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SEA WATER INTRUSION IN THE SALALAH PLAIN AQUIFER, OMAN

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Salalah is situated on a fresh water aquifer that is replenished during the annual monsoon season with an average vertical precipitation (rainfall) of 245 mm/yr in Jabal AlQara and 104 mm/yr in the Salalah plain. The aquifer is the only source of water for Salalah city. A rainfall and mist precipitation in the Jabal AlQara recharges the plain with significant renewable fresh groundwater resources that have allowed agricultural and industrial development to occur. In Salalah city where groundwater has been used extensively since the early 1980s for agricultural, industrial and municipal purposes, the groundwater resource has been withdrawn from the aquifer more rapidly than it can be replenished by natural recharge. In turn, the heavy withdrawal of large quantities of the groundwater from the aquifer has lead to intrusion of sea water. Agricultural activities usually utilize over 70% of the groundwater. In order to investigate the salinity intrusion and nitrate pollution, the study area was divided into four strips on the basis of land use plans in the area. Water samples were collected from 18 water wells. Chemical analysis of basic ions and pollution parameters in natural waters was carried out. The electrical conductivity, chloride and nitrate concentrations were highest in the agricultural and residential strips, and Garziz grass farm. The present status of groundwater quality in most of the agricultural and residential strips does not meet drinking water standards. The study suggests an approach to protect the groundwater in the Salalah plain aquifer from further encroachment, by artificial recharge with reclaimed water, preferably along the Salalah coastal agricultural strip. This scheme can also be applied to other regions with similar conditions.

INTRODUCTION

Sea water intrusion resulting from over-abstraction of groundwater occurs in many coastal aquifers around the globe. Sea water intrusion in Salalah plain aquifer in Oman has been reported by Dames and Moore International (D&MI, 1991, 1992), Shammas (1998), and Geo (2004). Large areas of agricultural land have become unusable over the last ten years because of sea water intrusion due to over abstraction of groundwater. The problem is most pronounced along the Batinah coast (Northern Oman) and in Salalah (Southern Oman) (Mott MacDonald, 1996). ENTEC (1998) found that the groundwaters of the aquifer are less mineralized, and their mineral contents, in terms of major ion concentrations, fall within the Omani drinking water standards. This paper is based on the existing water chemistry data from 18 wells in the Salalah plain (Shammas, 1998).

Coastal aquifers in south and southeast Asia are important sources for water supply. The coastal areas are often densely inhabited, especially the river deltas where good soils and abundant water availability have been able to support large population centers (Volker, 1983). However, overuse of groundwater in many places has resulted in sea water intrusion as far as 15 km inland (Geyh and Soefner, 1996). In larger aquifers the salinity may be due to past periods of transgression (Shivanna et al., 1993; Jacks and Rajagopalan, 1996). The aquifers tend to be mostly of Quaternary and Tertiary age.

The Salalah plain is located in Oman on the Eastern margin of the Arabian Peninsula (Figure 1). It is situated on a fresh groundwater aquifer that is naturally recharged during the annual monsoon season. Salalah currently has grown to a population of more than 134,000 inhabitants living in the city. Salalah city has a yearly population growth rate of 2.2% (Oman Census, 2003). This rapid increase in population, along with agricultural and economic growth, has severely depleted water resources in the Salalah area. In the early 1980s, significant decreases of water levels in the Salalah aquifer were recorded, and evidence of sea water intrusion due to over abstraction of groundwater became apparent in coastal areas (D&MI, 1992).

Reduction in the fresh groundwater flow towards the coastal zone has caused the fresh water salt water interface to move inland, intruding into areas of the aquifer that previously held fresh water. There are at least three reasons for the seawater intrusion:

1. Pumping of inland wells, particularly Garziz farms, which are extracting large amounts of groundwater for cultivation of animal fodder (zone C).

2. Heavy pumping from coastal wells for irrigating traditional agriculture, such as banana, coconuts and vegetables, (zones A & B).

3. Annual recharge is not keeping pace with the heavy discharge from the aquifer.

The size of the intruded sea water wedges is likely to continue increasing, unless good technical solutions are found in the near future.

The objective of this paper is to examine groundwater quality and identify zones of sea water intrusion in the aquifer within the study area, discuss the sources of the salt and nitrate in relation to recent investigations, and investigate the aquifer conditions as shown by the sea water intrusion problems.

SITE AND METHODS

Salalah is located in the southern region of the Sultanate of Oman. The residents of Salalah have traditionally used this aquifer as the only source of water for all agricultural, potable, and domestic

