Sea water/fresh water interaction in the Red Sea coast around Port-Sudan town-Red Sea State-Eastern Sudan

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Abstract
Port-Sudan area is considered as one of the most vulnerable areas along the Red Sea coast of Sudan in terms of shortages in water supply. This study is concerned with the fresh/saline water interface along the coastal area around Port-Sudan town based on the chemical analysis of groundwater along the coastal zone. The brackish groundwater along the coastal plain may represent one of the available water resources that can help to solve the problem of shortage in water supply. The interaction is determined near the sea coast at Khor Mog and Khor Salalab, where sea water reaches a maximum value of 16% and 14% of the total amount of water using Cl\CO3+HCO3 and Clf\Cls ratios, respectively. The boundary between the fresh and the brackish water was estimated to take place at about 8 km from the sea coast, where the interface between fresh and saline water is calculated at a depth of 200m below the ground surface at one km away from the sea shore. The groundwater along the coastal zone in the study area is classified as Ca^{+2}, Na^{+}, Cl^{-}, $SO4^{-2}$ water type.

Keywords: fresh/saline water interaction, coastal zone, Port-Sudan, Red Sea, Sudan

1. BACKGROUND

Water is a landscape element and as a chemically active mobile substance, it is always on continuous move through the surface and subsurface of the earth (Igboekwe and Akankpo, 2011). The coastal aquifers in different parts of the world are considered as an important source of groundwater supply. Some of the coastal areas are heavily urbanised leading to a greater demand for groundwater. In arid and semi-arid regions, the presence of fresh water resources is a vital factor controlling live activities and development. The study area is the most important residential and economic area on the Red Sea coast of Sudan. The hydrological and meteorological studies carried out in the Red Sea coast reveal that there is adequate amount of water from summer and winter rains (Elsheikh, 2002).However, huge amounts of water are lost due to evaporation and surface runoff. The assessment of groundwater storage in the coastal zone is important issue to increase the fresh water supply of the town which is suffering from inadequate fresh water resources.

2. THE STUDY AREA

The Red Sea area of Sudan extends from the Egyptian border in the north at latitude 23° 00´´ N to the Eritrean border in the south at 18° 00´´ N, and from longitude 35° 00´´ E to the Red Sea coast at 37°15´´ E. The study area is around Port-Sudan town in approximately the central Red Sea coastal area between lat. 19° 00´´ N to 19° 30´´ N, and long. 36° 45´´ to 37° 15´´, (Fig.1).

The availability of fresh water governs the population distribution and settlement (Elsheikh et al., 2014). Port-Sudan town and its surrounding areas depend mainly on groundwater and surface water from Khor Arbaat seasonal valley that is located at about 35 km NW of the town.

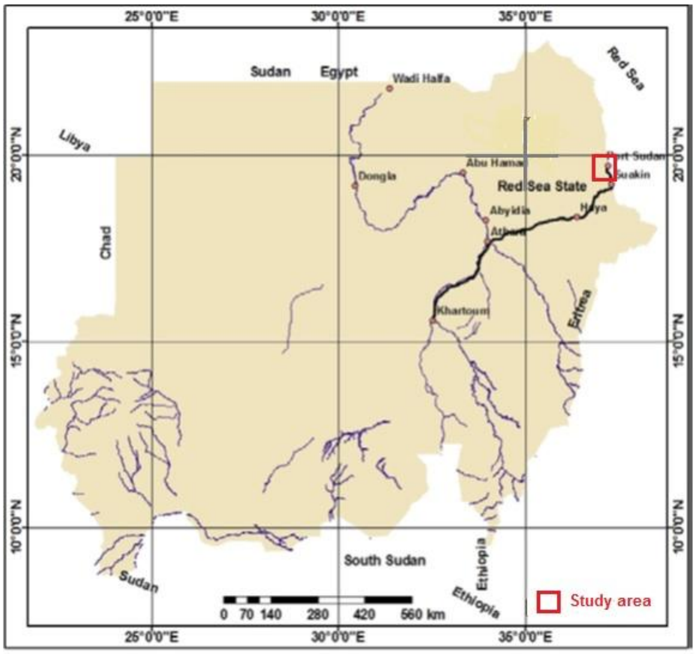

Figure 1: Location map of the study area

The Red Sea area of Sudan is a typical arid region, where the average rainfall is less than the average potential evapotranspiration. The Red Sea Hills represent a climatic border, where the western part of the Hills is only affected by summer rains from July to September. The coastal area is affected by the winter rains from November to January, with an average annual precipitation of about 200 mm, (Sudanese German Exploration Project, 1980).

