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Sea Water Intrusion in a Coastal Aquifer: A Case Study for the Area Between Seeb and Suwaiq, Sultanate of Oman

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تداخل مياه البحر بساحل الباطنة – حالة دراسية للمنطقة الواقعة بين السيب والسويق (1984م – 2005م)

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الخلاصة: تقع الأجزاء الساحلية من سهل الباطنة بين سلسلة جبال الحجر الغربي والبحر على امتداد المنطقة الواقعة بين محافظة مسقط والحدود مع دولة الإمارات العربية المتحدة . وهي من أكثر المناطق ملائمة لتواجد المياه الجوفية . تعاني الأجزاء الساحلية من سهل الباطنة، خاصة ولايتي بركاء والسويق من تدهور كبير في نوعية المياه الجوفية . وتهدف هذه الدراسة إلى مراجعة وتقييم المسوحات الحقلية التي قامت بها الوزارة منذ عام 1984م وحتى عام 2005م الخاصة بقياس الموصلية الكهربية للمياه الجوفية في أكثر من 1000 بئر تقع بالأجزاء الساحلية بالباطنة . تم استخدام تقنية نظم المعلومات الجغرافية لتحليل البيانات وتحديد نطاقات الملوحة حيث تم اسقاط مواقع الآبار وقيم الموصلية الكهربية على خرائط ومن ثم تم حساب مساحة هذه النطاقات ومقارنتها بالمساحة الإجمالية للمستجمعات المائية المختلفة بالإضافة إلى مقارنتها بالمسوحات الحقلية السابقة . أظهرت نتائج الدراسة تدهورا كبير في جودة المياه الجوفية وهو ما يؤكده انخفاض مساحة الأراضي الصالحة للزراعة بمقدار 7 % خلال الفترة2000 – 2005م ، وهو ما يعادل 2714 هكتار. كما تشير النتائج إلى استمرار تحرك أسفين المياه المالحة باتجاه اليابسة ليصل إلى 12 كم بحوض وادي الطو في منطقة بركاء . ومما لاشك فيه أن جميع هذه الشواهد تشير إلى استنزاف الخزان الجوفي الساحلي بمنطقة الباطنة ولذلك فمن الضروري الاستمرار في مراقبة التغير في جودة وكمية المياه. واتخاذ الإجراءات التي تهدف إلى تطبيق أفضل لمبدأ الإدارة المتكاملة للمصادر المائية خاصة بالأجزاء الساحلية وهو ما يتطلب تعاون كافة المؤسسات الحكومية والأهلية ومستخدمي للمياه للسيطرة على كميات الضخ المتزايدة من الخزان الجوفي ووقف تلوثه الحفاظ على المصادر المائية.

ABSTRACT: The Batinah Coastal plain, located between the Hajar mountains and the sea, from Muscat to the UAE border, is a favorable region for groundwater occurrence in Oman and the main source of fresh water in this coastal area. The coastal parts of the Batinah plain, particularly Barka and Suwaiq, have suffered from groundwater deterioration over the past 20 years. This paper reviews the monitoring activities of groundwater electrical conductivity in the Batinah coastal plain between Seeb and Suwaiq over the period 1984 to 2005, an area of approximately 394 km^2. GIS and Auto-Cad techniques were applied to illustrate different salinity zones as the wells coordinates and their field EC were digitized on maps with contours. Zones of salinity ranges are identified and their areas were computed and compared to the total catchment area of each wadi. All samples were collected from the same upper gravel layer, ranging in depth 20-100 meters. There has been a substantial deterioration in water quality as indicated by a 7% reduction in areas of water suitable for agriculture use (2.000 – 6.000 µS/cm), reflecting a loss of 2,714 hectares of irrigated land. Also, a saline interface is reported 12 km inland at Wadi al Taww, Barka area, an indication of aquifer over-exploitation. It is therefore critical that monitoring of water quality and quantity is continued. It is recommended to improve implementation of the standard water resources management solutions to coastal aquifer saline contamination. Cooperation of different organizations and water users is essential to conserve these precious water resources.

Keywords: Groundwater, water quality, water resources management.

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Introduction

The Batinah coastal plain extends 270 km along the Gulf of Oman from Muscat to the U.A.E. border, north of Shinas. The area is of critical importance to the agricultural economy of the Sultanate; 50% of the total agriculture area is located here. Population growth and rapid industrial and agricultural development in this area, and hence the conjugate increase in different human activities, have imposed an increasing demand for fresh water. This increased demand has been met by the extensive pumping of fresh groundwater water, causing a subsequent lowering of the water table and upsetting the natural balance between the fresh and saline water body. The result is salt water intrusion.

Being heavier than fresh water, salt water occurs as a wedge beneath the fresh water; the two mix in a transition zone or zone of diffusion, in which the water becomes progressively more saline downwards and towards the sea. The existence of a transition zone indicates that there is a significant circulation of seawater into and out of the aquifer. A continuous movement of fresh water through the zone produces a natural barrier that prevents saline water from moving further inland. Under limited pumping of water from wells, the through flow of fresh groundwater to the sea is maintained by recharge in the upper parts of the aquifers and the transition zone holds a fairly constant position. When excessive pumping alters this equilibrium, particularly near the coast, groundwater levels fall, with the flow of fresh water being reduced and the transition zone moving inland and upwards. As a result, water pumped from wells near the coast becomes progressively more saline.

Groundwater abstraction for irrigation in the South Batinah areas is extremely high compared to the North Batinah areas. Therefore, groundwater recharge and abstraction are important factors controlling saline intrusion in the South Batinah. Preventing the saline water intrusion along the Batinah coast depends on continuous recharge events from rainfall and wadi flows and also on controlling the over pumping from wells.

This study focuses on monitoring of the groundwater salinity in the area between Seeb and Suwaiq to detect the lateral variation in salinity of the shallow upper gravel layer of the Batinah aquifer.

Hydrogeology of Al Batinah

The hydrogeology of the Batinah is an important factor in the occurrence of groundwater. Through millions of years, the plain has been formed by the effect of natural processes such as rainfall and weathering. Rainfall on the mountain area has spread sediments to build up the plain and complex patterns of gravel and clay have been formed in the braided wadi channels (Stanger, 1984).

The Batinah area can be divided into two main parts, differentiated by rock type and geological setting, namely: the mountains, composed of hard rocks mainly igneous rocks overlain by ophiolite sediments with some sandstones and conglomerates underlain by several thrust sheets of pelagic sediments and tertiary limestone; and the lowland and coastal plain, consisting mainly of coarse gravels and boulders with occasional cemented beds. The latter is the main aquifer with a total depth of more than 300m in the Sohar-Saham area and more than 600 m in the Seeb-Barka area in the South Batinah. The alluvial deposits generally become finer toward the coast and the interfluve area between the systems of braided channels.

