Possible Impacts of Climate Changes on Freshwater in Coastal Aquifers

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Abstract

Groundwater resources in coastal aquifers constitute a main source of freshwater in many regions around the globe. This is typically true in arid and semi-arid regions where rainfall is scarce and infrequent and the surface water resources are almost absent. The consequences of climate changes and global warming on the freshwater in coastal aquifers have been investigated by several researchers over the last two decades. Due to the expected increase in the global temperature and the associated expansion of water in oceans and seas, the seawater is expected to rise. This seawater rise would lead to land submergence along the coastline and also an increase in the hydraulic head of seawater at the seaside boundary. Investigations revealed the seriousness of the problem and undesirable possible consequences on land loss and degradation of groundwater quality in coastal areas. In addition, groundwater in would be subjected to extensive pumping which may lead to depletion of aquifers. This paper investigates the possible impacts of climate change on two coastal aquifers located in arid regions; namely, the Nile Delta Aquifer, in Egypt and the Wadi Ham aquifer in United Arab Emirates. For the case of the Nile Delta aquifers and due to the low altitude and flat nature of the coastal zone, vast areas will be submerged was seawater. A numerical model, FEFLOW was used to simulate the possible impacts of seawater rise under different pumping scenarios. It is concluded that the groundwater in both aquifers will be affected but with significantly different degrees.

Keywords: coastal aquifers, seawater intrusion, groundwater, climate change

Introduction

Many researchers investigated seawater intrusion problems in different coastal aquifers using different approaches and different models under steady and transient flow conditions (Henry, 1964; Lee and Cheng, 1974; Sherif *et al*. 1988; Galeati *et al*. 1992; Kacimov and Sherif, 2006; and Kacimov *et al.* 2009). Some researchers considered the effect of climate change and possible rise of seawater level on the groundwater flow and seawater intrusion using both the sharp interface approach and dispersion zone approach (Oude Essink, 1996; Navoy, 1991; Sherif and Singh, 1999; Langevin and Dausman, 2005; Warner and Simmons, 2009; Yechieli *et al*. 2010; Sefelnasr and Sherif 2014). All investigations revealed the significance of climate change and the possible impacts of seawater level rise on seawater intrusion processes.

The Intergovernmental Panel of Climate Change estimated that the global mean seawater levels have risen by 10-20 cm during the last century. It is also estimated that during this century the seawater level rise will be in the range of 11 to 88 cm (IPCC 2001). The increase of the seawater level will have major impacts on groundwater resources in coastal aquifers which are of particular importance to seawater intrusion problems. First, the shoreline will shift to a new position and depending on the land topography this shift might be significant. In other words, the sea boundary will be shifted landward and the groundwater in the affected zone will become completely saline. Second, the increase in the seawater level would cause additional pressure head at the seaside and, hence, the seawater water would advance more inland. Third, the climate change may cause some variations in rainfall which would affect the natural replenishment of groundwater. Fourth, due to the anticipated reduction in rainfall and surface water resources, exploitation of groundwater would be more extensive to substitute for the scarcity of surface water resources and meet the water demands of various sectors.

Sherif and Singh (1999) reported that the hydraulic gradient of water table and /or piezometric head in the Nile Delta aquifer would decrease due to the expected seawater rise. They also reported that deep coastal aquifers with mild hydraulic gradients would be more vulnerable under the conditions of climate change and seawater rise. They concluded that a 0.5 m rise in the seawater level in the Mediterranean Sea would cause equiconcentration lines 35, 5 and 1 g/l in the Nile Delta aquifer to move inland by distances of 1.5, 4.5 and 9 km, respectively, under the steady state conditions. Lower equiconcentration lines were hence reported to be more sensitive to seawater level rise. Using the Sharp interface approach, Werner and Simmons (2009) concluded that their analysis of the effect of seawater intrusion under global warming conditions is in agreement with the results of Sherif and Singh (1999). An inland toe migration in the order of 5 km was achieved in both studies for a 0.5 m sea-level rise.