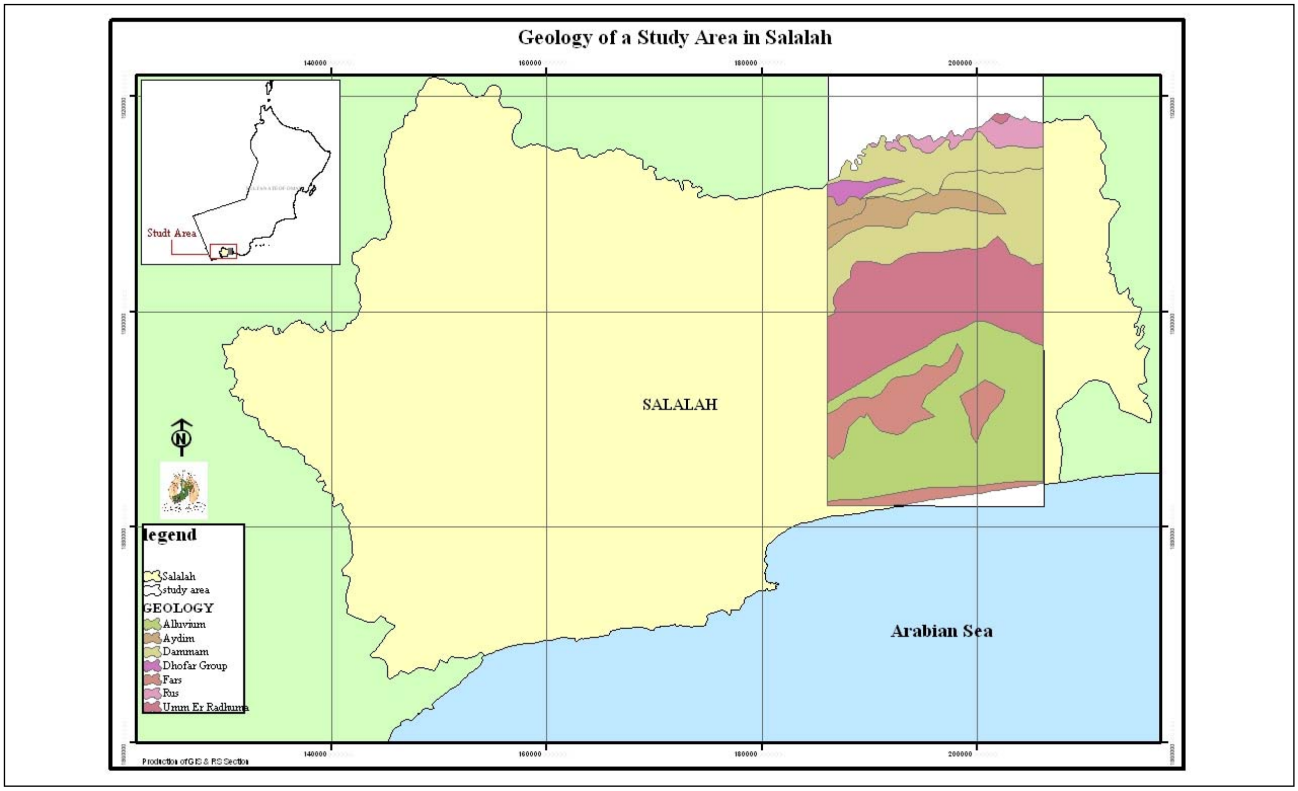

Figure 1. Location map and geology of the study area.

needs. Historically, the population of Salalah has been fairly small, and demands on the aquifer were in balance with its recharge capacity. However, increases in national wealth over the last 30 years have resulted in dramatic improvements to public health and quality of life, resulting in a significant increase in population.

The Salalah plain is a flat-lying coastal plain, which is bound by Jabal AlQara and low hills to the north, west and east and the Arabian Sea in the south. The plain is approximately 55 km across and 15 km wide. Jabal AlQara has two principal scarp directions. West of Sahalnawt valley the crest trends east-northeast, whereas to the east of the valley it trends east-southeast. The south facing slopes are characterized by deep valleys, which cut across the steep faces. These cliff sections contain limestone and travertine outcrops close to the springs in the area (Roger and Platel, 1987). Jabal AlQara extends 65 km in an east-west direction and is rather flat in some areas. The average altitude is 840 m. Grass and rather dense tree and shrub vegetation is typical along the cliffs.

The mean annual temperature in Salalah city is 26 ºC and 21 ºC in the adjacent Jabal AlQara. The climate of the Salalah plain and the adjacent Jabal AlQara is quite different from the typically arid conditions of the rest of Oman and the Arabian Peninsula. This is a result of a combination of two factors – the summer monsoon and local topography. The monsoon occurs between late June and late September when southwesterly winds persist.

The monsoon provides precipitation on an annual basis, although its duration and intensity varies from year to year. The precipitation is a combination of drizzle, rain, mist and fog. According to COWIconsult (1992), the moist air condenses over the coast and moves inland to the mountains causing foggy humid conditions and low intensity rain. A significant part of the fog is intercepted by the native grass (Savannah type vegetation) and trees. The rainfall in the Jabal AlQara areas averages 230-450 mm/yr, whereas the average rainfall in the plain is around 110 mm/yr (Chebaane and Alesh, 1995). This provides the basis for much of Salalah's fresh groundwater supply. The average evaporation rate in the plain is about 1700 mm/yr.

A broad gently dipping belt of Tertiary limestone dominates the geology of the Dhofar region. The major plain aquifer horizons occur in the karstic limestone of the Fras Group of Tertiary age and the overlying alluvium of Quaternary age in the Salalah Graben (Flint and Rippon, 1986). After deposition of The Hadramhaut Group there was major tectonic activity in Dhofar related to the rifting between the African and Arabian plates. This resulted in the down-faulting of the Salalah plain. As a result deep turbidites of the Mughsayl Formation and shallow littoral deposits belonging to the Adawnib Formation were deposited within the limits of present Salalah plain (Roger and Platel, 1987).

The Hadramhaut Group is composed of karstic limestone of late Tertiary age (Lower Eocene) with a maximum thickness of 700 m. On the Salalah Plain, the Fars Group comprises mainly the Nar and Adawnib Formations. The maximum saturated thickness of Fars Group is approximately 120 m. The Adawnib Formation deposited in the Tertiary period (middle to early Miocene age) contains the main aquifer and the freshwater thickness is on the order of 60-70 m. Underlying the Fars Group is the low permeability and saline Mughsayl Formation (6,400 to 9,600 mg/l TDS), composed of limestone of Tertiary age (Early Miocene to Oligocene) which is up to 800 m thick.

The presence of coarse alluvium, particularly pebbles, cobbles and boulders, gives the soils of the Salalah plain a highly permeable and well-drained texture. The soils consist of sandy loams and loamy sands; depths are generally in excess of 1.0 m (Taylor and Sons, 1985).