These deposits form a single deep groundwater basin along the Batinah containing relatively fresher groundwater inland where saline intrusion exists near the coast. They are hydrogeologically divided into upper gravels, clayey gravels and cemented gravels. Low lands or Piedmont Zone comprise the upper gravel unit and constitute the main productive zone as the thickness increase towards the sea. Although grain size, degree of sorting, and cementation with calcium carbonate affect this unit hydraulically, its storage and transmissivity are generally good, with average transmissivity values of 550 m^2/day in the Barka–Suwaiq area (South Batinah). The transmissivity in the Sohar-Saham area (North Batinah) is 3000 m^2/day or even larger (6500 m^2/day), due to either higher proportion of coarser materials caused by the narrowness of the coastal plain or a greater aquifer thickness. Underlying the upper gravels are the clayey gravels, marked by the appearance of brown and red marly gravels and clayey sands associated with decreased well yields and average transmissivity about 223 m^2/day. Located at the bottom of the clayey gravel sequence are the cemented gravels with the smallest specific capacities and biggest drawdowns, thus making them markedly poorer aquifers (MWR, 1995).

Groundwater quality along the Batinah is extremely varied. In the mountains near the recharge source, water quality is good, with TDS of less than 1500 mg/l. In the plain and lowland area, water quality decreases as groundwater dissolves many salts (calcium carbonate) on its way to the sea, with higher TDS values in the range 1500 to 6500 mg/l associated with the larger settlements. In the coastal zone the freshwater aquifer is underlain by a saltwater wedge.

The prevailing rainfall pattern in the area is characterized as having the wettest months from February to April, which account an average for 40% of the total annual rainfall. A second but less pronounced relatively wet period is July and August, accounting for another 23%. Mean Annual Rainfall (MAR) varies from about 55 mm at the coast to about 310 mm in the mountains. During the period covered by this study (1984-2005), three significant dry periods and four significant wet periods can be identified (MWR, 2000): dry periods are 1979-81, 1984-86, 1991-94. The five year moving mean plots for all the available long-term stations (22-years) in the area indicates that there is no particular long-term trend and there is no evidence of any statistically significant trend to suggest any climatic change is occurring in the area.

Materials and Methods

Monitoring salt-water intrusion beneath the Batinah coastal plain is carried out at hundreds of hand dug coastal wells. The Public Authority for Water Resources undertook three extensive surveys, covering the entire Batinah coast over the period 1982 to 1984. The surveys were repeated during 1985, 1986 and 1988 for some parts of the Batinah coast, and then in 1989, 1991, 1993, 1995, 1997, 2000 and 2005. The field surveys included measurements of 716 wells (90% of them being productive) located along the study area (394 km^2) on both sides of the Batinah Coast highway: 221 wells located in the Seeb area, 186 wells at Wadi Al Taww, 113 wells at Wadi Al Maawil, 99 wells at Wadi Bani Kharous, and 97 wells at Wadi Al Fara'a.

Water samples were collected from all productive wells and non-pumped wells were pumped using an MP1 pump with 2 inch diameter. To obtain a representative groundwater sample, it was necessary to purge the bore to remove the stagnant water from the bore water column. This was achieved by removing about three times the volume of water contained in the borehole before a sample was collected. The well depths ranged from 20 to 100 meters, tapping only the same upper gravel layer of the Batinah aquifer. The well locations (coordinates) and their field EC were digitized on maps where contours were produced using Auto-Cad techniques. Zones of salinity range were colored, their areas computed and compared to the total catchment area of each wadi, and the results plotted on the maps.

These surveys were designed to provide an overall picture of coastal salinity conditions and to demonstrate that a serious saline intrusion problem existed.

Results and Discussion

Present conditions indicate that fresh water discharge to the sea along the Batinah coast is largely intercepted by pumping in the coastal zone. The salt-water wedge is located several kilometers inland in some places and could pose a serious threat to existing municipal well fields. The top of the interface is approximately delineated by the red colored zones with EC > 16000 mmhos/cm shown on Figures 1, 2 and 3.

Table 1 shows a severe water abstraction from the aquifer compared to the water available, particularly in the Barka area (Wadi Al Taww, Wadi Al Ma'awil) and the Suwaiq area (Wadi Al Fara, Wadi Bani Kharus). The Water Resources Master Plan (MWR, 2000), reported that total deficit amounts to 92.8 Mm^3 which is covered by storage depletion (47 Mm^3) and sea water intrusion (45.8 Mm^3). It should be also noted that both the storage depletion and saline intrusion flow components are not in steady state and may increase or decrease as the aerial extent of the depletion zone and the hydraulic head within that zone vary in response to changes in the groundwater abstraction pattern.

The 2005 Salinity Survey Results

The total study area covered 394 km^2 and 716 wells, with an average spacing of 0.6 km^2 per well. This study compares the 2005 survey with all the available ones since 1983. This comparison illustrates and emphasizes the extensive and serious expansion of the saline water intrusion beneath the Batinah coast, particularly in the area between Seeb and Suwaiq. The following are the most important results of the project (Figs. 4-8):

- 47% of the total measured wells (537) had salinity above 6.000 µS/cm, 18% with a salinity over 16.000 µS/cm, with the highest salinity equal to 57.000 µS/cm at Wadi Taw.
- The southern Batinah areas showed progressive salinity increases during the last decade in spite of the exceptional rainfall during 1995-1997. Figure 4 shows

Table 1. Water balances and areas of over-abstraction (all values in MCM).

Area	Recharge	Water Available	Water Consumed			Deficit
			Agriculture	Dom/ Ind/Mun	Total	
Seeb	52.9	53.2	45.82	9.39	55.2	-2
Barka- Suwaiq	71.7	83.3	173.68	0.38	174.1	-90.8
Total	124.6	136.5	219.50	9.77	229.3	-92.8

Source: Water Resources Master Plan (MRMEWR, 2000).

the increasing trend in salinity during 1993-2005 at three selected different catchments.

- There has been substantial deterioration in water quality, indicated by the 7% reduction in areas of water suitable for agricultural use (2.000 – 6.000 µS/cm), reflecting a loss of 2,714 hectares of irrigated land and indicated by the closure of 116 wells along the study area during the last five years.

In general, the variation in the degree of deterioration or improvement of the upper aquifer at the coastal area is a direct response to the rate of abstraction at each catchment, rainfall periods and to the enhancement of recharge dams located at the upstream part of each catchment. For example, near Seeb, Wadi Samail has markedly improved and the EC has decreased over large areas. Al Khod recharge dam is directly upstream of the area of greatest improvement. It is known that the dam has contributed many millions of cubic metres of fresh water to the aquifer. However, it is beyond the scope of this study to separate and quantify the change in salinity due to the effect of the dam from that caused by natural recharge via wadi flow and rainfall.

Seeb Area: Wadis Rusayl, Samail and Al Hayl, Al Maabila and Al Manumah

These catchments (Fig. 1) were highly salinized by the time of the survey in 1991. During the five years 1995-2000, the area with high salinity water (>10,000 µS/cm) that could not be used for economic cropping decreased by 53% at Wadi Rusayl (Fig. 5). and by 37% at Wadi Al Hayl. However, the area with potable water in Wadi Maabilah reduced gradually to zero in 2000, compared to 12% in 1995 and 5% in 1997 (Fig. 6). In the five years, 2000-2005 there has been a general deterioration in water quality in Wadi Samail and a decrease in the area covered by potable water (<2000 µS/cm). Also at Wadi Manumah there has been a notable deterioration in water quality as the area covered by the potable water reached zero in 2005, compared to 4% in 2000.

