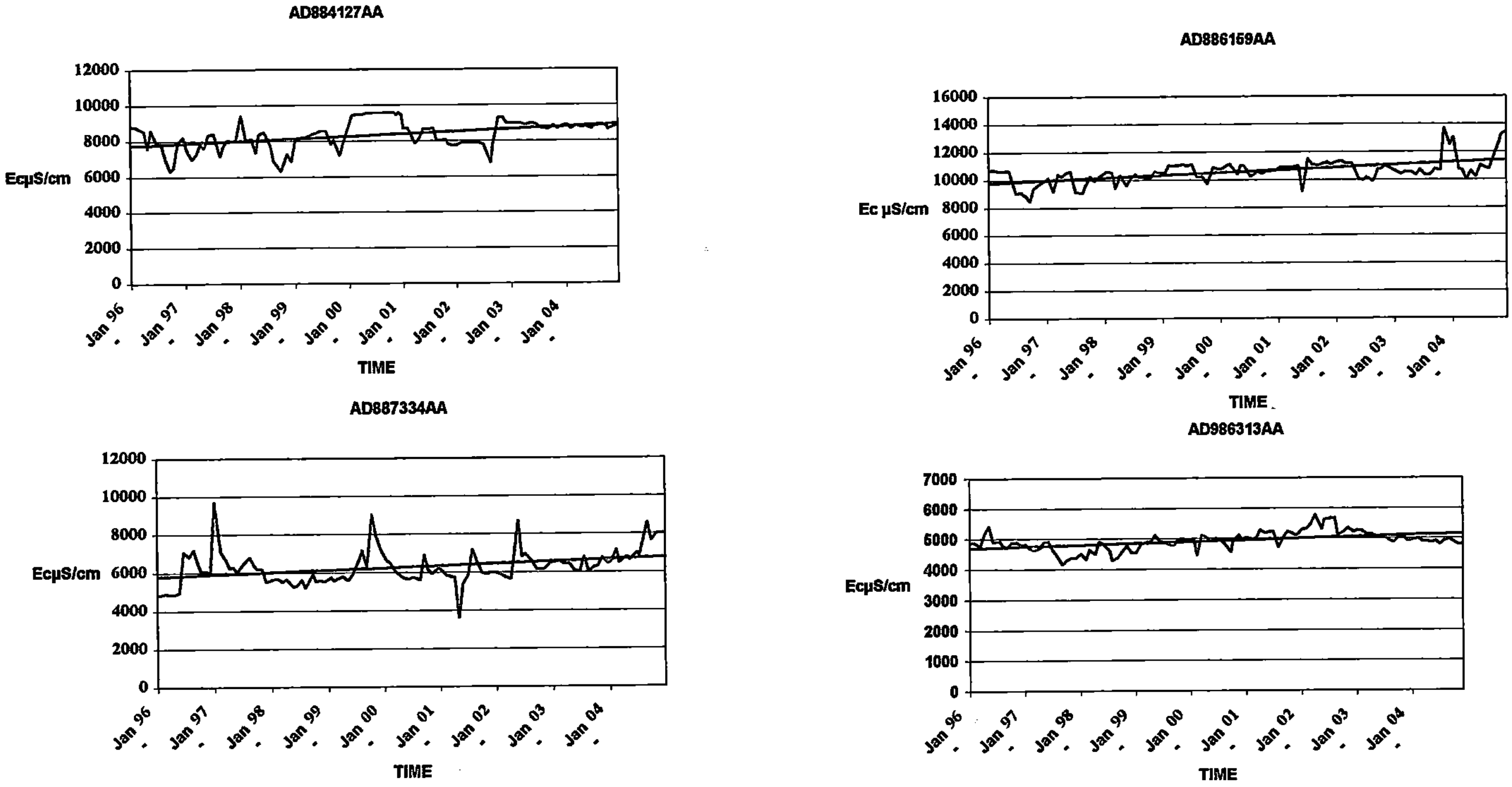


Figure 15. Hydrographs of salinity monitoring wells 0.5 to 1 km from coastline

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study highlights the importance of the Southern Region wellfields as a water supply source. Previous studies were the main source of information. On the basis of this study the following conclusions are drawn:

- Groundwater quality of production wells complies with Omani standards for drinking water for all parameters, which were mentioned in the study.
- The upper catchment water quality is usually very good. This is related to the close proximity of these areas to areas of recharge, but further from the recharge area, where the water quality becomes salty due to dissolved minerals.
- Despite the fact that groundwater levels did not change during the study period, groundwater salinity increased marginally. This may be due to fluctuation of groundwater levels, in response to groundwater pumping, irrigation return flow and recharge in Monsoon months. It is hyposized that fluctuation has resulted in mixing of saline water from the sea, with aquifer freshwater.
- Changes in the water levels of the aquifer do not reflect negative net recharge of groundwater.

6.2 Recommendations

Groundwater in Salalah is the only source of fresh water for the city. Therefore, it is very important that it be managed and protected. On the basis of the findings of this study, the following recommendations are made for water resources management:

Specific Recommendation:

- **Adopting the Best Management Practices (BMP)**

This study shows that the groundwater at present is not contaminated. It is, however, imperative that best management practices be adopted and enforced in the future. For all agricultural sites storage of fertilizers, herbicides and pesticides should be in concrete standing and sewage should be collected in holding tanks. Appropriate amounts of irrigation water using modern technology, such as trickle or drip methods, should be applied. For all Livestock sites construction of containment areas for manure, slurry pits and holding tanks for sewage are needed.

Implementation of BMP measures will assist with the long-term protection of the wellfields. Therefore, all sites should be visited, particularly in the protection zones, at frequent intervals to ensure that best practices are being implemented.

Novotny and Chesters (1981) defined BMP as a combination of practices that is determined by a state after problem assessment to prevent or reduce the amount of pollution generated by diffuse or point sources to a level compatible with water quality goals.

General Recommendations:

- **Using Geographical Information System for managing the Groundwater Resources (GIS).**

A successful wellfield protection program requires accurate and timely information for defining problems and evaluating prevention strategies within WPZ.

The establishment of a GIS is recommended. GIS is a planning tool that links spatial data with tabular information. This makes it a powerful tool for analyzing and decision-making (Flockhart at el., 1993). Once appropriate data are fed, GIS can be used effectively to derive outcomes of various land use plans and regulations. Al-Harthy (1995) and Bait- Ishaq (1996) used GIS for evaluating water resources status in their study areas for easy implementation and maintaining the balance between the protection of groundwater and economic development.

- **Residential and Agricultural Water Management Programs**

The program involves the following:

1. User pays pricing. By charging the true cost of water, water demand can be reduced.
2. Water meters should be set up in individual existing units. This will provide a complete picture in terms of how much water in total is being consumed.
3. Public awareness campaigns urging water conservation should be conducted by radio, newspapers and television and by way of lectures in schools and civic centers.

- **Review of Wellfield Protection Regulations**

A comprehensive review for the wellfield protection regulations in the Southern Region and the remaining wellfields in the Sultanate should be undertaken in order to decide which regulations are the most beneficial to the wellfield. Considerations should be given to the Omani cultural, socio-economic and existing legal background in formulating them.