The geological structure shown in Figure 2 shows that the freshwater on which the city depends is mainly a product of recharge from the adjacent mountain areas (D&MI, 1992). Salalah is situated on limestone terrain, and due to the lack of local surface water supplies, potable water is taken from the underlying aquifer. Natural groundwater recharge to Salalah plain is primarily derived from precipitation falling onto the Jabal AlQara during the monsoon, which infiltrates to groundwater and moves across the plain to the coast (D&MI, 1992). Groundwater flow on the plain is north to south with groundwater levels at 9 m amsl near the Jabal front (zone D), declining to about sea level near the coast (zone A) (Figure 2) with isolated pockets extending below sea level in areas of very high abstraction. The location of abstraction wells in the Salalah plain is shown in Figure 3 (DWR, 2005).

The underflow from Jabal AlQara to the plain aquifer was estimated by D&MI (1992) and ENTEC (1998) at 32.4 and 43.2 Mm^3, respectively. Both reports used modeling to estimate the subsurface recharge from the Jabal. The first author of this work estimates aquifer replenishment rates at 51 Mm^3, of which underflow is 50 Mm^3 and the rest is recharge on the plain. The system flow model and salinity calibration procedures consisted of history matching of 14 years (1992-2005) of available water levels and salinity data of the Department of Water Resources (DWR) in Salalah that was used under steady state and transient conditions.

The average yearly use for irrigation is 31.7 Mm^3 (D&MI, 1991), which means approximately 80% of the groundwater is being used for irrigation and 20% for public and domestic supplies. The deficit in the aquifer balance of the Salalah plain was estimated to be 8 Mm^3 in 1990 (D&MI, 1991). The groundwater abstraction from the plain aquifer was estimated by D&MI (1992), ENTEC (1998), DWR (1999) and Geo (2004) at 40.4, 49.2, 54.31 and 80.54 Mm^3, respectively.

This work revealed a water quality deterioration, which is apparently due to over-pumping,

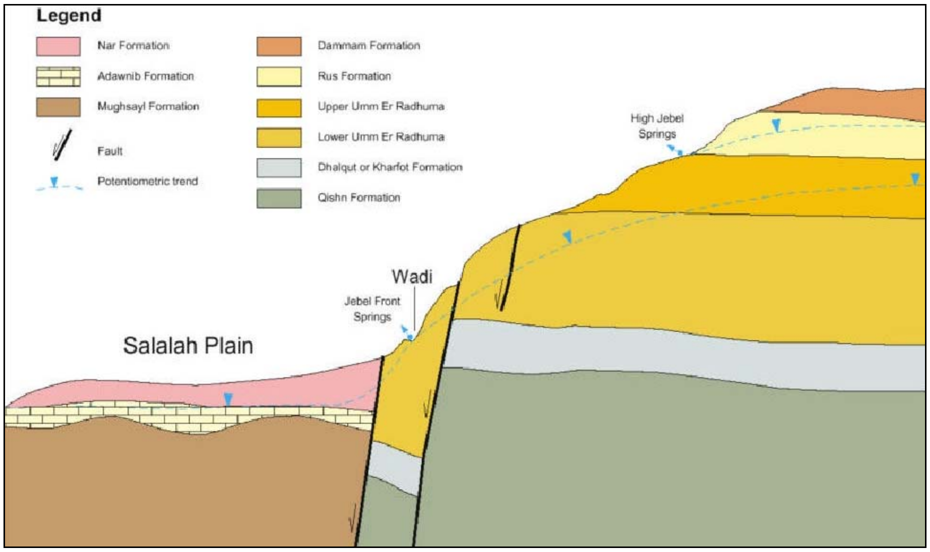

Figure 2. Hydrogeological cross-section of Salalah plain and adjacent Jabal AlQara (after Geo, 2004).

particularly by agriculture, based on existing data from the DWR in Salalah city. The analyses for anions and cations were carried out in the laboratories of the Royal Institute of Technology (KTH). Fieldwork as well as laboratory work was mainly aimed at verifying the deductions from the groundwater data. An electrical conductivity meter was used for rapid and inexpensive characterization of the status of sea water intrusion in the area to compare it with previous data to determine variations in salinization.

Besides taking the water samples, some data were collected in the field, such as pH; electrical conductivity; temperature and alkalinity. The results are shown in Table 1. According to the Omani water quality regulations, the maximum permissible limit for drinking water is 1500 mg/l TDS, equivalent to 2500 μS/cm EC. Equation (1) was used to convert the EC values into equivalent TDS (based on 1500 mg/l TDS equivalent to 2500 μS/cm EC).

$$TDS = EC * 0.62 - 50 \tag{1}$$

Eighteen water samples were collected in 1998 from 18 wells in the plain, up to a distance of 8.5 km from the coastline. The samples were collected as follows:

- Six water samples from wells located along the coastal strip, denoted zone A;
- Six samples from wells located along the residential strip denoted zone B;
- Four samples from inland wells exactly from Garziz farms area denoted zone C and;
- Two samples from the freshwater strip (near the mountain front) denoted zone D, which were anticipated to be unaffected by sea water intrusion.

The zones are considered based on land use and salinity differences. Zone A is an agricultural belt, zone B is a residential strip, zone C is the Garziz grass farm site which is about 5 km inland from the coast, and zone D is considered the freshwater zone within the municipality wellfields area about 9 km inland. The Salalah and Saada wellfields (zone D) province Salalah city potable water.