Barka Area : Wadis Al Taw and Al Maawil

In both these catchments (Fig. 2), the area underlain by very saline water has increased gradually since 1991. Compared to 2000, the area covered by water not suitable for agriculture (6,000 µS/cm) has increased by 2000 hectares at both wadis (Fig. 7). In addition, the fresh water zone (<2000 µS/cm) in both wadis has decreased from 23 km^2 in 1991 to zero in 2000 and 2005. In Wadi Maawil the area covered by high salinity water (>16.000 µS/cm) has increased from 17% in 2000 to 32% in 2005. The continued inland movement of the saline intrusion is proceeding in connection with the steady decline in water levels below sea level. Even the exceptional rainfall during 1995-1997 was not enough to prevent the saline intrusion in this area. Low average rainfall and wadi flow during 1998-2004 allowed further water quality deterioration.

Suwaiq Area: Wadis Bani Kharous and Al Fara

In Wadi Bani Kharous, the water quality has deteriorated since 1991 (Fig. 3). Groundwater has become unsuitable for most crops at half of the wells in the area , as indicated by a steady increase in the area of very high saline water (>16000 µS/cm) since 1991 (29 % to 38 %). Compared to 1997, the area of potable drinking water (<2000 µS/cm) has decreased by 2 % to reach zero in 2000 and 2005 (Fig. 8).

The same situation was recorded at Wadi Al Fara; there has been an increase in the area of high

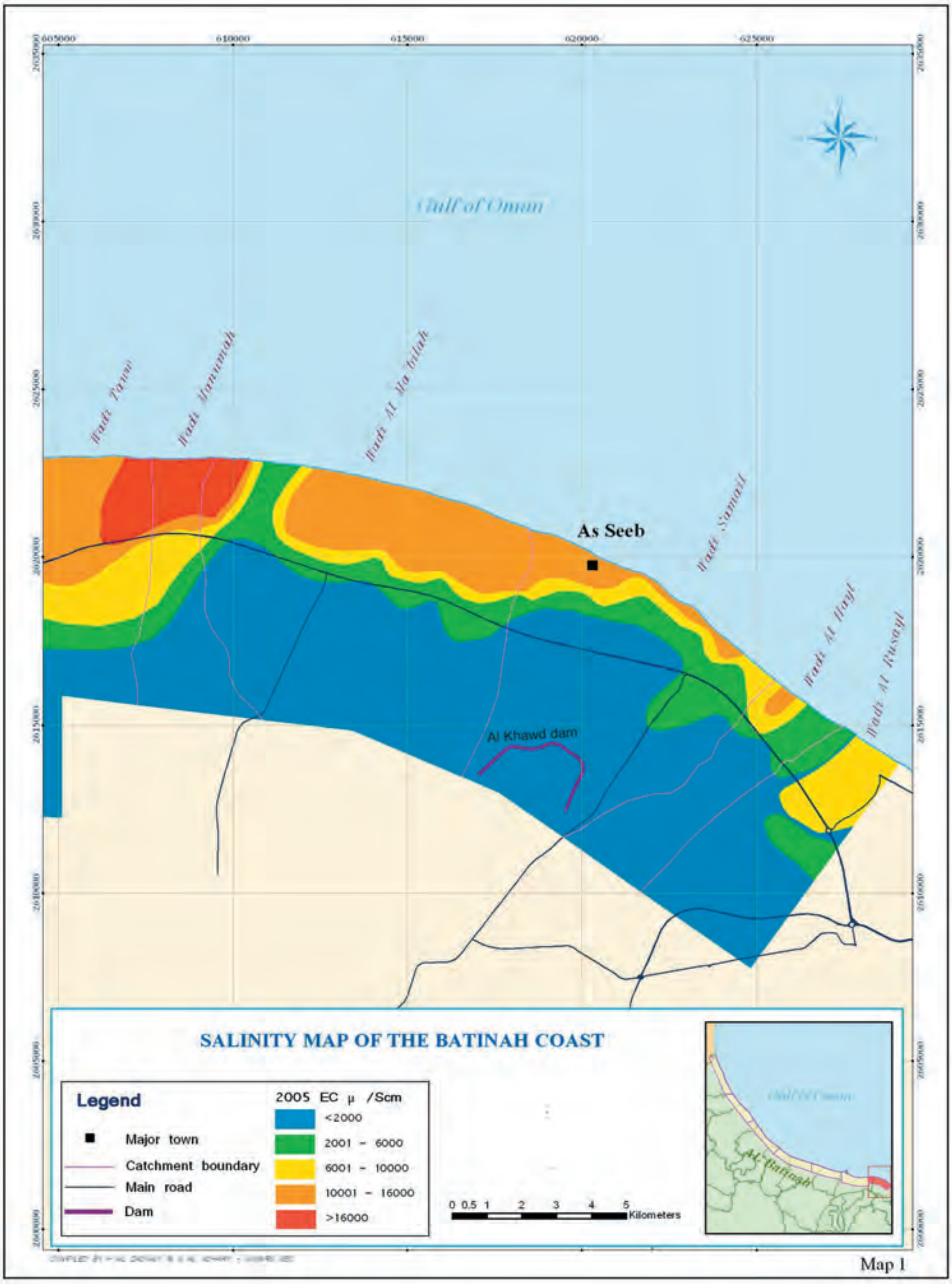


Figure 1. Groundwater salinity map for the Seeb area.