- **Accident Management, Emergency and Disaster in Wellfield Protection Zone.**

Wellfields are subject to accidents and disasters that threaten their well-being. This puts the users of these wellfields at severe risks due to pollution that can lead to death. If this occurs, the situation requires mobilization of regional and national resources for management purpose. This should be coordinated by the Royal Omani Police, Fire department, Wail's office, Sheikh Mantaqa, MRMER &WR regional office, Ministry of Housings and Electricity regional office, Ministry of Agriculture and Fisheries regional office and Ministry of Defense.

- **Monitoring of Groundwater**

Groundwater monitoring in terms of quality and quantity should be carried out regularly to establish whether contamination is occurring and to detect any change in groundwater. This allows early detection of groundwater, so that potential remedial measures to be taken.

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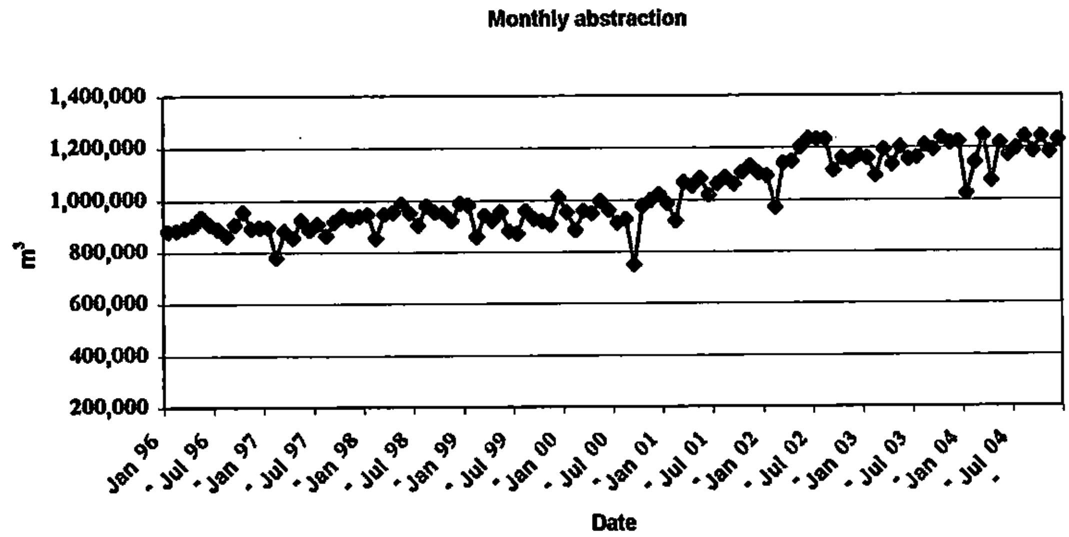
Appendix 1: Monthly abstraction readings of Salalah and Saada production wells



Appendix 2 Omani drinking water standards (OS 8/98)

Components	*Unit*	*Level of Quality*	*Max. Level*
PHYSICAL PARAMETERS:			
Colour	-	1	15
Turbidity	-	1	<5
Taste and Odour	-	without	acceptable
Temperature	-	acceptable	acceptable
Inorganic Constituents:			
Ammonia*	mg/L	-	1.5
Chloride	mg/L	≤ 250	600
Copper*	mg/L	<1	1.5
Total Hardness (Calculated as calcium carbonate)	mg/L	≤ 200	500
Hydrogen Sulphide	mg/L	-	0.1
Iron*	mg/L	<0.3	1.0
Manganese*	mg/L	<0.1	0.5
pH	-	6.5-8.0	9
Sodium	mg/L	≤ 200	400
Sulphate	mg/L	≤250	400
Total Dissolved Solids	mg/L	≤800	1500
Zinc*	mg/L	<3	5
Magnesium	mg/L		$30^{\$}$ or 150^{+}
Aluminium	mg/L	<0.05	0.02
INORGANIC CONSTITUENTS:			
Arsenic	mg/L	-	0.01
Barium	mg/L	-	0.7
Boron	mg/L	-	0.3
Cadmium	mg/L	-	0.03
Chromium	mg/L	-	0.05
Cyanide	mg/L	-	0.07
Fluoride	mg/L	-	1.5
Lead	mg/L	-	0.01
Mercury (total)	mg/L	-	0.001
Molybdenum	mg/L	-	0.07
Nickel	mg/L	-	0.02
Nitrate (as NO_3)	mg/L	-	50.0
Nitrate (as NO_2)	mg/L	-	3.0
Selenium	mg/L	-	0.01
Antimony	mg/L	-	0.005
ORGANIC CONSTITUENTS:			
a. Chlorinated alkanes			
Carbon tetrachloride	µg/L	-	2
Dichloromethane	µg/L	-	20
1, 2 –dichloroethane	µg/L	-	30
1,1,1-trichloroethane	µg/L	-	2000
b. Chlorinated ethenes		-	
Vinyl chloride	µg/L	-	5
1,1-dichloroethane	µg/L	-	30
1, 2 –dichloroethane	µg/L	-	50
Trichloroethene	µg/L	-	70
tetrachloroethene	µg/L	-	40
c. Aromatic Hydrocarbons			
Benzene	µg/L	-	10
Toluene	µg/L	-	700

Components	*Unit*	*Level of Quality*	*Max. Level*
Xylenes	µg/L	-	500
Ethyl-benzene	µg/L	-	300
Styrene	µg/L	-	20
Benzopyrene	µg/L	-	0.7
d. Chlorinated benzenes			
Monochlorobenzene	µg/L	-	300
1,2-dichlorobenzene	µg/L	-	1000
1,4-dichlorobenzene	µg/L	-	300
trichlorobenzene	µg/L	-	20
e. Miscellaneous Organic Chemicals			
Di ethylhexyl adipate	µg/L	-	80
Di ethylhexyl phthalate	µg/L	-	8
Acrylamide	µg/L	-	0.5
Epichlorohydrin	µg/L	-	0.4
Hexachlorobutadiene	µg/L	-	0.6
E.D.T.A.	µg/L	-	200
Nitrilotriacetic acid	µg/L	-	200
Tributylin Oxide	µg/L	-	2
RESIDUAL CHLORINE	mg/L	0.2-0.5	5.0
FAECAL COLIFORM (treated water in distribution system) only E.Coli	Number per 100 ml	Nil	Nil
FAECAL COLIFORM (untreated underground water)	Number per 100 ml	Nil	Nil
TOTAL COLIFORM BACTERIA (untreated underground water) Both E.coli and Coliform	Number of colonies per 100ml	Nil	10#
TOTAL COLIFORM BACTERIA (water transported by water transport vehicles)	Number of colonies per 100ml	Nil	3#

Notes: $: If sulphates is equal to or greater than 250 mg/L * : if They exist
+ : If sulphates is less than 250 mg/L # : They do not