The following instruments were used for chemical and physical analysis. In the field, during the sampling phase a Hanna meter was used for measuring the pH, EC, temperature and a 0.02 HCl

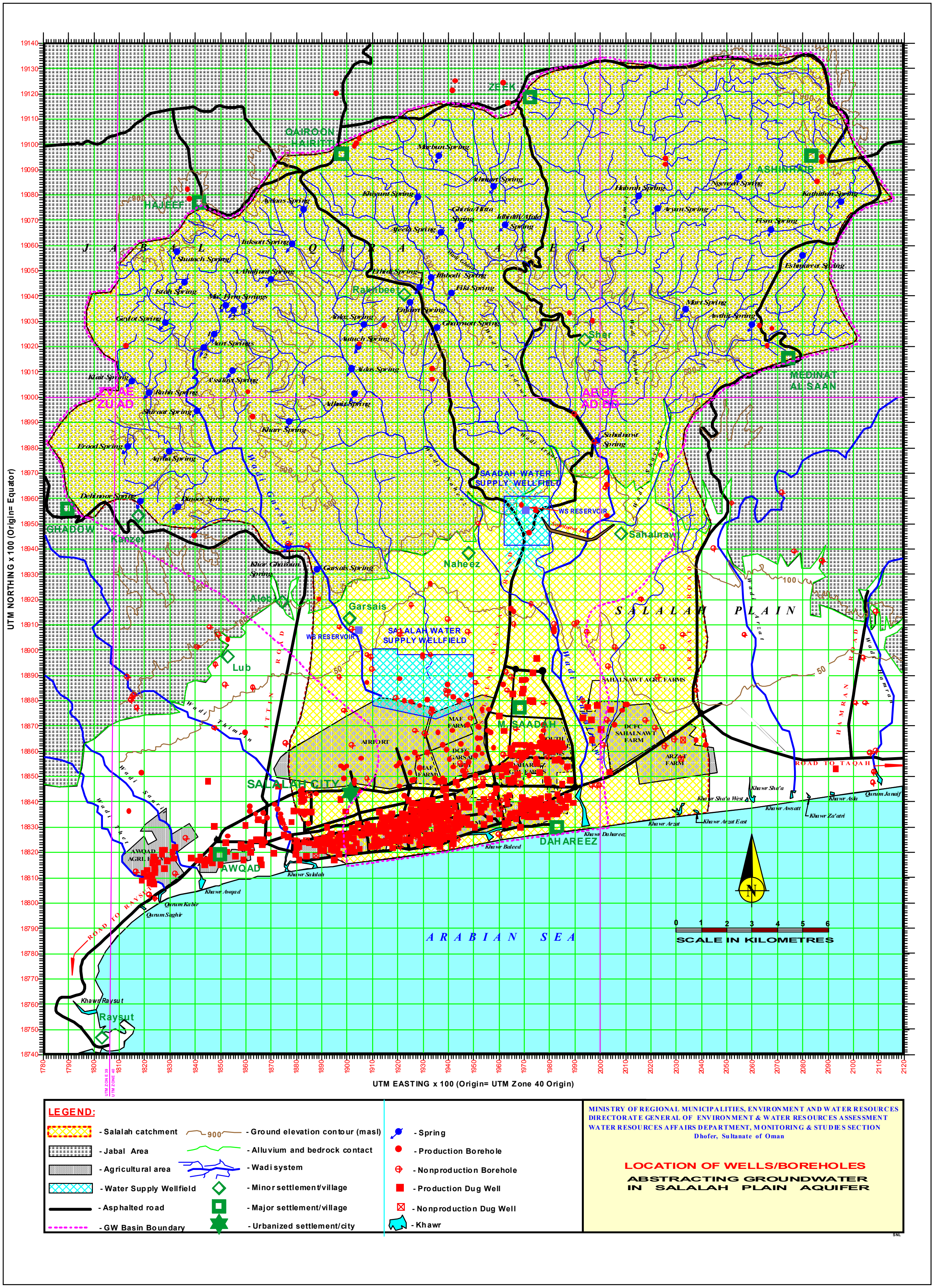

Figure 3. Map showing location of abstraction wells in the Salalah plain (DWR, 2005).

Table 1. Chemistry of basic ions and pollution parameters, all constituent concentrations are in mg/l, unless otherwise stated (after Shammas 1998).

Well (zone)	pH	T ºC	TDS (mg/l)	Na	Ca	Mg	K	Cl	NO_3-N	HCO_3	SO_4	PO_4
A2	7.12	29	6305	1682	326	249	45	3200	43.1	332	674	0.022
A3	7.05	29.6	4860.4	1150	412	176	25	2123	48	288	891	0.017
A1	7.03	29.7	1475.2	202	289	52	15	340	20	303	573	0.007
A4	7	28.2	2262.6	410	289	86	9	780	23	317	490	0.01
A5	7	28.8	2665.6	530	228	91	12	1119	18	311	189	0.011
A6	7.28	28.9	4606.2	478	96	68	12	2072	38	482	474	0.017
C4	7.54	30.1	1066	139	135	29	2.8	244	13.3	288	137	0
C1	7.09	29.1	1066	138	152	32	4.6	246	14.5	327	158	0.004
C3	7.41	29.6	942	102	121	27	3.8	211	11	317	64	0.006
C2	7.38	29.6	1066	135	140	30	9.5	243	14	298	132	0.005
B6	7.48	30	1934	352	184	70	21	658	25	459	178	0.015
B4	7.05	29.8	1500	311	138	51	13	426	20	390	227	0.005
B3	7.09	29.8	1555.8	267	196	60	12	512	24	307	231	0.006
B1	7.19	29.3	2337	553	145	80	23	951	21	390	220	0.009
B5	7.39	29.2	2306	440	217	82	14	977	20	283	159	0.008
B2	7.15	29	2368	440	196	78	19	1038	18	156	133	0.009
D1	7.42	29.4	446	48	94	17	1.6	86	6.5	342	33	0
D2	8.01	29.2	495.6	40.5	90	16	1.6	67	6.2	307	32	0.003

concentration solution was used for titration of the alkalinity. In the laboratory an Ion Chromatograph Dioncx DX 120 was used for analysis of anions and cations. Tecator flow injection analysis was used for phosphate concentrations.