The temperature shows wide variations throughout the year, and also during the day time with average temperature degrees during summer of about 38°C and about 20°C during winter. The humidity in the coastal area ranges between 50% and 80%.

The geology of the coastal area consists of continental and marine sediments present along the sea coast overlying unconformably the basement rocks. They are formed of Tertiary carbonates, sandstones and conglomerates overlain by clastic deposits and Quaternary alluvial sediments. These sedimentary sequences reach considerable thickness, recognized through oil exploration activities which reach more that 3km in some areas along the sea coast.

3. OBJECTIVES OF THE STUDY

The main objectives are to study the saline and fresh water interface and to evaluate the groundwater quality in the coastal zone around Port-Sudan town as one of the available water supply source to secure the water needs for the Port-Sudan town.

4. METHODOLOGY

The method of investigation is based mainly on chemical analysis of water samples portrayed as tables and graphs according to the well-known standard methods of analyses in addition to the measurements of water table on the coastal plane to define the interface between fresh and saline sea water.

5. SALINE/FRESH WATER INTERACTION

Seawater intrusion is the movement of saline water into freshwater aquifers (Arslan et al, 2012). The degree of seawater intrusion in an aquifer depends upon the hydraulic gradient of groundwater that is affected by the groundwater flow path and the hydraulic properties of the aquifer (Kumar, 2006).

In the coastal areas fresh water is dominated by Ca^{+2} and HCO_3^{-1}, whereas the sea water is dominated by Na^{+1} and Cl^{-1} ions. When sea water intrudes fresh water in a coastal aquifer, an exchange of cations takes place (Appelo & Postma, 1994):

$Na^{+1} + ½\ Ca\ X_2 \longrightarrow Na\text{-}X + ½\ Ca^{+2}$ ………………………………………….... (1)
Where, X indicates the soil exchanger.

When the sea water invaded the land; the water facies changes from Na-Cl water type to Ca-Cl water type. The reverse process takes place when fresh water flushes a salt water aquifer in the processes called refreshing:

$½\ Ca^{+2} + Na\text{-}X \longrightarrow ½\ Ca\ X_2 + Na^{+1}$ …………………………………………. (2)

For determining saline/fresh water interaction, the concentration of Cl^{-1}, CO_3^{-2} and HCO_3^{-1} are used; (Watkins, 1969; William, 1997; Kumar, 2006). In the study area the fresh/saline water interaction takes place near the sea coast. In this area the sea water intrusion can be classified as active salt water encroachment which is due to the extensive pumping that increases the risk of salinization near the sea coast. The sea water reaches up to16% of the total water volume in Khor Mog and Khor Salalab as shown in Table1.

Table 1: Shows the degrees of interaction between the fresh and saline water based on the concentration of Cl, CO_3 and HCO_3 ions in the dry season (ppm).

Well No.	Cl^{-1}(ppm)	CO_3^{-2}(ppm)	HCO_3^{-1}(ppm)	Cl \ CO_3+HCO_3	Cl_f \ Cl_s
M11	1136	18	531	2 %	6%
M3	2769	6	164	16 %	14%
M10	2520	6	213.6	11 %	13%
M2	1271	6	164	7%	6%
M5	1250	6	116	10%	6%
M6	1028	3	171	6%	5%
M7	921	3	195	5%	5%
M8	849	0	122	7%	4%
S1	1276	0	146	9%	6%
S2	1063	0	183	6%	5%
S3	999	12	268	4%	2%
S4	475	12	170	3%	1%
S5	184	3	164.7	1%	0.6%
S7	269	3	165	2%	0.9%
S9	128	3	140	0.9%	0.6%
S6	177	0	262	0.7%	0.8%
Cl \ CO_3 + HCO_3 Ratio: < 1.0 normal groundwater 1 – 5 contaminated groundwater 5 – 200 injuriously contaminated 200 < Sea Water			Cl_f \ Cls % Cl_f is the concentration of Cl ions in fresh water Cls is the concentration of Cl ions in Sea water (20,000 ppm)		

The water quality of the coastal area was studied by the analysing water samples from Khor Salalab, Khor Mog and along the sea coast in Port-Sudan town. This analysis indicates that the Total Dissolved Solids (TDS) values increase toward the coast, where it reaches more than 5000 mg/l near the sea coast. The contour line of 1500 mg/l TDS value is considered to be the boundary between the fresh and brackish groundwater in the area (Fig. 2). Based on these results, the boundary between the fresh and the brackish water in the Red Sea coastal area of Port-Sudan was identified at about 8 km from the coast.