Langevin and Dausman (2005) evaluated the interface movement in response to sea level rise based on the generalized characteristics of the highly permeable Biscayne aquifer of Broward County, Florida. The seawater intrusion was investigated under three cases of variable annual rates (0.9, 4.8 and 8.8 mm/year) of sea-level rise. The freshwater isochlor line (250 mg/l) moved inland by distance of 40 m, 740 m and 1800 m, respectively, for the three cases over a simulation period of 100 years. The last scenario represented the worst scenario of an anticipated seawater level rise by 88 cm during this century (IPCC 2001).

Yechieli *et al*. (2010) studied the response of the Mediterranean and Dead Sea coastal aquifers to sea level variations. A fast response was observed in the Dead Sea coastal aquifer, exhibited both in the drop of the water levels and the location of the fresh-saline water interface. The simulations of the Mediterranean aquifer indicated that a steep coastal topography, simulated as a cliff, the shoreline and the interface are not expected to shift inland. A considerable inland shift of the shoreline and the interface is expected for the flat coastal topography. They also concluded that reduced recharge due to climate change and/or overexploitation of the groundwater would enhance the shift of the interface.

This paper investigates the possible impacts of climate change on two coastal aquifers located in arid regions; namely, the Nile Delta Aquifer, in Egypt and the Wadi Ham aquifer in United Arab Emirates. Although both aquifers are located in arid regions, they have different domain scale and geological and hydrological settings. The Nile Delta aquifers is one of the largest coastal aquifers of the world with huge water bearing capacity, while the Wadi Ham aquifer is a relatively small in size and capacity. The thickness of the Nile Delta aquifer various from about 200 m in the southern part to more than 900 m at the sea boundary. On the other hand, the thickness of the Wadi Ham aquifer varies from a minimum of about 10 m to a maximum of about 70 m. A numerical model, FEFLOW was used to simulate the possible impacts of seawater rise under different pumping scenarios. It is concluded that the groundwater in both aquifers will be affected but with significantly different degrees.

The Nile Delta Aquifer

The Nile Delta, along with its fringes, occupies an area of about 23,284 km^2. It lies between latitudes 30º 05’ and 31º 30’ North and longitudes 29º 50’ and 32º 15’ East. At a distance of about 20 km North West of Cairo and at an elevation of 17 m above mean sea level, the Nile Valley begins to open out into triangular alluvial Delta with its base (245 km) at the Mediterranean Sea. The length of the right Nile branch (Damietta) is about 240 km and that of the left branch (Rosetta) is about 235 km, Figure 1. The Nile Delta aquifer underlies about 3.0 million acres of fertile lands. It fills a vast underground bowl situated between Cairo and the Mediterranean Sea and is considered among the largest groundwater reservoirs in the world. Several investigations in the last three decades have confirmed that seawater intrusion has migrated inland, at some locations, to a distance of more than 100 km from the Mediterranean coast, measured along the bottom boundary of the aquifer (Sherif *et al*. 1988 and Sherif, 1999).

The ground surface elevation in the Nile Delta area lies above the mean sea level except in some locations in the northern part where depressions are encountered. Field observations indicated that the major alluvial aquifer (south of Tanta), Figure 1, is generally of good groundwater quality, with salinity values of less than 1000 ppm. The salinity increases toward the north due to the effect of seawater intrusion from the Mediterranean Sea. In the northern Delta, the salinity ranges from 5000 ppm to 35000 ppm. On the other hand, due to the density effects, the salinity of the groundwater increases with the depth below the mean seawater level (Sherif *et al.* 2012 and Sefelnasr and Sherif 2014).