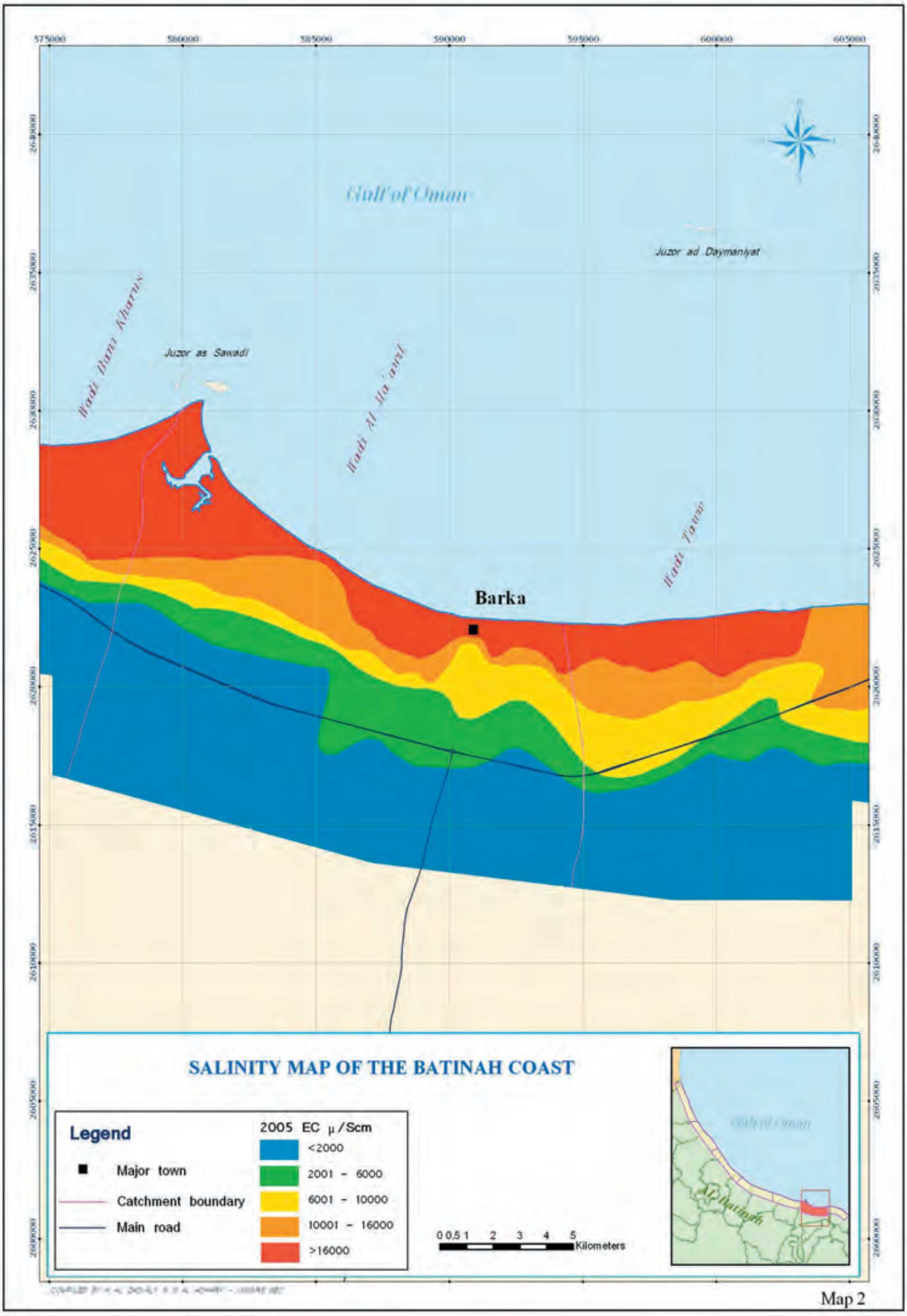


Figure 2. Groundwater salinity map for the Barka area.

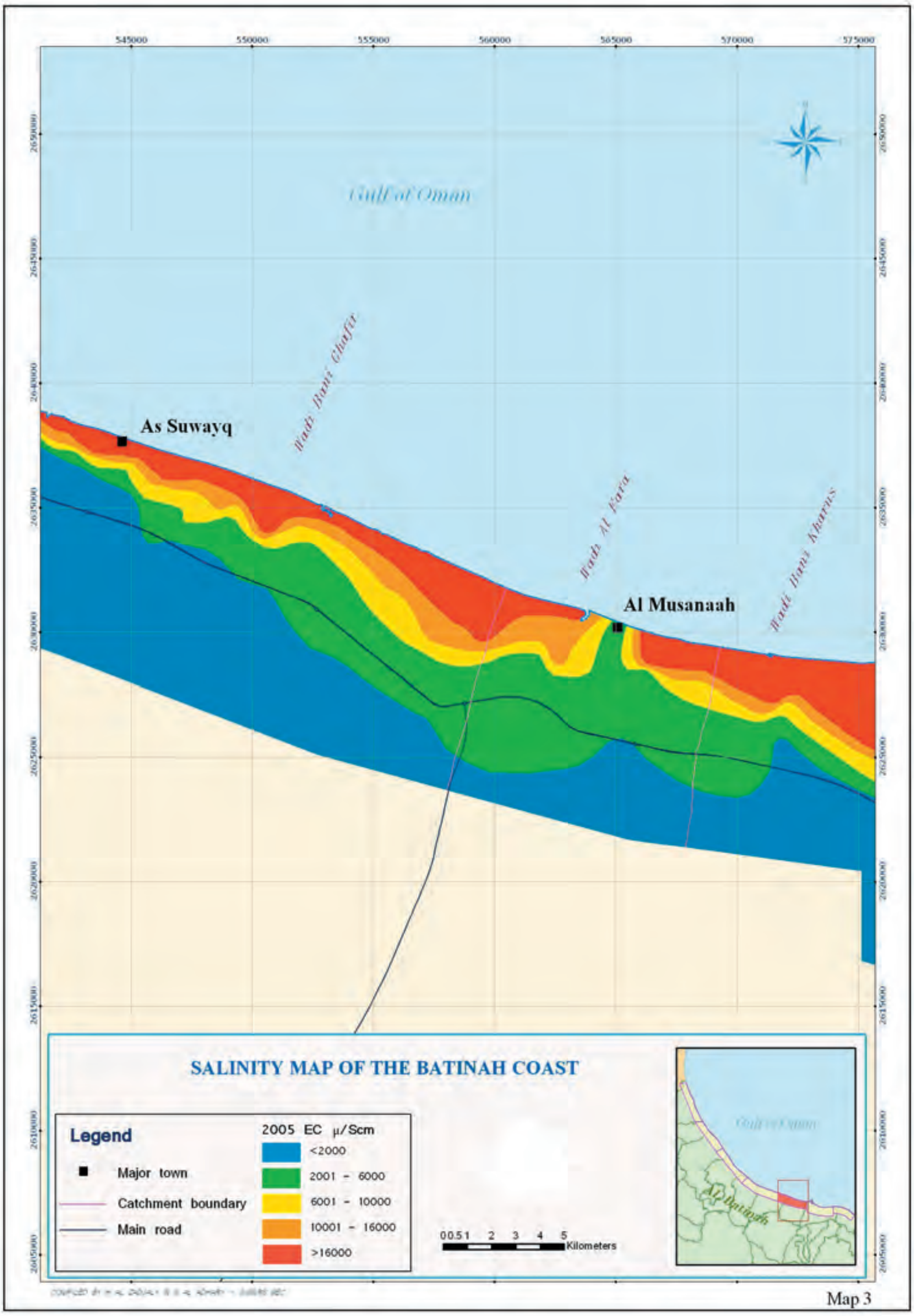


Figure 3. Groundwater salinity map for the Suwaq area.

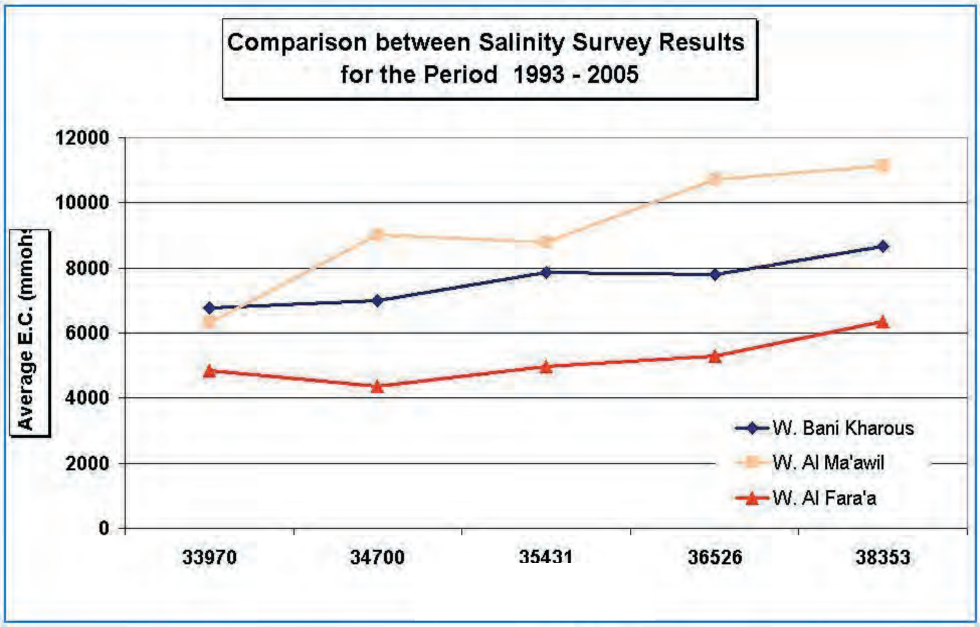


Figure 4. Increasing trend in salinity 1993-2005 at three different catchments.

saline water (>10.000 µS/cm) from 4% in 2000 to 8% in 2005. On the other hand, there has been a slight improvement in the area with potable water located in Wadi Fara. This could be a result of the recharge effect of Al Fara dam, situated upstream. In general there has been a notable water quality deterioration during the last ten years in the Suwaiq area.