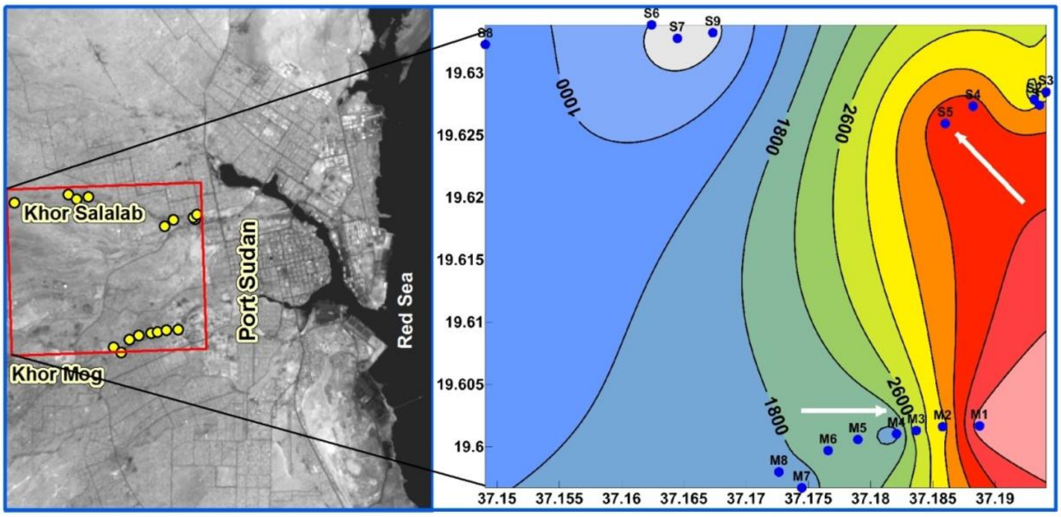

Figure 2: TDS iso-concentration map in Port-Sudan area

Salts in water usually originate from dissolution or weathering of the rocks and soil, including dissolution of lime, gypsum and other soil minerals (Ravikumar and Somashekar, 2013). In the coastal area, generally the water quality shows wide variations with respect to the ions concentration, where the groundwater is more saline and of higher amounts of dissolved solids toward the sea direction (Fig. 3). The $Cl^{-1}$and SO_4^{-2} ions are most dominant anions, where the common cations are K^{-1}, Na^{+1} Ca^{+2} and Mg^{+2}.

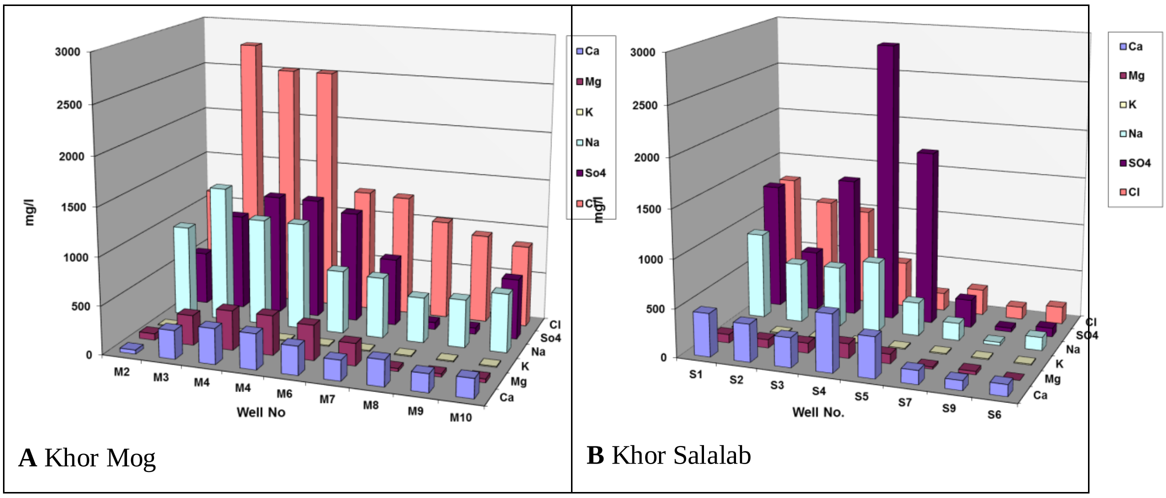

Figure 3: The concentration of the dominant anions and cations in the study area.