Hydrogeological setting and boundary conditions of the Nile Delta Aquifer

The Nile Delta aquifer system is a leaky aquifer in the southern, northern and middle parts and a phreatic aquifer near the western and eastern borders. On the regional scale, flow within the Pleistocene aquifer is considered essentially horizontal as the vertical flow is relatively insignificant except in the vicinity of seaside. This assumption of horizontal flow within the Pleistocene aquifer is supported by the fact that the dimensions of the aquifer in the horizontal view are more than 100 times the depth at any point. The aquifer thickness is very small as compared to its horizontal extension. Within the clay cap, however, the flow is essentially vertical and the horizontal flow in the clay cap is negligible. The most permeable water bearing strata in the Nile Delta aquifer has been found at depths between 55 and 150 meters from land surface. Sherif (1999) elaborated that the transmissivity reaches its minimum values in the southwestern area, where it ranges between 2000 and 3000 m^2/day and its maximum values in the middle and southeastern parts, where it ranges between 9000 and 15000 m^2/day.

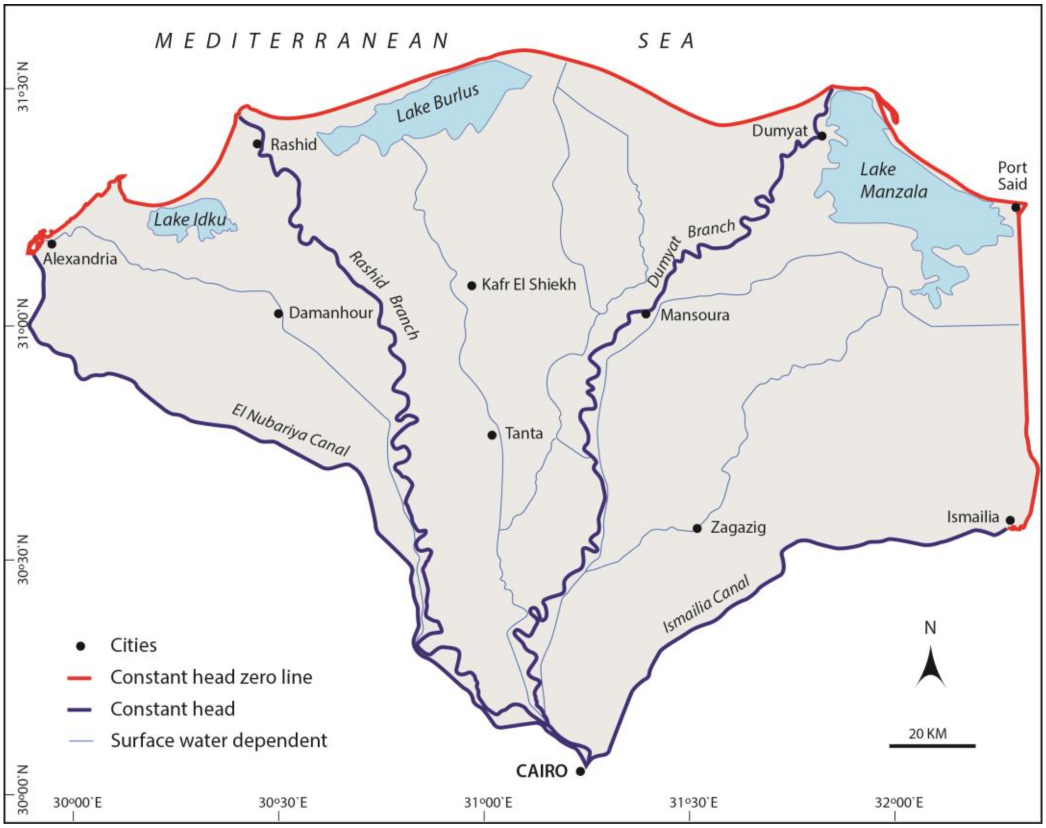

Figure 1. The Nile Delta aquifer in Egypt.

The hydraulic conductivity of the Nile Delta aquifer is relatively high and ranges between 70 and 100 m/day. The effective porosity over the whole area ranges between 12% and 19%, and total porosity varies between 25% and 40%, which indicates that the aquifer is mainly composed of coarse sand and gravel, Sherif (1999). The storativity of the aquifer varies between 0.01 and 0.001 in the southern parts. In the southeastern and southwestern areas, the storativity ranges between 0.1 and 0.01, which indicates that the aquifer is unconfined to semiconfined in these areas. In the northern area, the storativity ranges between 0.0005 and 0.0009, indicating confined conditions. The vertical hydraulic conductivity in the cap layer was estimated to be about 0.67 mm/day. Sherif *et al.* (1988) estimated the longitudinal dispersivity and the lateral dispersivity for the Nile Delta aquifer as 100 m and 10 m, respectively. Detailed discussions related to the hydrological setting and parameters are given in Sherif (1999).