Rainfall

The analysis of rainfall data in twenty nine rainfall stations, which goes back to 1990 in south Batinah and Muscat reveals that the annual average rainfall is 158 mm in South Batinah and 100 mm in Muscat. The analysis of the average rainfall at Al Khadrah rainfall station in South Batinah shows that water years, 1990, 1992, 1994, 1995, 1997, 1999 recorded above average annual rainfall (Fig. 9). The water year 1997 is considered a wet year for the Sultanate in general and for the Batinah specially: the total recorded cumulative rainfall was 608 mm in South Batinah. This is the highest on record since 1990. Figure 10 represents the departure from mean annual rainfall at Muscat rainfall station for the last one hundred years. The figure shows that the area has been subjected to a severe dry period during the past seven years.

Effects of rainfall on groundwater levels

The water levels response to recharge events along the Batinah coast was variable. The levels in Musannah, Suwaiq and Seeb have risen slightly but less in Barka. Although there has been a slight water table rise as a result of rainfall during the mentioned period, this is not above sea level, especially in Barka and Suwaiq, due to over abstraction of the aquifers and so failing to reach water balance. Figure 11 illustrates how groundwater levels fluctuate with time at two wells located near the coast along Wadi Maawil and Wadi Fara.

The presence of recharge dams along the Batinah coast has caused some rise in water levels, resulting in slightly lowered salinity, which has been observed in some of the wadis (MWR, 1995). But unfortunately the over abstraction in recent years has led to the lowering of water levels near the coast, causing salinity intrusion inland. Two main features can be distinguished: a general downward trend in water levels throughout the period of record, and a general correspondence between preceding rainfall and rises in water levels in the well. For instance, it is noticeable that the period 1990-1995 was relatively dry. This is reflected in the downward trend of water levels

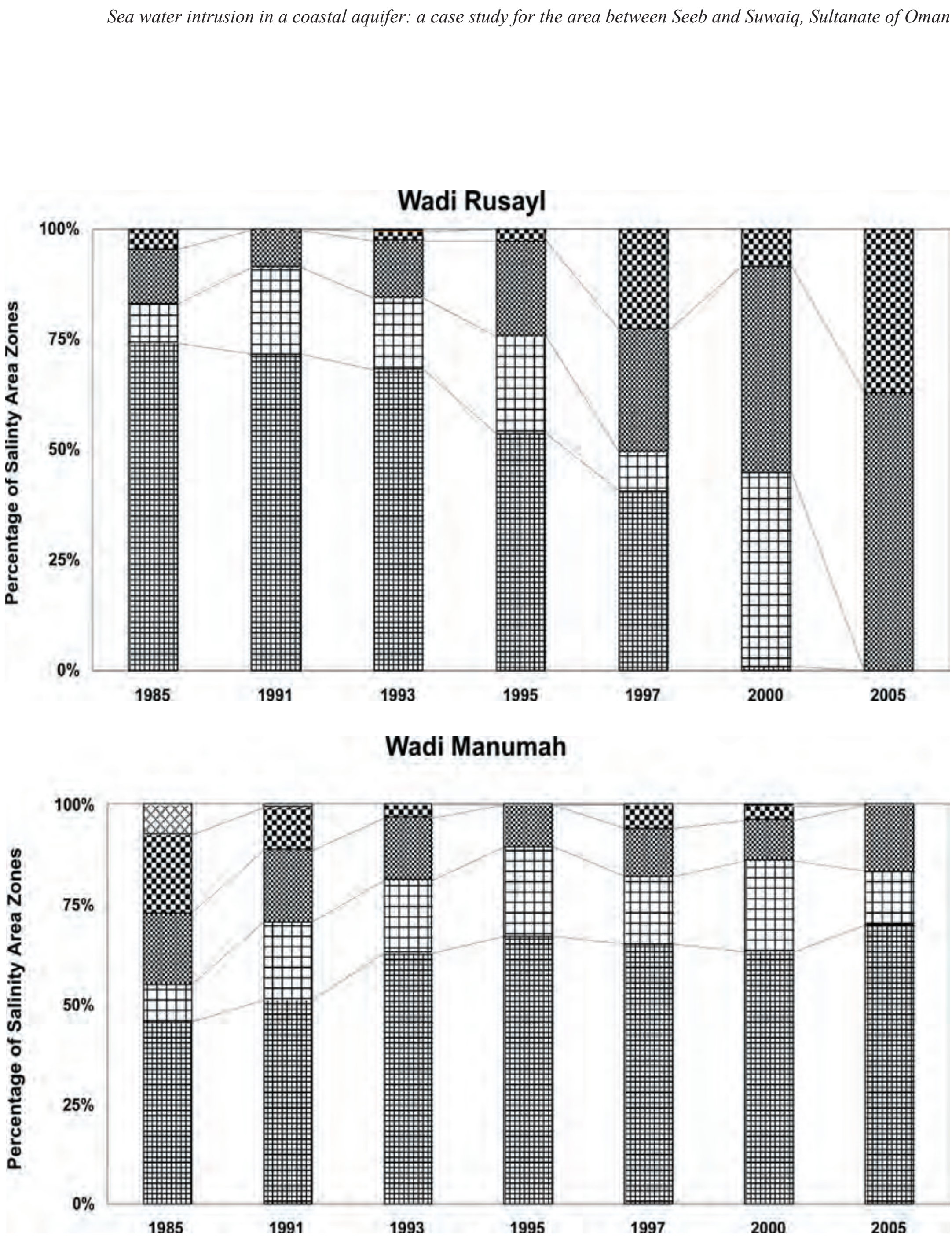
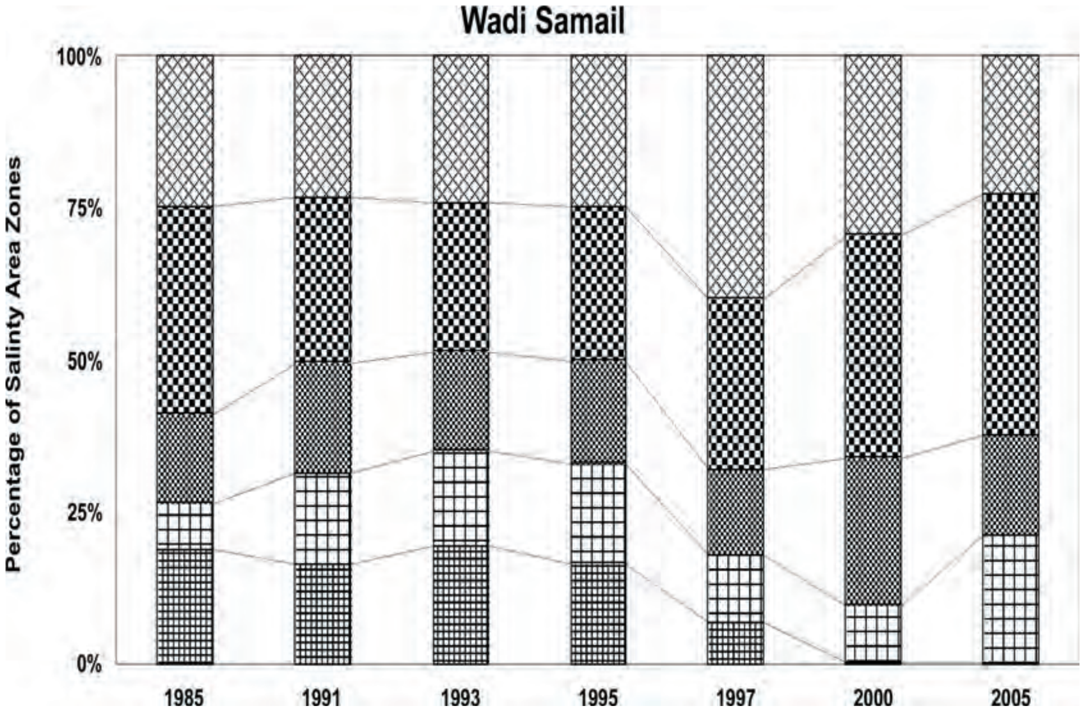