Appendix 3. Water quality data from MRME&WR environmental database

SiteID	Samdate	EC	PH	ALK-T	Cl	SO4	F	NO3-N	TDS	HAR.T	Ca	Mg	Na	K
TP2	13/01/1983	722	1426	7.52	23	0	0	0	0	313	72.8	31.8	48	2.4
TP2	16/05/1983	699	7.6	180.28	86.9	39	0	0	0	267	78.95	17.01	49	2.3
TP2	11/12/1983	650	7.45	182.58	82.5	42	0	0	0	278	83.37	17.02	55	2.4
TP2	18/03/1984	724	7.4	181.66	82.5	28	0.2	3.16	0	273	82.56	16.29	54	2.4
TP2	07/06/1984	740	7.67	198.52	87.74	32	0	3.2	478	264	78.96	16.29	55.5	2.35
TP2	12/09/1984	798	7.57	208.53	84.29	35	0	0	456	310	82.97	25.04	49	2.5
TP2	03/12/1984	661	7.64	205.92	85.27	22	0	0	450	270	79.36	17.5	49	1.3
TP2	12/02/1985	724	7.16	199.65	88.69	24	0	4.13	458	274	13.63	58.34	49	2.2
TP2	30/06/1985	693	6.41	215.5	84.4	44	0	0	438	284	47.7	40.11	55	2.3
TP2	24/07/1985	719	6.72	0	91.4	0	0	3.6	444	0	0	0	0	0
TP2	06/02/1991	579	7.31	178	65	22	0.18	2.81	366	210	58	16	36	1.6
TP2	06/02/1991	579	7.31	178	65	22	0.18	2.81	366	210	58	16	36	1.6
TP2	01/09/2000	846	7.7	149	118	0.03	9	516	274	214	15	0	0	0
TP2	01/03/2002	854	7.25	172	132	34	0.23	16	496	290	85	19	33	0.7
TP2	12/12/2002	895	7.21	87	134	34	0.17	17	443	304	90	19	38	0.8
TP3	13/01/1983	714	7.49	210.52	84.76	23	0	0	0	270	76.4	19.2	48	2.3
TP3	16/05/1983	704	7.41	186.71	87.5	40	0	0	0	278	78.15	20.17	49	2.25
TP3	16/11/1983	688	7.63	186.25	84.9	38	0	0	0	275	82.16	17.02	54	2.2
TP3	15/02/1984	0	0	0	0	0	0.22	0	0	0	0	0	0	0
TP3	18/03/1984	735	7.37	185.33	84.2	28	0.2	3.62	0	289	82.16	20.42	55	2.4
TP3	07/06/1984	747	7.26	217.36	88.63	30	0	3.63	500	279	77.35	20.91	55	2.3
TP3	12/09/1984	724	7.45	212.71	85.47	32.5	0	0	460	305	84.57	22.85	50	2.1

TP3	04/12/1984	703	7.45	208.01	92.68	25.4	0	0	432	317	88.18	23.58	52	2.1
TP3	12/02/1985	735	7.22	200.69	91.87	23	0	4.11	456	322	14.03	69.77	57	2.3
TP3	30/06/1985	745	6.53	236.15	93.8	40	0	0	488	273	40.08	42.06	58	2.4
TP3	15/09/1985	672	7.76	262.39	88.4	24	0	0	444	262	36.04	41.77	54	1.95
TP3	06/02/1991	730	7.35	224	89	19	0.22	3.18	474	300	88	19	47	1.9
TP3	06/02/1991	730	7.35	224	89	19	0.22	3.18	474	300	88	19	47	1.9
TP3	01/09/2000	882	7.4	149	123	26	0.05	12	526	276	228	12	0	0
TP3	01/03/2002	902	7.27	312	166	36	0.46	15	510	312	92	20	36	0.7
TP3	12/12/2002	903	7.24	87	137	31	0.19	17	443	304	90	19	38	0.8
TP4	16/05/1983	828	7.47	194.05	118.2	38	0	0	0	309	89.78	20.66	60	2.5
TP4	16/11/1983	800	7.39	194.51	119	40	0	0	0	341	92.18	26.98	65	2.3
TP4	15/02/1984	0		0	0	0	0.19	0	0	0	0	0	0	0
TP4	18/03/1984	861	7.34	194.51	119.1	31	0.18	3.06	0	334	94.19	24.07	68	2.5
TP4	16/04/1984	871	7.93	0	118.53	31.2	0	3.13	504	282.5	0	0	100	3.9
TP4	12/09/1984	861	7.4	221.6	123.63	34	0	0	554	341	93.79	26.01	63	2.2
TP4	30/06/1985	861	6.49	235.62	125.5	25	0	0	492	250	40.08	36.47	73	2.5
TP4	15/09/1985	798	7.29	252.69	128.1	24	0	0	534	290	48.05	41.28	68	2.1
TP4	06/02/1991	825	7.26	225	111	0	0.5	2.92	530	300	68	31	55	2
TP4	01/09/2000	950	7.5	151	142	23	0.05	11	526	290	228	15	0	0
TP4	01/03/2002	955	7.32	153	177	38	0.23	17	516	314	99	16	46	0.9
TP4	12/12/2002	950	7.32	102	150	33	0.2	16	552	302	87	21	38	0.8
TP5	16/05/1983	906	7.36	194.51	135.8	47	0	0	0	318	97.79	17.98	70	2.7
TP5	11/12/1983	820	7.56	197.72	132.2	46	0	0	0	323	94.19	21.39	77	2.51
TP5	18/03/1984	903	7.34	194.96	132.6	32.5	0.19	3.08	556	339	98.2	22.85	73	2.7
TP5	07/06/1984	918	7.48	236.22	132.94	39	0	3.3	568	320	91.78	21.88	77	2.65

TP5	12/09/1984	987	7.44	222.64	133.88	42.5	0	0	538	322	94.19	21.15	69	2.4
TP5	03/12/1984	619	0	179.79	82.51	19.8	0	0	402	267	63.73	26.25	49	1.1
TP5	03/12/1984	861	7.42	239.89	133.95	18.4	0	0	550	338	94.19	25.04	78	2.5
TP5	12/02/1985	861	7.01	213.24	134.33	36	0	3.61	562	304	12.83	66.12	67	2.5
TP5	30/06/1985	892	6.53	236.68	137.5	37.5	0	0	564	326	60.12	42.79	80	2.7
TP5	05/10/1985	834	6.88	260.35	124.4	22	0	0	508	305	83.29	23.56	79	2.6
TP5	23/02/1986	866	7.05	234	125	38	0.52	0	520	330	100	19	55	2.4
TP5	19/07/1986	908	7.22	273	134	27	0	0	556	350	95.2	27.2	71	2.3
TP5	18/11/1986	876	7.33	293	136	39	0	0	592	321	87.7	24.77	69	2.3
TP5	10/03/1987	892	7.44	227	133	31	0.29	2.86	606	301	89.7	18.7	77	2.2
TP5	02/07/1988	903	7.64	0	136	0	0	0	0	0	0	0	0	0
TP5	08/01/1989	914	7.92	0	136	0	0	0	0	0	0	0	0	0
TP5	06/02/1991	838	7.43	233	124	35	0.18	0.01	518	310	92	19	60	2.2
TP5	06/02/1991	838	7.43	233	124	35	0.18	2.93	518	310	92	19	60	2.2
TP5	03/06/1992	940	7.57	220	140	42	0.2	3.2	0	290	82	20	69	2.5
TP5	27/12/1993	928	7.63	207	130	26	0.2	12.3	0	294	77	25	56	3.7
TP5	27/06/1994	759	7.96	121	132	29	0.1	3.4	0	195	48	18	68	1.5
TP5	13/06/1995	974	7.84	217	154	33	0.1	14.8	0	285	77	23	68	2
TP5	18/12/1995	940	7.3	208	161	37	0.3	14.9	0	307	80	26	64	2.2
TP5	09/06/1996	979	7.55	208	151	41	0.1	16.9	515	317	91	22	62	2.4
TP5	07/12/1996	976	7.39	217	164	40	0.2	16.2	560	374	112	23	67	2.5
TP5	09/06/1997	943	7.74	216	170	38	0.2	15.3	0	338	105	18	59	2.2
TP5	24/12/1997	956	7.38	221	145	29	0.1	10.4	0	309	91	20	68	2.4
TP5	09/06/1998	963	7.4	222	164	31	0.1	15.4	0	337	102	20	62	2.4
TP5	23/12/1998	990	7.43	230	162	35	0	24.8	0	330	100	20	65	2.5