The main objective of this work is to determine the groundwater quality conditions as they relate to sea water intrusion in the aquifer. The threat posed by intrusion of sea water into the Salalah plain aquifer is highlighted. The paper suggests that recharge of treated wastewater in infiltration basins located along the coastal agricultural strip could protect the aquifer from sea water intrusion.

A three-dimensional flow and solute transport model was constructed that covers the Salalah aquifer. The model was calibrated by history matching under steady-state flow and salinity conditions against the observed hydraulic heads reported by DWR in 1992. The underflow recharge was derived from the calibrated steady-state flow model at 50 Mm^3. The period between 1993 and 2005 was modeled for transient flow and solute transport. The history of inputs and outputs of the aquifer were reconstructed in the transient calibration from 1993 to 2005 in order to reproduce the observed potentiometric head distribution during that time. The transient case used the potentiometric heads of the steady-state abstraction case. The transient calibration was run for a total of 13 years (1993-2005). Predictive simulation of the aquifer under transient conditions was conducted to predict the future behavior of the aquifer under the proposed demand management programs for the next 15 (2006-2020) years to combat sea water intrusion.

RESULT AND DISCUSSION

Salinity conditions

Salt water intrusion occurs in the southern part of the plain, along the coastal agricultural strip, and its development is detected in the east and west part of the plain. The TDS and chloride concentrations were high in agricultural, residential strips and at the Garziz fodder farm. Major anion analysis shows that chloride predominates in most of the wells studied. Among the cations, sodium predominates in most of the wells, except in zone D. In the central freshwater strip (zone D) there are no predominant cations, however calcium is rather high in comparison to other cations, probably as a result of limestone leaching in the adjacent mountains, since limestone is predominant in the Jabal AlQara geology. Along the central coastal zone where the sea water intrusion is occurring, the groundwater is a mix of the brackish, sodium chloride (Na-Cl) type of water and the fresh subordinate calcium carbonate (Ca-HCO3) water from the freshwater zone. This reflects a zone of mixing between fresh groundwater flowing towards the coast and sea water intrusion. Groundwater quality varies across the plain, with salinity ranging from 446 mg/l in the freshwater aquifer strip (zone D) to over 6,150 mg/l and 4606 mg/l in the east and west respectively of the coastal agricultural strip (zone A).

Water chemistry variations in the aquifer

Chemical variables and chloride concentrations are shown in Figures 4-7. The curves were obtained from the results of anion and cation analysis by the first author in 1998 to characterize the sea water intrusion problem in the Salalah aquifer.

Na/Cl Ratios

The plot of Na/Cl ratio versus chloride concentrations (Figure 4) indicates both fresh water flushing and sea water intrusion. Since the Na/Cl ratio is always < 1, this shows intrusion, and also demonstrates that the aquifer has low freshwater flushing. This is a coastal strip with high abstraction. Al-Mashaikhi (1997) stated that the sea water ratio in the Salalah plain aquifer is 0.66. In this work the sea water ratio is between 0.5 and 0.6, which means that sea water intrusion is progressing every year. In zone A, Figure 4 shows the Na/Cl ratio decreases to 0.4. The standard deviation of the Na/Cl ratio was reported to be about 0.1 by Al-Mashaikhi (1997) and Shammas (1998). The model Na/Cl ratio versus chloride concentrations (Jacks and Rajagopalan, 1996) is considered.

Mg/Cl Ratios

The Mg/Cl ratio is 0.14 (Figure 5) showing the effects of freshwater flushing and saltwater intrusion. It is clear that most of the Mg/Cl ratios are above 0.05, except for one well. According to the Olofsson Mg/Cl ratio test, a value greater than 0.05 means that the source of contamination is pollution such as sea water intrusion (Olofsson, 1996).

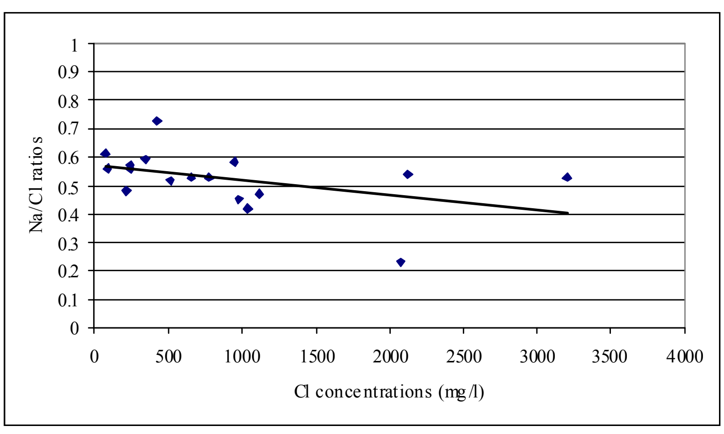

Figure 4. Na/Cl ratios versus chloride concentrations in the Salalah plain aquifer in 1998.

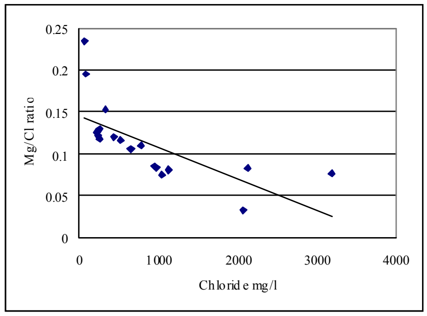

Figure 5. Mg/Cl ratios versus Cl concentrations in 1998.