Figure 5. Salinity changes at Wadis Rusayl and Manumah areas, 1983-2005



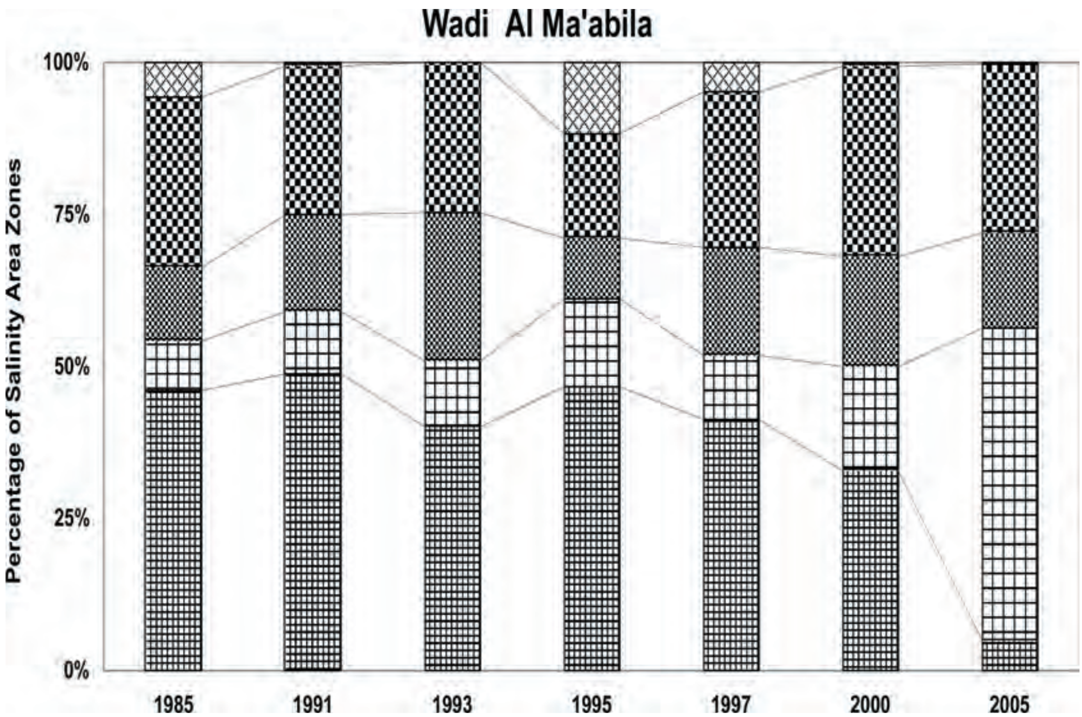


Figure 6. Salinity changes at Seeb area, 1983-2005

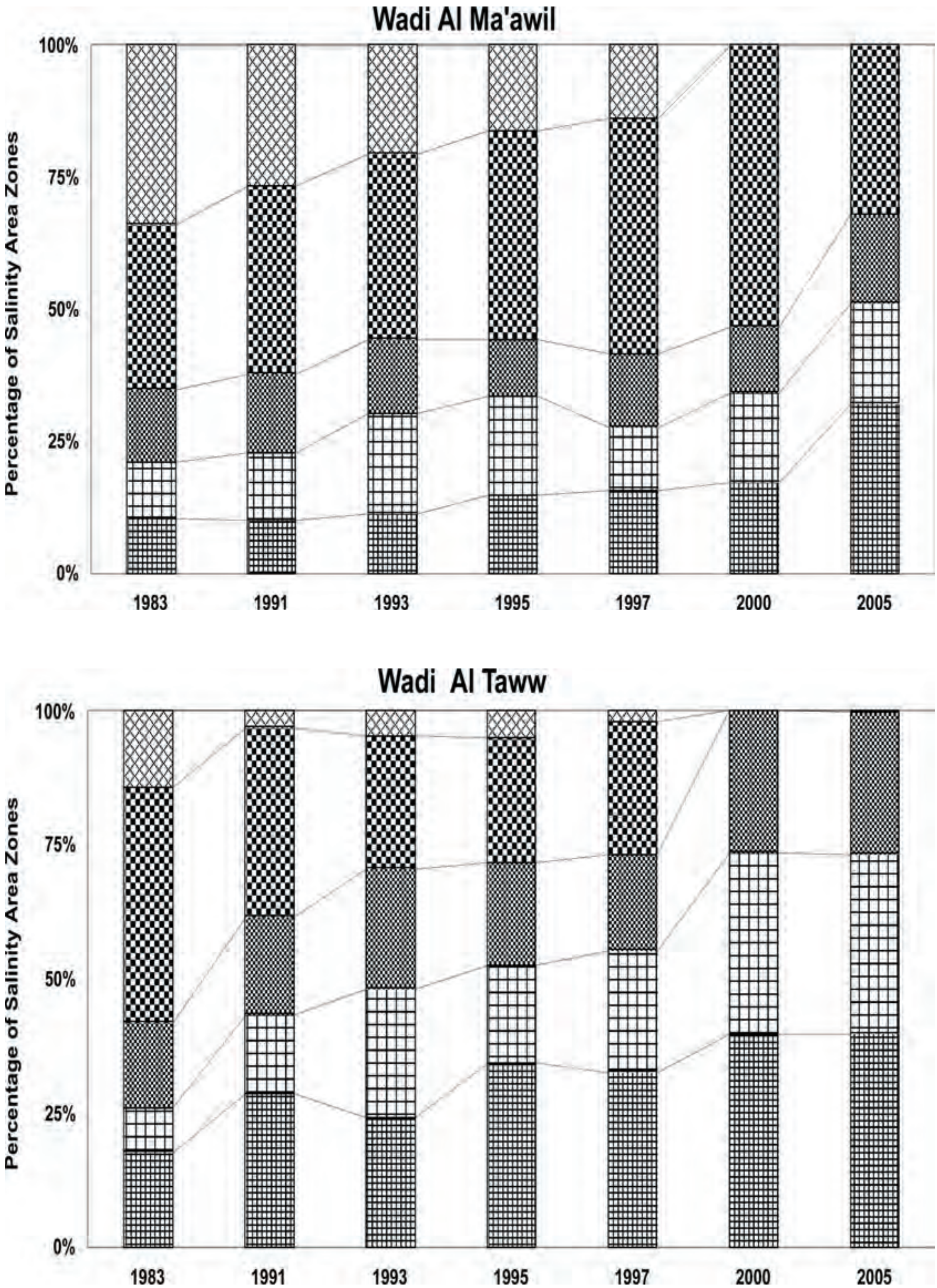
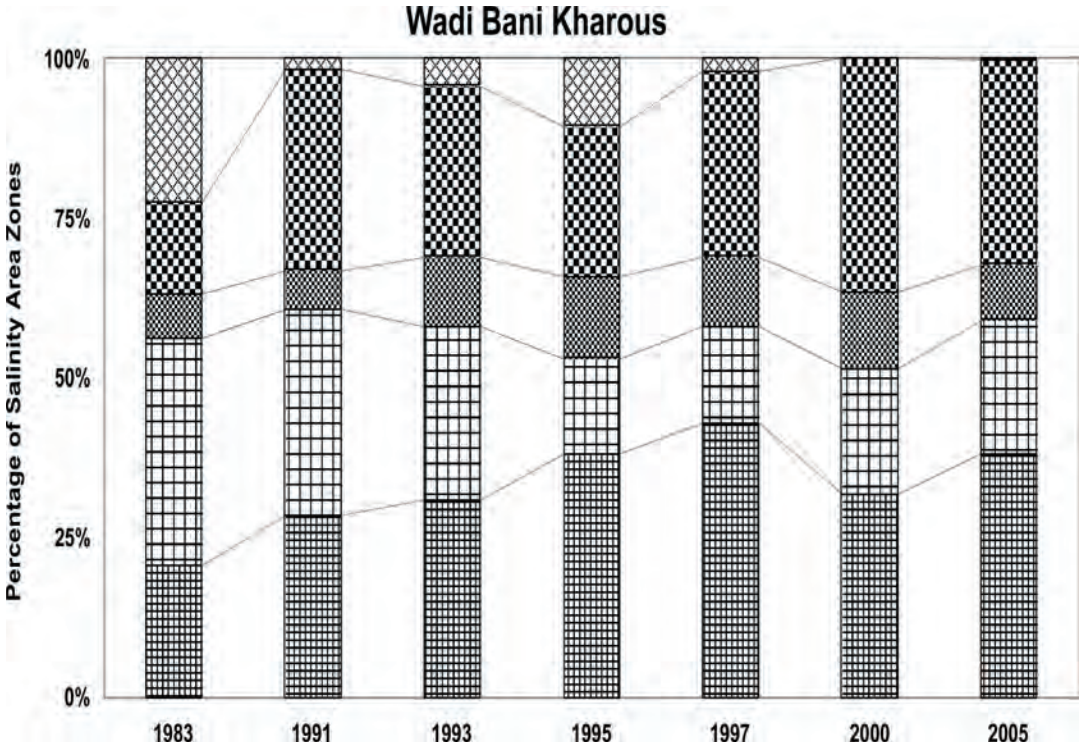