TP5	16/06/1999	995	7.19	220	151	38	0.1	15.9	0	373	112	22	70	2.7
TP5	01/09/2000	1005	7.5	149	155	0	0.05	12	572	313	232	19	0	0
TP5	03/03/2002	1000	7.16	145	196	43	0.21	19	546	313	91	21	60	1.2
TP6	13/01/1983	673	7.54	180.44	84.68	29	0	0	0	210	67.6	10	49	2.4
TP6	16/05/1983	928	7.56	156.89	38.4	247	0	0	0	181	16.04	52	2.3	156.89
TP6	11/12/1983	635	7.7	157.35	85	39.6	0	0	0	248	73.35	15.8	56	2.2
TP6	18/03/1984	682	7.53	158.26	83.7	29	0.2	3.84	0	266	71.74	21.15	55	2.4
TP6	07/06/1984	672	7.37	188.53	86.85	32	0	3.68	412	227	24.45	14.83	55	2.3
TP6	12/09/1984	651	7.54	177.17	83.49	35	0	0	410	287	70.94	26.74	50	2
TP6	12/02/1985	630	7.03	174.04	126.57	24.4	0	4.78	420	258	8.02	57.86	50	2.1
TP6	30/06/1985	661	6.47	181.08	82.5	24	0	0	440	235	56.51	22.85	57	2.3
TP6	06/02/1991	750	7.28	191	87	20	0.2	3.85	444	255	62	24	44	1.9
TP6	01/09/2000	761	7.4	232	106	19	0.09	13	434	232	185	11	0	0
TP6	01/03/2002	762	7.45	122	83	37	0.3	20	410	280	83	18	22	0.5
TP6	03/12/2002	778	7.2	73	111	29	0.19	29	405	253	77	15	38	0.8
TP7	13/01/1983	692	7.86	182.06	88.26	52	0	0	0	252	63.6	22.6	53	3
TP7	16/05/1983	675	7.58	161.02	86.9	39	0	0	0	244	66.93	18.71	52	2.65
TP7	16/11/1983	680	7.47	161.02	87.1	37.6	0	0	0	246	69.74	17.5	51	2.7
TP7	15/02/1984	0	0	0	0	0	0.2	0	0	0	0	0	0	0
TP7	18/03/1984	703	7.57	161.48	86.5	32.5	0.21	1.26	0	260	70.14	20.66	57	2.7
TP7	07/06/1984	715	7.14	194.07	88.63	36	0	4.5	438	243	66.53	18.72	57	2.7
TP7	12/09/1984	682	7.54	181.36	88.23	36	0	0	440	300	73.35	28.44	53	2.4
TP7	04/12/1984	619	7.54	181.88	88.63	18.4	0	0	432	275	74.95	21.39	51	1.5
TP7	12/02/1985	682	7.05	178.22	89.05	23.6	0	4.9	442	265	11.62	57.37	52	2.6
TP7	30/06/1985	651	6.43	204.91	88.8	44	0	0	408	248	48.9	30.63	59	2.7

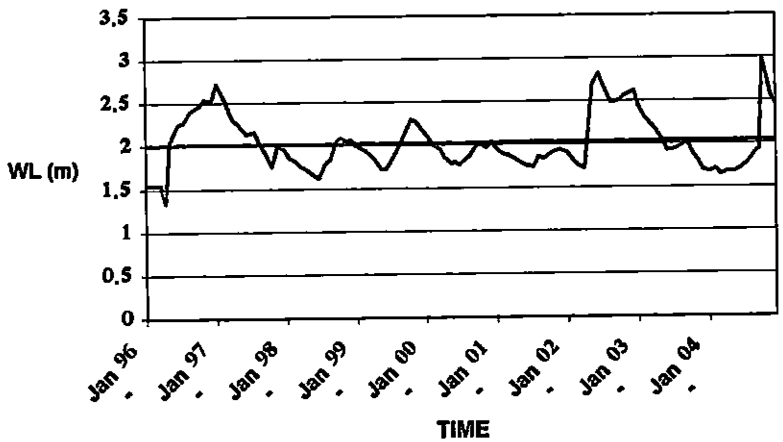
TP7	15/09/1985	630	7.58	241.97	87.7	28	0	0	420	260	48.05	34	58	2.4
TP7	03/10/1985	661	7.48	223.08	90.9	22	0	0	466	296	46.45	43.6	60	2.4
TP7	23/02/1986	698	7.16	208	83	25	0.52	0	422	255	72	18	41	2.4
TP7	03/06/1986	718	7.29	225	87	29	0	0	418	245	71.2	16.27	41	2.3
TP7	31/08/1986	751	7.67	206.55	86	33	0	0	410	250	56.06	26.71	41	2.1
TP7	06/02/1991	530	7.27	159	72	18	0.17	2.8	364	190	52	14	37	1.9
TP7	01/09/2000	855	7.5	127	128	12	0.09	12	556	266	197	17	0	0
TP7	01/03/2002	870	7.18	104	131	27	0.74	15	492	271	66	26	12	0.2
TP7	12/12/2002	921	7.31	87	158	32	0.21	21	499	278	87	15	38	0.8
TP8	16/05/1983	911	7.61	173.86	143.9	63	0	0	0	311	92.18	19.69	73	2.9
TP8	16/11/1983	884	7.37	194.46	135.9	51	0	0	0	340	89.78	28	75	2.8
TP8	15/02/1984	0	0	0	0	0	0	0	0	0	0	0	0	0
TP8	18/03/1984	913	7.39	190.84	131.1	36	0.18	2.96	0	334	94.19	24.07	78	3
TP8	12/09/1984	871	7.38	218.46	128.44	50	0	0	534	332	92.99	24.31	69	2.6
TP8	12/01/1985	914	7.12	214.8	133.44	32.5	0	3.28	592	306	34.47	20.91	7.3	3.01
TP8	12/02/1985	856	6.77	212.19	130.37	36	0	3.9	544	318	13.23	69.28	77	3
TP8	03/07/1985	903	6.49	249.27	130.5	50	0	0	554	344	85.77	31.6	60	2.7
TP8	15/09/1985	819	7.31	248.61	126.9	30	0	0	530	276	40.04	42.74	77	2.6
TP8	16/06/1999	1055	7.07	211	185	47	0.1	23.9		383	114	24	77	3.2
TP8	01/09/2000	1057	7.5	147	162	0	0.09	12	646	320	235	21	0	0
TP8	03/03/2002	1051	7.45	169	200	63	0.33	19	566	326	101	18	73	1.5
TP8	12/12/2002	1131	7.46	87	193	52	0.19	30	620	338	100	22	62	1.2
TP9	13/01/1983	885	7.65	225.02	131.6	29	0	0	0	295	83.6	20.9	70	3
TP9	16/05/1983	890	7.4	194.51	133.1	42	0	0	0	314	92.58	20.17	69	2.75
TP9	11/12/1983	820	7.56	193.13	130.2	44.8	0	0	0	305	92.18	18.23	77	2.7