Electrical conductivity variations

The values of EC in the wells located along the coastal zone (zone A), show that since 1988 EC increased in all the wells, until 1997. Then EC decreased, due to high monsoon precipitation in 1996 (Figure 6). This reflects positively on the groundwater storage of the aquifer. However, EC increases again in 1998. The results indicate that the sea water intrusion front undergoes a change in position under the influence of seasonal recharge patterns and resulting groundwater table fluctuations.

A comparison was carried out of recent EC results with previous DWR data. There is increase in EC in most of the wells in the plain aquifer with respect to the previous data for the same wells. Figure 6 shows a comparison of the DWR data (1988-1997) with the first authors work in 1998 of the salinity levels in 6 wells, particularly at zone A. The results consistently increase in the constituent values in most of the wells. Also, there is an increase in TDS values in most of the same wells. Groundwater quality has been degraded by sea water intrusion.

Figure 7 and Table 2 show the TDS and electrical conductivity values and chloride concentrations (mg/l) versus the distance (km) from the coastline northwards to the mountain front. The area was divided into four zones, denoted A, B, C, and D on the basis of land-use plans. Relative distance from the coast for zone A is 0-1.2 km, zone B 1.2-2.4 km, zone C 2.4-5.5 km, and zone D greater than 5.5 km. The figure shows that both TDS values and Cl concentrations decrease with distance from the coastline. Zones which are close to the coastline have high values of EC and chloride concentrations, such as zones A and B. However, wells in zone C show lower TDS values and Cl concentrations, but both TDS and Cl constituents are still higher than the Omani wastewater standards for treated sewage effluent reuse. The average of chloride in zone A is 1605 mg/l Cl (650 mg/l Cl), and in zone B the average 760 mg/l Cl (650 mg/l Cl). Also, the average of EC in zone A is 3867 mg/l, (1106 mg/l) and in zone B the average is 2116 mg/l, (1106 mg/l). Zone D, which is expected to be non-polluted, shows reasonable TDS values and Cl concentrations in comparison

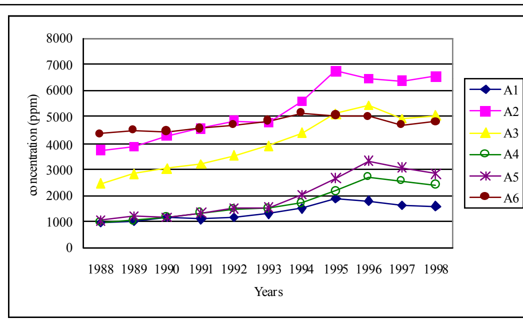

Figure 6. The salinity levels in the wells along the coastal zone (mg/l) in zone A.

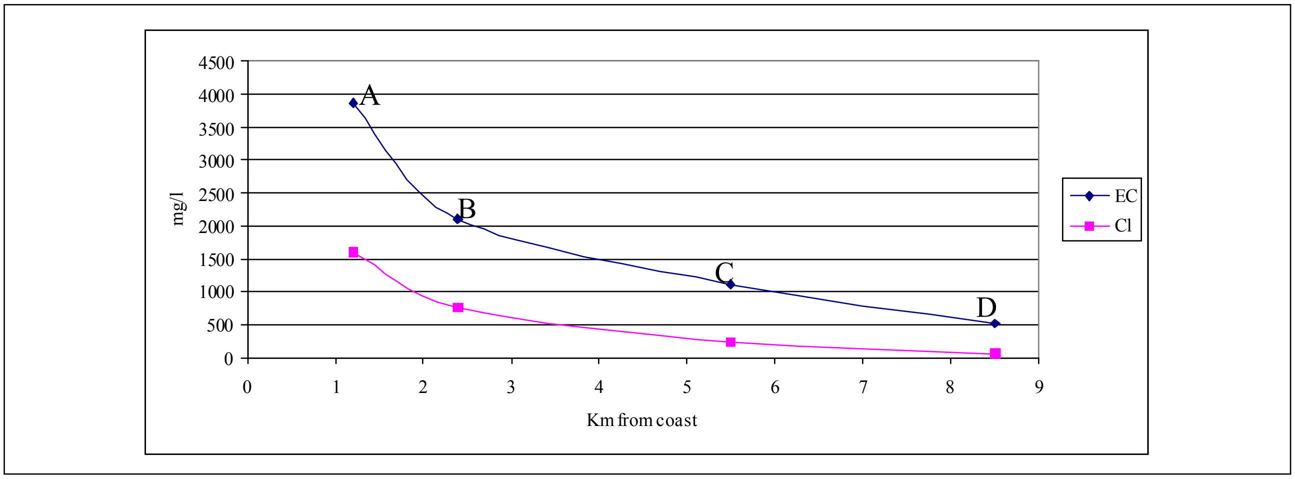

Figure 7. Average of TDS (mg/l) values and Cl (mg/l) concentrations in Zones A, B, C and D versus the distance of zones from the coastline.

Table 2. Average values of TDS & chloride concentrations in each Zone versus the distance of the zones from the coastline northwards.

Description	Distance from coast (km)	TDS (mg/l)	Cl (mg/l)
Zone A	1.2	3696.16	1605.642
Zone B	2.4	2000.36	760.173
Zone C	5.5	1035	235.765
Zone D	8.5	470.8	76.42

to Omani drinking water standards. This curve supports and demonstrates the previous discussion about the occurrence of sea water intrusion in the Salalah plain. It also shows that the intrusion always increases along the coastal zone and residential zone (zones A & B) as a result of over-pumping for irrigation purposes from these areas. TDS and chloride are indicators of salt content of groundwater, and this graph shows the difference between zones and highlights the threat posed by sea water intrusion to fresh groundwater further inland.