Figure 7. Salinity changes at Barka area, 1983-2005



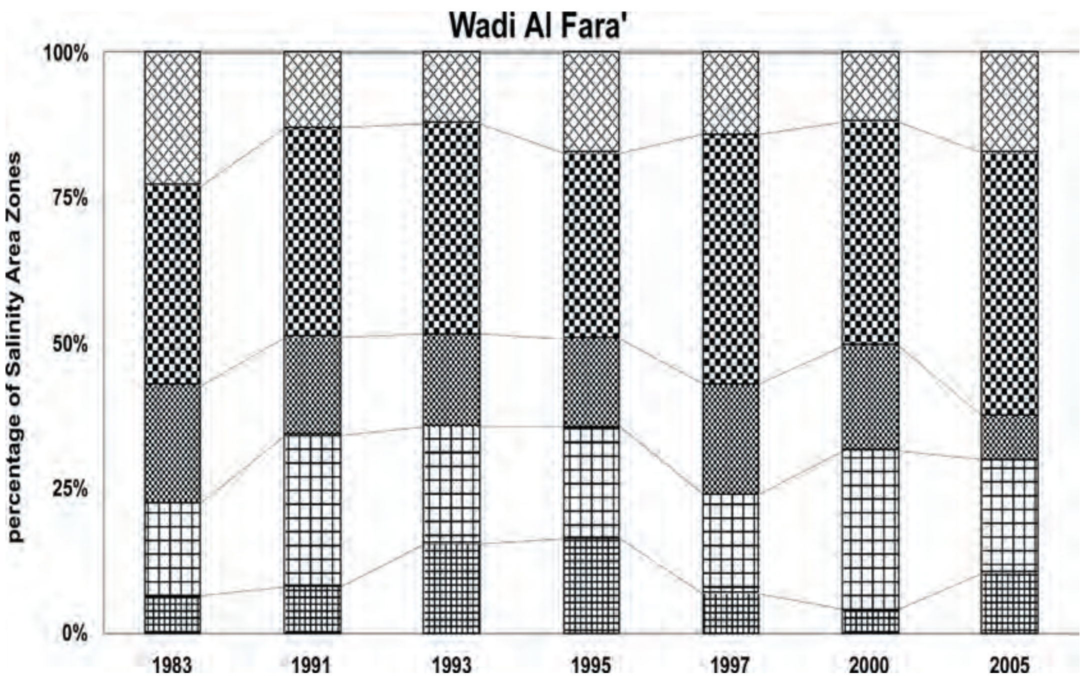


Figure 8. Salinity changes at Suwaiq area, 1983-2005

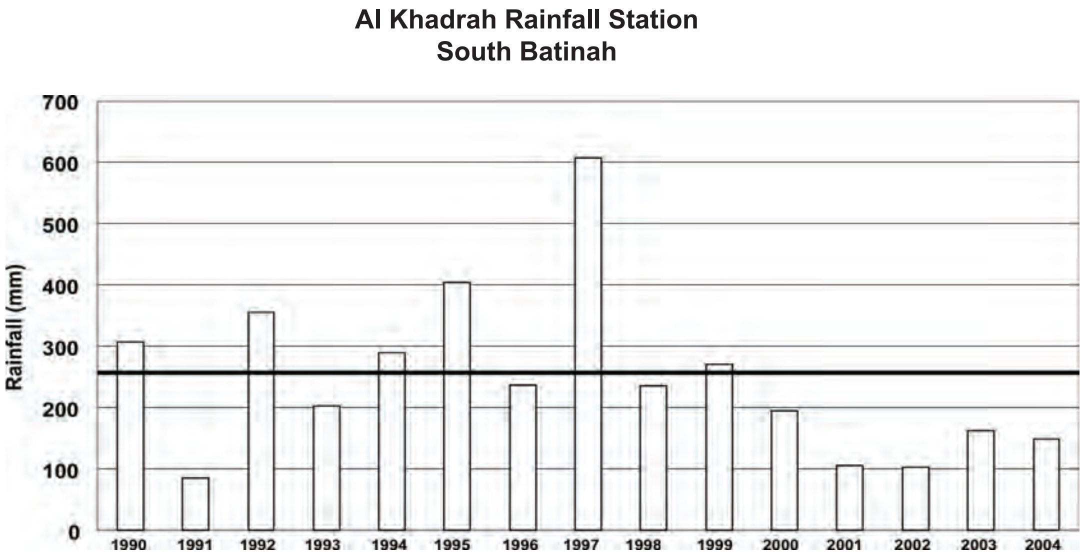


Figure 9. Yearly and average rainfall for Al Khadrah rainfall station.