TP9	18/03/1984	882	7.48	195.42	130.4	50.5	0.19	3.06	562	328	91.78	24.07	74	2.8
TP9	07/06/1984	913	7.21	106.46	132.94	36	0	3.72	586	299	86.97	19.93	74	2.6
TP9	12/09/1984	892	7.5	220.03	129.4	42.5	0	0	548	328	88.98	25.77	69	2.5
TP9	03/12/1984	850	7.63	247.21	129.47	18.4	0	0	534	362	89.38	33.79	71	2.5
TP9	12/02/1985	861	7.42	215.33	128.22	36	0	3.76	556	323	94.59	21.15	74	2.7
TP9	24/07/1985	866	6.76	277.98	131.8	40	0	3.48	546	313	64.53	36.95	53	2.5
TP9	15/09/1985	840	7.47	275.16	130.1	28	0	0	534	300	34.44	51.97	74	2.4
TP9	16/06/1999	1025	7.21	213	165	40	0.1	21.6	0	395	117	25	70	2.7
TP9	01/09/2000	1031	7.5	151	162	0	0.09	12	630	316	239	19	0	0
TP9	03/03/2002	1002	7.21	169	195	53	0.29	15	558	338	101	21	60	1.2
TP9	12/12/2002	1034	7.2	73	179	44	0.17	19	557	318	94	20	50	1
Saada2	22/06/1983	747	7.43	196.34	78.7	41	0	0	0	291	88.57	17.02	44	1.8
Saada2	30/01/1991	763	7.31	225	64	0	0	0	0	0	0	0	0	0
Saada2	30/01/1991	777	7.26	231	68	18	0.21	3.43	438	300	78	25	36	1.6
Saada2	30/01/1991	777	7.26	231	68	18	0.21	3.43	438	300	78	25	36	1.6
Saada2	01/09/1991	633	7.47	221	58	12	0.2	3.6	422	285	92	13	32	1.3
Saada2	01/09/1991	660	7.48	224	68	17	0.2	3.56	0	250	74	16	34	1.3
Saada2	01/09/1991	660	7.48	224	68	17	0.2	3.56	0	250	74	16	34	1.3
Saada2	01/09/1991	685	7.61	225	73	24	0.2	3.38	516	285	90	15	39	1.6
Saada2	01/09/1991	685	7.61	225	73	24	0.2	3.38	516	285	90	15	39	1.6
Saada2	01/09/2000	710	7.5	147	80	0	0.1	13	410	282	224	14	0	0
Saada2	12/12/2000	725	7.5	0	0	0	0	0	0	0	0	0	0	0
Saada2	03/03/2002	737	7.22	179	100	31	0.35	16	454	309	88	22	5	0.1

0= not analyzed

Appendix 4 Hydrographs of water level monitoring wells 7-9 km from the coastline

AD 983739AA



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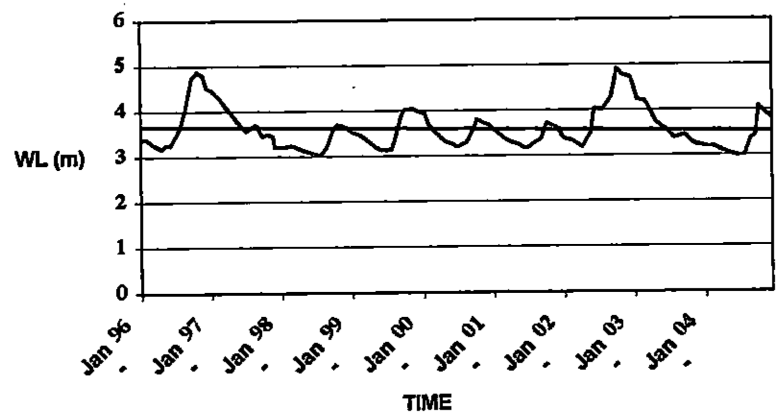

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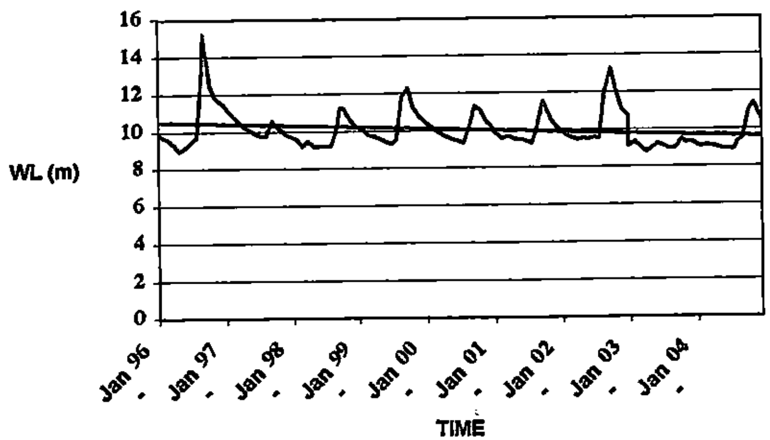