Chloride concentrations are much higher in the residential and agricultural strips than in the Garziz farm area. The increase of chloride, particularly in wells located in the residential and coastal agricultural zone is likely to be due to both sea water intrusion and septic tank infiltration. However, the high values in the coastal area are a direct result of sea water intrusion as the chloride content is 18,980 ppm. Chloride, sodium, sulfate and magnesium make up more than 96% of the dissolved substances in sea water (Konrad et al., 1967). In this study these four constituents are elevated in wells located in residential, coastal agricultural, and Garziz & MAF farms zones in comparison with other constituents. This is associated with sea water intrusion.

Figure 8 shows that the chloride concentrations are much higher in the residential and agricultural strips than in the Garziz farm area. Both strips are much closer to the coastline than the Garziz zone 5 km inland. It is clear that recharge occurs in the central part of the Jabal front and sea water intrusion in the south.

Figure 9 shows salinity differences in the aquifer in 1998 and 2004. The observation data of the salinity in 1998 is from the first author's work and the salinity raw data of 2004 was obtained from DWR.

It is obvious that groundwater quality of Salalah plain aquifer is deteriorating with time. The coastal plain aquifer is unconfined and is prone to sea water intrusion. This type of highly fractured limestone aquifer in combination with karstic structures and over extraction is a reasonable explanation for the high amounts of salt affected wells in the study area. The increasing abstraction of water from the fresh water zone has resulted in a decline in water levels and intrusion from the both brackish zones, and along the coast.

The lowest salinity groundwater occurs beneath the central portion of the Salalah plain. This indicates that the central zone, from the central mountain front towards the central coast is an area of higher transmissivity and is a major pathway for groundwater flow through the freshwater zone. This explains why on either side of the plain, the groundwater is brackish (Figure 9). Salinity encroachment upwards and laterally is also seen in Figure 9.

Water level conditions

Figure 10 shows potentiometric level differences in the aquifer in 1993 and 2005. The calculated water levels were developed by numerical simulation. A 3-D flow model was constructed that covers the Salalah aquifer. The model was calibrated by history matching under steady state flow and salinity conditions against the observed hydraulic heads of DWR of 1992. The underflow recharge was derived from the calibrated steady-state flow model at 50 Mm3. The period between 1993 and 2005 was modeled under transient flow and with solute transport. The history of inputs and outputs of the aquifer were used in the transient calibration from 1993 to 2005.

Figure 10(b) shows the drop in the potentiometric heads. The abstraction from the plain aquifer in 1993 was estimated at 46 Mm^3, whereas in 2005 the abstraction was 65 Mm^3. The contours in 2004 show the effect of the increase in pumping in the aquifer. Ataie-Ashtiani et al. (1999) concluded that less freshwater discharged to the sea not only causes the sea water to intrude further inland but also causes the area between the 0.1 and 0.9 contours to increase. In the Salalah plain the area between the 0 and 0.5 contours increases by more than 2 km from 1993 to 2005.

Groundwater modeling and chemistry results of the Salalah plain aquifer wells indicate that the fresh water zone will contract substantially over the next years if irrigation and potable abstractions continue to increase. The increase in agricultural and potable water consumption has caused the

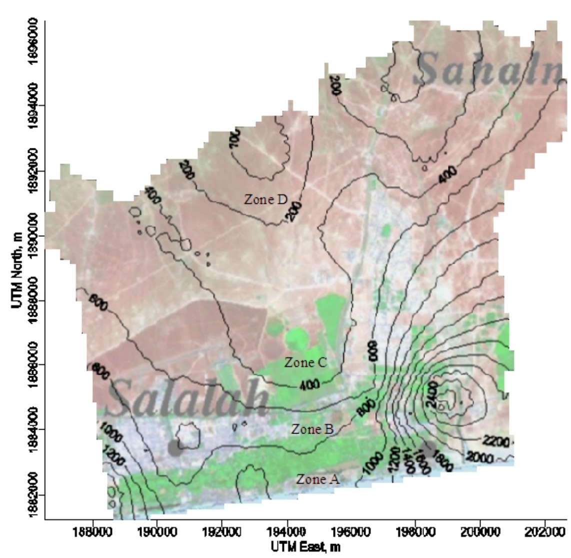

Figure 8. Chloride concentrations in the plain aquifer, the first author data in 1998.