during the same period. In contrast, water levels rose considerably, in 1995-1997, as result of significant rainfall at this time. Generally, in most of the selected wells the rises due to the 1997-1999 rains were much less than those following other wet periods.

Effects of rainfall on salinity

In terms of groundwater salinity, the impact of rain differs from place to place. There has been notable water quality deterioration in many catchments, such as Wadi Al Maabila, Manumah, Taw, Maawil, Bani Kharous, and Al Fara. Despite the heavy rainfall in 1997, as shown in al Khadrah station at Wadi Bani Kharous with an average annual rainfall 254 mm, the amount was not enough to prevent groundwater deterioration in these areas. This is related to below average rainfall during 1999 – 2004 and to the over abstraction, particularly in the Rumais-Barka area.

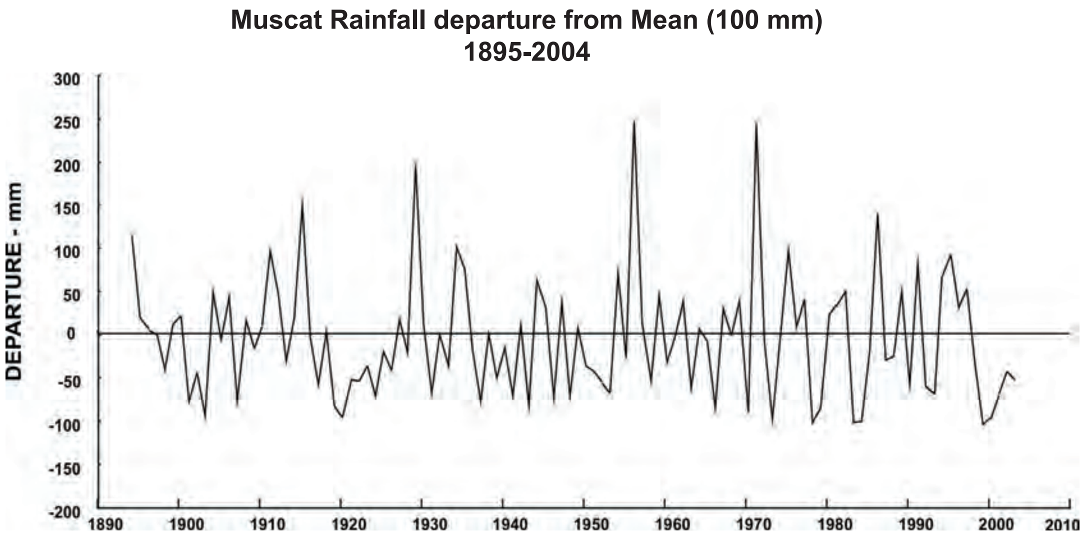


Figure 10. Muscat rainfall, departure from mean.

Monitoring Wells at South Batinah Area
Wadi Al Fara'

Monitoring Wells at South Batinah Area
Wadi Al Ma'awil

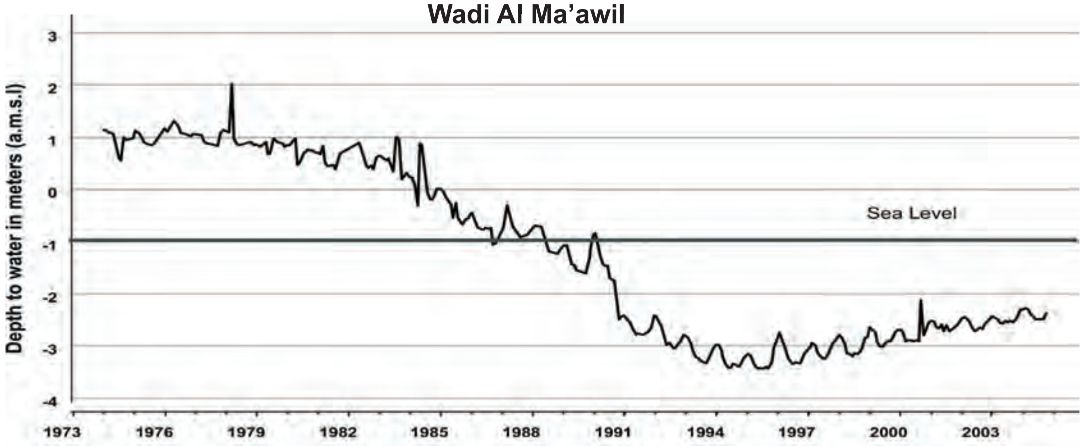


Figure 11. Groundwater levels in Wadis Al-Fara' and Maawil, 1973-2003

Conclusion

Despite exceptional natural recharge and years of water conservation, recharge enhancement and aquifer protection programmes, groundwater salinity continues to deteriorate over large areas of the Batinah. Rising salinity is probably the most economically devastating water resources problem facing the country at present. The groundwater reservoirs are still adjusting to the enormous increase in water consumption that occurred during the 1970s, 1980s and the early 1990s. Indeed, the situation may get worse, despite the improvements that occurred during the mid 1990s. Nevertheless, the situation can be addressed if all necessary actions are taken and all users behave responsibly towards this precious national resource. There is, and has been for a decade, strong evidence that tougher water resource conservation policies are required to reduce abstraction and preserve the quality of groundwater in areas where EC is consistently on the increase.

Recommendations

Based on these monitoring results, it is recommended to apply the following management solutions for coastal aquifer saline contamination:

- Reduce abstraction in areas of EC increase by water licensing, water tariffs, stricter control on abstraction by non-bona fide farmers, increased water conservation practices, improved irrigation practices, reduction of factors contributing to soil salinization, and limiting crop types according to consumption/yield.

- Enhance programs of awareness of conservation practices and farming of economic crops amongst farmers.

- Ensure all abstraction wells in problem areas are legally registered via the National Well Inventory Project records and ground checks. Abstraction at non-registered wells should be halted.

- Continue to investigate the feasibility of recharge dams, where economically viable, to prevent loss of flood water to the sea.

- Continue to develop regional management plans.

- Encourage the creation of local water user associations to engage in self-regulation.

- Change cropping patterns to low water consumption crops, stop abstraction at the amenity farms, and eliminate non economical plants.

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