The chemical element contents in water are influenced by the intrusion of the sea water and by the amount of recharge during the rainy seasons. The high content of Cl^{-1} and SO_4^{-2} ions indicate sea-water intrusion near the coast, in which the Cl^{-1} ions reach the maximum concentration of 2,769 mg/l in well M3 in Khor Mog, while the SO_4^{-2} ions reach the maximum value of 2,875 mg/l in well S4 in Khor Salalab. The water type of the coastal area was classified as Ca, Na, Cl, SO_4 water type using Schoeller and Piper diagrams (Fig.4).

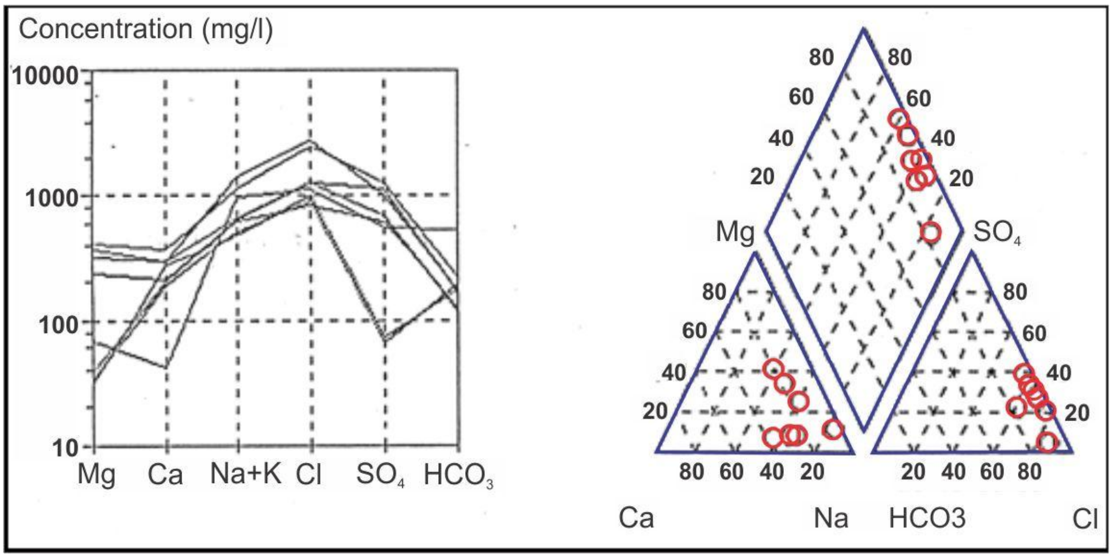

Figure 4: Schoeller and Piper diagram used for groundwater classification in the study area.

6. GROUNDWATER EXPLOITATION

The coastal aquifer should be exploited carefully aiming to avoid the salt water encroachment as passive due the natural processes or active salt water encroachment due to unplanned pumping. Considerable amount of fresh water can be discharged into the sea water by the hydraulic gradient from the aquifers. So the boundary between fresh and sea water (transition zone) should be determined for safe exploitation. The depth of fresh - sea water interface ($\mathbf{h_s}$), is calculated according to Ghijben-Herzberg relationship by the equation (Fetter, 1994):

$$\mathbf{h_s = (p_f / p_s - p_f)\, h_f} \quad \text{...} (3)$$

Where, $\mathbf{h_f}$ is the height of water table above the sea level. $\mathbf{p_f}$ and $\mathbf{p_s}$ are the densities of fresh and sea water respectively, (Fetter, 1994).

If the $\mathbf{p_f}$ = 1.00 gcm^{-3}, $\mathbf{p_s}$= 1.025 gcm^{-3}, the depth to the interface below the sea level is 40 times the height of the fresh water table above sea level (z = 40h), (Fetter, 1994). Accordingly, the coastal area of the Red Sea could be a promising area in terms of fresh groundwater resources that can be used for different purposes.

The hydraulic gradient is calculated as 0.075 and the groundwater flow direction is toward the sea, (fig. 5). The water table is 5m above sea level near the sea coast, and reaches about 20 m along the frontier of the town at about 2km. away from the coast. According to the above mentioned formula (Z = 40 h), the depth to the fresh/saline water interface along the coast is expected to take place at about 480 m (40x12m) below sea level, whereas the depth to interface along the frontier of the town can reach up to 800m (40 x 20m) below sea level. This result is rather conditional because many factors can affect the position of the interface such as geology and the rate of annual recharge and discharge. The rate of pumping should be controlled to avoid the risk of salt water up-doming, since the drop of water table by one meter shall raise the interface 40 m upward.