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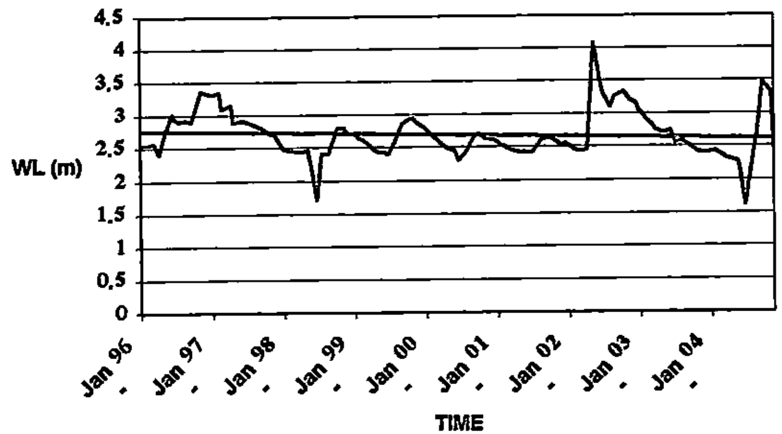
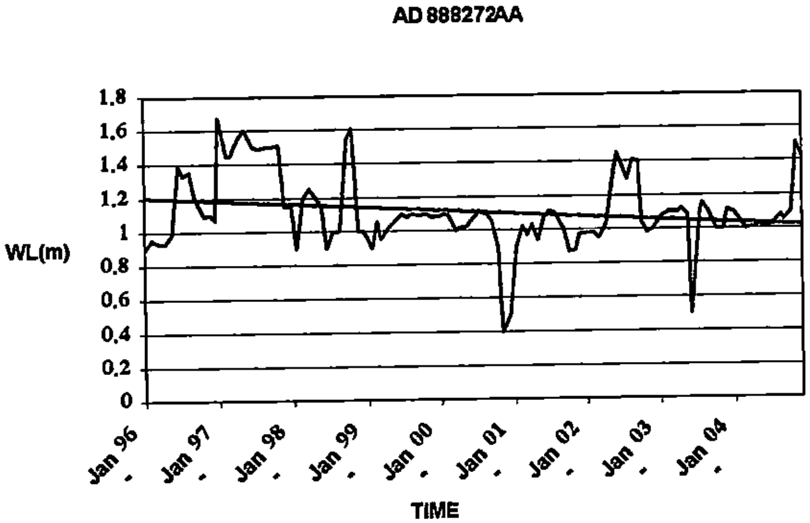
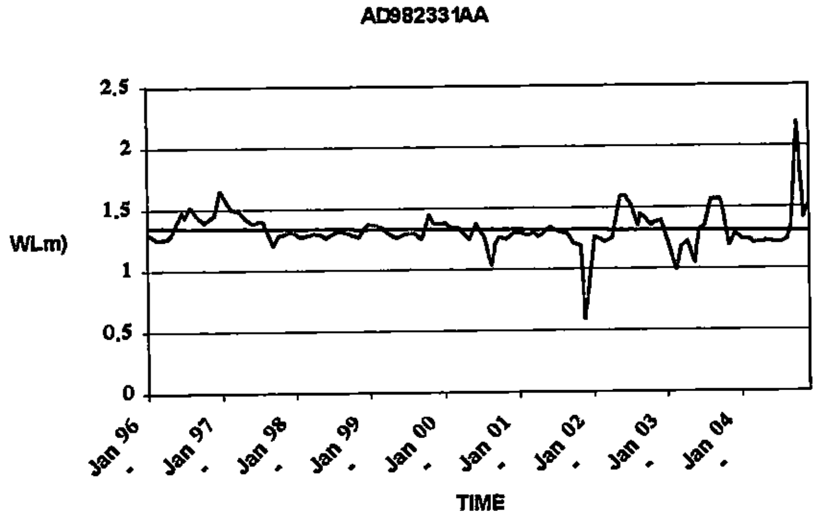
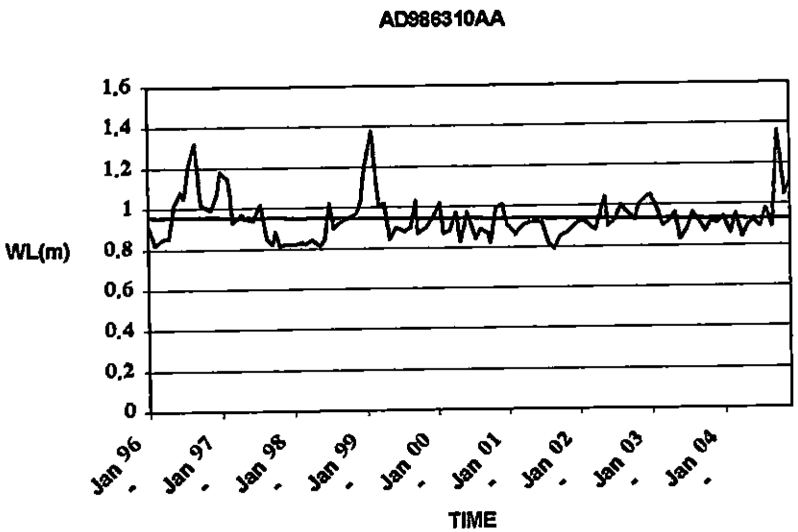
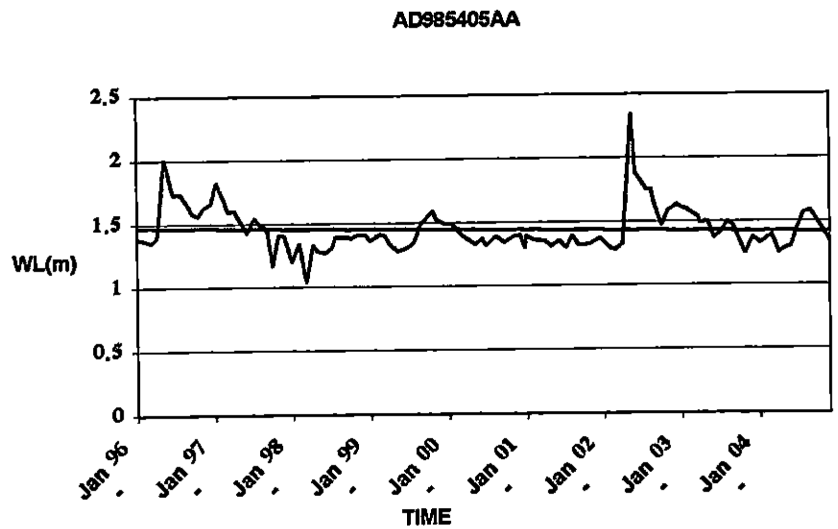


Appendix 4 (continued) Hydrographs of water level monitoring wells 3-5 km from the coastline

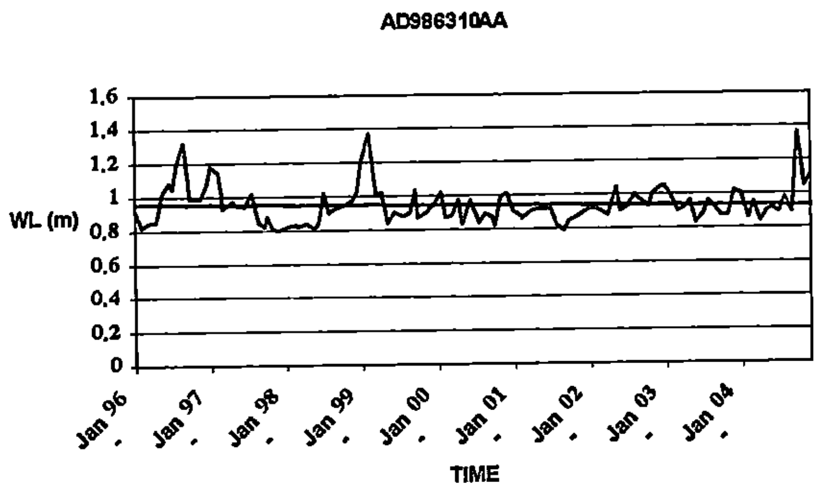








Appendix 4 (continued) water level monitoring wells 0.5-1 km from the coastline



Appendix 5 Activity matrix

ACTIVITY	ZONE			
	RED	ORANGE	YELLOW	BLUE
AGRICULTURE:				
LIVESTOCK	A	C	C	C
ARABLE/VEGETABLE/ TRADITIONAL	B	C	C	C
CHEMICAL FERTILIZERS, INSECTICIDES PESTICIDES, AND HERBICIDES	A	B	C	C
BIODEGRADABLE AND NON-PERSISTENT FERTILIZERS	B	C	C	C
BURIAL GROUND	A	B	C	C
DISCHAGE OF REJECTED WATER FROM DES. PLANS THROUGH EVAP PONDS	C	C	C	C
DISCHAGE OF REJECTED WATER FROM DES. PLANS THROUGH BOREHOLE	A	B	C	C
GOVERNMENT DAMS	C	B	B	C
PRIVATE DAMS	B	B	B	C
RESIDENTIONAL PLANS	B	C	C	C
SURFACE STORAGE TANKS	A	C	C	C
UNDERGROUND STORAGE TANKS	A	B	C	C
INDUSTRIAL SITES	A	B	C	C
QUARRY	A	C	C	C
MINE	A	B	C	C
OIL INDUSTRY:				
DRILLING AND OIL PIPELINE	A	B	C	C
REINJECTION OF PRODUCTION WATER	A	A	A	B
PROTECTED ROADS	B	C	C	C
UNPROTECTED ROADS	A	B	C	C
SEWERAGE SYSTEMS:				
SEPTIC TANKS AND CESS PITS	A	A	B	B
HOLDING TANKS	A	C	C	C
SMALL BUSINESSES	B	C	C	C
SOLID WASTE DISPOSAL SITES	A	B	C	C
LIQUID WASTE DISPOSAL SITES	A	A	C	C
HAZARDOUS WASTE DISPOSAL SITES	A	A	A	A
TEMPORARY CAMPS	A	C	C	C
DRILLING OF GOVERNMENT WELLS	C	C	C	C
DRILLING OF PRIVATE WELLS	B	B	D	D
DEVELOPMENT WORKS:				
EXTENSION OF EXISTING DEVELOPMENTS UNRELATED TO GOVERNMENT GROUNDWATER MANAGEMENT	A	C	C	C
CHANGE OF ACTIVITY USE	B	C	C	C