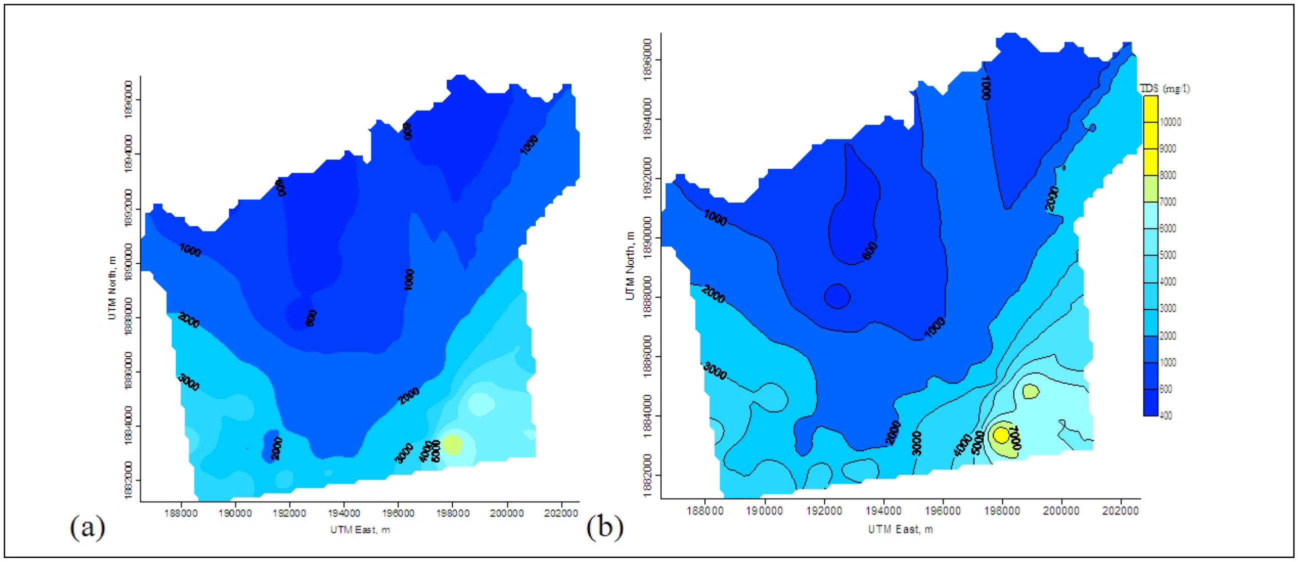

Figure 9. Observed salinity TDS (mg/l) in Salalah coastal aquifer (a) average TDS in 1998 (b) average TDS in 2004.

water budget to change from a positive to a negative balance. By considering the underflow estimated by the first author at 50 Mm^3, it could be said that the aquifer was in a steady-state in 1993 and changed to a deficit of about 8.2 Mm^3 in 2005. In contrast there was surplus water in the system, which flowed to the sea and maintained salinities at a low level through flushing in the central zone. Since groundwater flow from Jabal AlQara varies within a limited range, the increased demand on water has been met by a contraction of the fresh water resource. This has occurred as a result of fresh water being drawn from storage. If over abstraction is allowed to persist, the process will eventually result in degradation of the entire aquifer and loss of the resource.

To halt sea water intrusion it is proposed that treated wastewater be used to create a groundwater ridge along the coastline through artificial recharge. Ballukraya and Ravi (1998) have demonstrated the efficiency of such a ridge formed by natural infiltration. The main infiltration basins should be placed along the coastline. This approach will provide the agricultural sector with good water in comparison to the water which they are currently utilizing in their farms. It is also probable that irrigation reuse with reclaimed water will provide water at a very low cost.

CONCLUSION

The aquifer of the Salalah plain is largely unconfined and is therefore prone to sea water intrusion and pollution from surface sources. This paper stresses the establishment of a groundwater quality-monitoring program. Monitoring of environmental pollutants including sea water intrusion and nitrates/nitrites in existing wells on the plain is necessary in order to establish a baseline for future studies. This work has been initiated as part of this paper but it is very important that it be continued.

It is clear that the groundwater quality in the plain aquifer is threatened by sea water intrusion. The freshwater outflow to the sea is decreasing and this causes the sea water to intrude inland. It is expected that the size of the deficit will increase in coming years.

Artificial recharge of treated wastewater in the Salalah aquifer can have very beneficial effects. It will create a barrier to prevent sea water intrusion, as well as stabilize groundwater levels of the aquifer in agricultural and residential areas. In addition, in terms of resource conservation, this

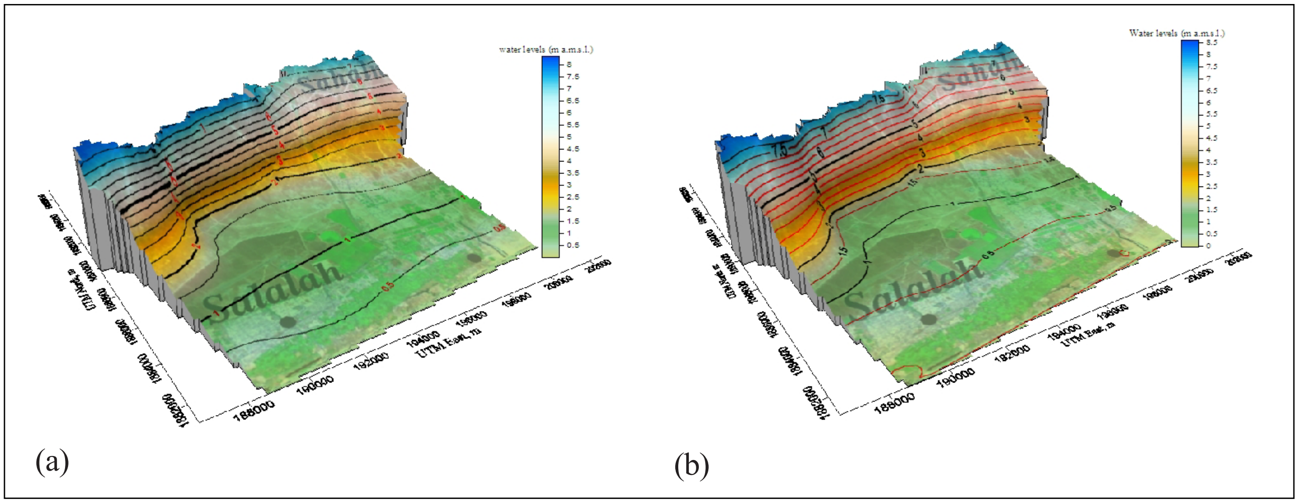

Figure 10. The calculated potentiometric levels in the aquifer in 1993 and 2005.

water will be useful as a source of water for irrigation in the future, particularly in the traditional farms.

Agricultural activities use over 70% of the groundwater. This consumption is far greater than urban water supply requirements, and if uncontrolled development in the aquifer continues, it will lead to a shortfall in urban supplies and a decrease in groundwater quality. It is also concluded that even with the management option proposed here, over development of the city is likely to threaten the aquifer again after a couple of years. New water sources and additional conservation measures should be taken into account before that time to ensure preservation of fresh water resources for future generations.

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