In recent research studies elsewhere regard the groundwater management in coastal areas; there are many suggestions to reduce the risk of salt water up-doming in coastal areas through artificial recharge methods to raise the levels of fresh water, or construction of sub-surface dams to reduce groundwater seepage toward the sea. Pumping from wells at different levels is considered as an effective method for protecting coastal aquifers, the upper one is for fresh water extraction while the lower one is for pumping saline water back to the sea to lower the saline water level (Kawasaki et al., 1993; Nagata et al., 1993). From a water management point of view, the moderately saline water near the coast can be directly used for other purposes without desalination.

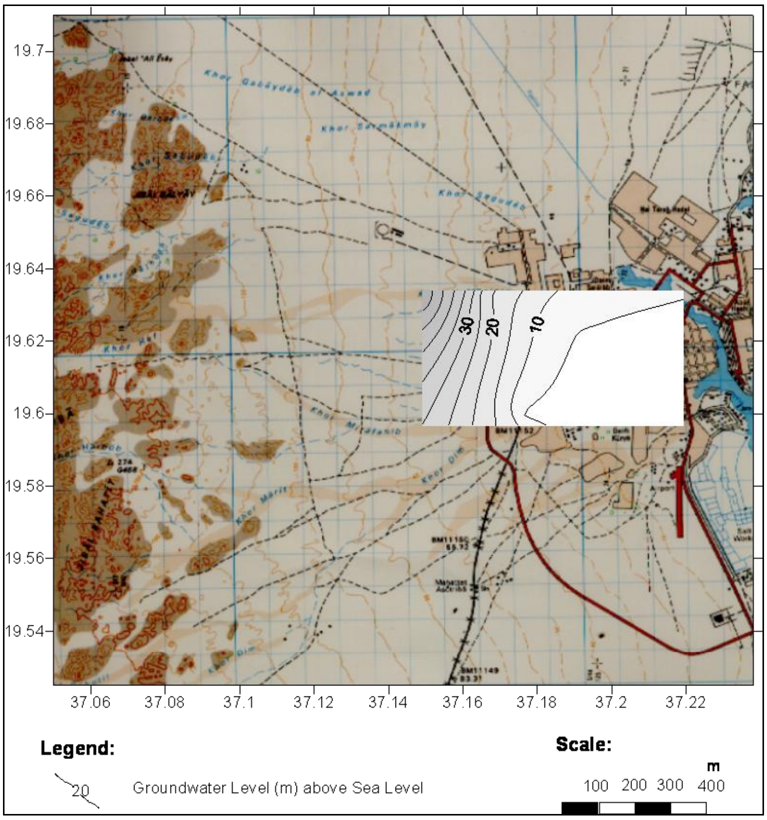

Figure 5: Groundwater flow map of the study area (values in meters amsl)

7. CONCLUSIONS

The coastal area of Port-Sudan town suffers mostly on the Red Sea coast from water supply shortage. The brackish groundwater on the sea coast is not exploited in an economic way to support the limited water supply of the town. The current investigations indicate that the TDS iso-contour 1500 ppm line represents the boundary between the fresh and brackish water at about 8 km from the sea coast. The most dominant anions in the coastal aquifer in Port-Sudan area are $Cl^{-1}$and $SO4^{-2}$ ions, where the common cations are K^{-1}, Na^{+1} Ca^{+2} and Mg^{+2}. The concentration of anions and cations are increasing toward the sea direction, where the mixing rates of sea water with fresh water at the costal plan is ranging from less than 1% (at wells S5, S6, S7 and S9) to the maximum of 16% near the Red Sea coast. The depth to the fresh/saline water interface along the frontier of the town at about 2 km from the Sea coast can reach up to 800m below sea level. The exploitation of groundwater in the coastal area should be done carefully to avoid induction of salt water intrusion due to over pumping. Adoption of water development techniques, such as applications of artificial recharge methods, construction of sub-surface dams and oriented pumping, can help in reducing the risk of salt water intrusion in coastal aquifers.

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9. SYMBOLS

Clf	Chlorine in fresh water
Cls	chlorine in saline water
ppm	part per million
TDS	total dissolved solids
mg/l	milligram per liter
gcm^{-3}	gram per centimeter cube
hf	is the height of water table above the sea level
pf	density of fresh water
ps	density of sea water
amsl	above mean sea level