Notes:
A = UNACCEPTABLE
B = UNDESIRED, EXCEPT WITH GOVERNMENT DISPENSATION
C = ACCEPTABLE
D = ACCEPTABLE WITH ABSTRACTION LICENCE

Appendix 6: Best practices of MD 196/2001

Activity	Potential Hazard	Best Practice	Comments
Solid Waste Disposal Site	Leachate. Windblown litter. Atmospheric pollution. Odors. Pesticides. Metals	Selection of appropriate site after hydro geological study. Compacting and covering of wastes daily.	Burning should not be undertaken due to aerial pollution. Good management of solid waste sites requires a bulldozer and sources of cover material. Leachate in Oman should not pose a significant problem due to the relative dryness and scanty rainfall.
Liquid Waste Disposal Sites	Leachate containing oils, chemicals, dyes, sewage etc. Nitrates	Sewerage should be treated separately in a STP. Integrated treatment plant for pH adjustment, separation of oil, mixture and treatment of chemicals. Properly lined sites.	Chemicals and oils should be analyzed and treated independently if possible. Nitrates leaching into groundwater may pose a future threat to water supplies if the sites are not lined or operated correctly.
Agricultural site	Fertilizers e.g. Nitrates, Pesticides, herbicides, Sewage, oil and Increasing salinity due to water recirculation.	Storage of all fertilizers, herbicides and pesticides on concrete standing. Use of recommended doses only. Use of non-persistent, biodegradable pesticides. Oil drums on concrete standing. Oil tanks should be bunded. Sewage collected in holding tanks. Application of correct quantity of irrigation water, using modern technology such as trickle or drip methods.	Application of fertilizers, herbicides & pesticides should not cause pollution problems if used correctly and at the correct application rate. Control may be difficult unless under strict supervision. Spillage should be immediately absorbed with sand and collected in drums for off-site disposal.
Auto Workshop Truck and Car Washing	Waste oil. Storage of lubricants and paints. Diesel and petrol storage. Oily water and detergents from vehicle washing. Domestic sewage.	All waste oil should be stored in drums for off-site disposal. Drums should be on a concrete standing to retain spills. All lubricants and paints should be stored on a concrete standing to prevent spillage entering the ground. Solvent based paints should be stored under shade or within building to avoid overheating. Underground tanks for storage are the norm but these should be checked daily for leakage by measuring the levels against usage. Pressure testing of tanks to be undertaken on a five yearly basis. If overground tanks are used, these should be bunded (110% of tank capacity). Washing should be undertaken in a dedicated area which should be fitted with grit trap and oil interceptor. If operated correctly, the wastewater can be used as irrigation water. Holding tanks required for sewerage.	All contaminated areas should be excavated and wastes removed to licensed dumpsite. Spillage on hard-standing areas should be mopped up with sand and contaminated sand removed off-site to an authorized dumpsite. Waste oil filters should be stored in drums to drain oil, then collected for disposal in waste oil drums. All maintenance should be undertaken on concrete areas. All metal, paper and wood wastes should be placed in suitable waste containers and disposed off-site to a licensed dumpsite. Maintenance of oil/grit traps as follows: daily cleaning of grit traps, weekly inspection of oil interceptor. Collected oil should be sucked out of interceptor and stored in waste oil drums for off-site disposal. Waste oil can be used as secondary fuel or disposed of for reprocessing if such a company/facility exists in the area. If not, disposal to an authorized site. Supervision of filling operations should be implemented.

Activity	Potential Hazard	Best Practice	Comments
Block Factories Cement Works	Fuel/Oil storage. Domestic Sewage. Fine cement/ceramic dust.	Drum storage on concrete pads. Settlement tank for fine particles. Holding tanks required for sewerage.	Waste collection issues not significant, packaging materials, wood, paper in Municipal waste disposal bins. Holding tanks should be cleaned and emptied regularly. Settlement tanks require to be baffled and solids removed periodically.
Shops	No hazards expected. Cooking oil spillage in large quantities may cause problems.	No action required.	Domestic sewage to holding tank. Waste vegetable not considered a problem if disposed daily to Municipal waste containers.
Restaurants	Grease.	Three stage grease trap required. Holding tanks required.	Grease trap requires regular inspection and emptied periodically when grease appears in the third chamber. Waste should be disposed to a licensed disposal site.
Civil Contractors	Storage of fuels. Disposal of sewage.	Concrete standing for drum storage. Bunded fuel tanks. Holding tanks.	Size of bunds should be 110% of total contents stored within bund. Holding tanks should be emptied, cleaned and checked for leakage regularly.
Tire Repair Auto Electrician	Fuel storage. Disposal of sewage.	Concrete standing for drum storage. Holding tanks for sewage.	Only small quantities of fuel oil are expected on site. Holding tanks should be emptied, cleaned and checked for leakage regularly.
Carpentry Workshop	Storage of paints or solvents. Sewage.	Paints/solvents should be stored under cover on concrete base. Holding tanks for sewage.	If spillage occur, the solvents are likely to evaporate rapidly. No problems with spillage envisaged on the scale used by carpentry. Holding tanks should be emptied, cleaned and checked for leakage regularly. Holding tanks should not overflow.
Graveyard	Biological and leachate	Holding tank required for leachate.	No problems expected from graveyard wastes but monitoring boreholes are recommended.
Explosives/ Chemical Factory	Fuel oil storage. Chemical storage. Sewage	Drum storage on concrete standing. Fuel tanks in bunded areas. Holding tanks for sewage and industrial wastewater.	Bunds to be sized at 110% of total stored contents. Powder chemical spills to be swept up and placed in waste bins. Liquid spills should be absorbed in sand and the contaminated sand removed off site to licensed dump site.
Filling Stations	Petrol leakage. Sewage.	Underground storage tanks should be: double skinned steel or single skin GRP; catholically protected; coated with coal tar epoxy. Monitoring of levels required/stock control carefully monitored. Pressure tested e.g. every 5 years. Holding tanks for sewage.	Careful monitoring of tanks required to prevent leakage to ground, including the use of electronic sensors for hydrocarbon detection. Old tanks should be abandoned and unfilled with concrete.

Activity	Potential Hazard	Best Practice	Comments
Rock Crushing	Lubricants. Fine sediments. Sewage.	Oil storage tanks to be bunded. Oil drums to be stored on concrete standing. Sewage should be collected in holding tank.	Oil tanks should be bunded with capacity of 110% of total tank capacity. All fill pipes should be contained within bund or small collection area constructed outside bund to collect drips. Fine sediments can block channels to groundwater.
Gas Pipelines	Leakage of oil and for gas.	Deep burial beneath Wadis. Regular pressure testing and inspection to check for leakage.	Avoidance of Red Zone and or Wadis if possible.
Plastics and Piping	Chemicals. Sewage.	Chemical drums should be stored on concrete standing. Installation of properly designed holding tank for sewage and industrial wastewater.	
Livestock	Animal waste products. Sewage	Construction of containment area for manure. Construction of slurry pit, collection and off-site disposal if no means for spreading on land. Construction. of holding tank for sewage.	Removal of solid animal waste by shovel initially and disposal of solids to manure heap. Animal waste may be used as fertilizers outside Red Zone.
Asphalt Plant	Tar products. Oil & Lubricants. Sewage.	Oil tanks to be bunded. Oil drums stored on concrete standing. Sewage to be collected in holding tanks.	Spillage of tar should be collected and placed in drums for off-site disposal. Capacity of bunding should be 110% of total capacity of stored oil.
Car Wash	Washing wastes. Detergents. Oils.	Construction of dedicated area for car wash. Construction of grit traps and oil interceptor.	Re-use of water if practicable. Treated water may be used for irrigation outside Red Zone.
Abattoir	Animal wastes, blood, intestines and sewage.	Separation of stomach contents and animal parts for off-site disposal to licensed site. Treatment of screened effluent in a STP. Sewage collected in holding tanks.	Abattoir wastes are highly polluting and should be effectively destroyed e.g. incineration of animal parts and treatment of liquid wastes in STP. Maintenance of grease trap essential to maximize efficiency.
Dairy Farm	Dairy wastes. Animal Wastes. Slaughter house wastes. Fuel tanks and lubricants. Sewage.	Dairy, animal and slaughterhouse wastes should be treated to a high standard in an effluent treatment plant. Oil tanks should be bunded. Oil drums should be stored on concrete standing. Sewage should be collected in holding tanks.	Treated wastewater and animal manure should not be applied to land within the Red Zone. Bunds to be constructed to contain 110% of total tank contents. Fill pipes to be contained within bund or provision of oil drum to collect drips from fill pipes. Sewage should not be permitted to discharge to the environment.
Airport	Aviation fuel. Sewage.	Fuel tanks should be bunded. Sewage should be collected in holding tanks.	Aviation fuel is highly flammable. Spillage of aviation fuel should be mopped up and disposed off site. Treated water should be taken off site and used for irrigation purposes outside Red Zone.

Activity	Potential Hazard	Best Practice	Comments
Surface Water	Diesel and Other waste oils.	Oil tanks to be bunded.	Spillage mopped up with sand and taken off site.
Supply Boreholes	Surface contamination (Oil, fertilizers, etc.) Downhole/uphole contamination (brackish, saline, polluted aquifer).	Minimum 5 m depth surface casing, annulus cemented. Concrete surface wellhead block. Seal off all brackish/contaminated aquifers.	
Abandoned Borehole	Surface contamination. Downhole/Uphole contamination.	Seal off all brackish/contaminated aquifers. Backfill with gravel. Minimum 10 m cement plug from surface. Cap/plate welded on Borehole at surface.	Seals should be placed either opposite or above/below the brackish/contaminated zone. Seals should consist of cement with 2-5% bentonite mix. It may be necessary to place additional seals of bentonite pellets where the aquifer is saline or significantly polluted.
Soft Drinks Manufacturer	Water treatment chemicals. Alkali wastes. Oil/lubricants. Sewage.	Chemicals to be stored under cover on concrete standing. Oil tanks to be bunded. Lubricants to be stored on concrete standing. Holding tanks for sewage.	Bund constructed to contain 110% of total contents.
Laundries	Detergents.	Holding tanks and off-site disposal to STP.	
Dry cleaners	Petrochloroethylene.	Drums to be stored on concrete standing.	Used dry cleaning fluid taken off-site for reprocessing or dumping.
Transformers	PCBs.	Transformers should be contained in an integral concrete bund.	No waste PCB should be allowed to spill on to the ground due to the toxicity of this material. Spillage or waste PCB should be taken off-site. PCBs should be destroyed by incineration in a properly designed high temperature hazardous waste incinerator. Otherwise wastes should be disposed in a secure landfill. Note that modern transformers do not contain PCBs.

Appendix 7: Water balance calculations

The calculations for water balance on Salalah Plain, was estimated by two methods as the followings:

- Using method by HMR (2004) with reference to Report on Groundwater Estimation Committee on the Groundwater Estimation Method, Ministry of Irrigation, Government of India, March 1984

Rainfall:

- Average rainfall in the catchment is estimated to be 110 mm/yr
- Volume of water received in the catchment (800 KM^2) by rainfall is 88 Mm3/yr ($8X10^2 X10^6 m^2$ X 0.11m)

Surface Runoff:

10% of total volume of water in the catchment runoff generated from rainfall in the Alluvial plain equals 8.8 Mm3/yr (88X0.1Mm^3/yr)

Recharge:

(i) Direct recharge from rainfall in the Alluvial area (25% of rainfall)

0.25X88 Mm^3 = 22 Mm^3 /yr

(ii) Direct recharge from Rainfall includes

A. Infiltration in Alluvial areas (25% of runoff) 0.25 X 8.8= 2.2 Mm^3/yr

B. Infiltration from the inflow into catchments from the springs along the mountain edge into the plain is 10 Mm^3/yr HMR (2004).

-Total Recharge from Runoff (A+B) equals 12.2Mm^3 /yr (2.2 Mm^3/yr + 10Mm^3/yr)

-Return from irrigation is 15% of agricultural Demand is 6.06 Mm^3/yr (0.15X40.40) HMR (2004).

Then the total recharge will be 40.26 Mm3/yr (6.06+12.2+22Mm^3/yr)

Average water use:

1. Abreacted from Salalah and Saada wells is 9.5 Mm3/yr
2. Domestic demand is 1.0 Mm^3/yr
3. Demand of agricultural is 40.40 Mm^3/yr
4. Demand from industries 1.0 Mm^3/yr

So total water is used is 51.9 Mm^3/yr. However, Benni & Partners (1999) recorded that the imbalance of water table met with storage depletion, saline intrusion and inflow from adjacent east and west that were recorded by GEO-Resources (2005) was 0.2 Mm^3/yr, 5.6 Mm^3/yr and 4.0 Mm^3/yr respectively which equals to 9.8 Mm^3/yr Then, net water balance in the aquifer is -1.8 Mm^3/yr (40.26 Mm^3/yr-51.900+9.8 Mm^3/yr).

- The Conventional Method:

  Recharge:

  - Rainfall and artificial recharge are estimated by GEO-Resources (2005) as 8.4 Mm^3/yr,
  - Irrigation return is 6.06 Mm^3/yr,
  - Throughflow from Jabel is 55 Mm^3/yr,

  The net recharge equals to 69.46 Mm^3/yr

Water used:

Lost by evaporation is 7.5 Mm^3/yr

Demand from agricultural is 40.40 Mm^3/yr

Outflow to sea is 13.7 Mm^3/yr

Wellfield Demand is 9.5 Mm^3/yr

The net water is a used equal to 71.10 Mm^3/yr

Then net water balance in the aquifer is water balance in the aquifer is

Net water balance = Volume of water recharge the aquifer – Volume of water used in the aquifer.

(Volume of recharge – Volume of Water used).

(69.46 Mm^3/yr-71.10 Mm^3/y r = -1.64 Mm^3/yr)