Vertical water fluxes are allowed through the upper semi pervious layer and the concentration gradient across this clay layer is set as zero. The aquifer is overlaying a thick impervious aquiclude, which does not allow for water or salt exchange. The average depth to groundwater table below the land surface ranges from 0.5 m in the north to about 5 m in southeast and southwest of the study area. With reference to the mean seawater level, the elevation of the groundwater table at Cairo, Tanta and El Mansura are 14 m, 7 m and 2 m, respectively. The average hydraulic gradient is estimated to be about 11cm/km in the flow direction toward the Mediterranean Sea. The hydraulic heads in the north and east boundaries were considered as zero as the domain is bounded by the Mediterranean Sea from the north and Suez Canal from the east, Figure 1. A concentration of 35000 mg/l is used along the coastal boundary and the initial concentration of the groundwater was set to 500 mg/l. The southern boundary along Ismailia Canal, and the west boundary at El Nubariya Canal are first type spatial dependent boundary conditions at which the water table level is controlled by the water level in the canals.

Results of the simulation

FEFLOW was calibrated to simulate the seawater intrusion under the current conditions and all the hydrological parameters were adjusted accordingly. For more details about the calibration process, reference is made to Sherif *et.al.* (2012) and Sefelnasr and Sherif (2014). To simulate the seawater intrusion under the condition of climate change, the water level in the Mediterranean sea was assumed to rise by 0.5 m and the pumping rate was doubled; i.e., increased from 2.3 to 4.6 billion m^3/year. Using the digital elevation models from ASRT with a special resolution of about 30 m, the shoreline was shifted in the different scenarios to match the seawater level rise of 0.5 m. Due to the flat nature of the topography of the Nile Delta aquifer, the seaside boundary is significantly shifted inland under the condition of seawater rise. The total area of the land of the Nile Delta under the current conditions (0.0 seawater level), as calculated by ARC-GIS is 23,284 km^2. A land area of 4,396 km^2, representing about 19% of the total land of the Nile Delta aquifer will be lost under the condition of a 0.5 m rise in the Mediterranean seawater level, Figure 2. The study domain was modified to reflect the appropriate conditions of seawater level rise and the boundary conditions at the seaside were revised accordingly.

The simulation, using the calibrated model, was conducted under the steady state conditions to reflect the ultimate conditions (worst case) under the suggested seawater rise and groundwater pumping. In reality, however, the shift of the shoreline, under the climate change condition, would possibly occur over a period of one century (IPCC 2001). The simulation exercise revealed that groundwater flow and heads would require few decades to reach the steady state conditions. On the other hand, the solute transport and the dispersion zone would require few centuries to achieve the steady state conditions. The flow adjusts more rapidly as compared to solute transport and groundwater concentration.

Figures 3 presents the final status of the seawater intrusion assuming a 0.5 m rise associated with a groundwater pumping of 4.6 billion m^3/year, respectively. The results of the current investigation reveal that both Sherif and Singh (1999) and Werner and Simmons (2009), underestimated the possible consequences of the seawater rise on the Nile Delta aquifer due to ignoring the significant landside shift of the seaside boundary.

The Wadi Ham Aquifer

Wadi Ham catchment is located in the north-eastern part of the UAE along Kalbha and Fujairah coast, Figure 4. The catchment lies between the city of Fujairah on the Gulf of Oman to the east and the town of Masafi located on the divide of the Masafi mountain chain. The total catchment area of Wadi Ham is 192 km^2. The upper part of the catchment is characterized by narrow alleys, with distinct channels in the alluvial fill, and steep flanks along the surrounding peaks. The lower eastern part of the catchment widens and forms a large fan until it reaches the Gulf of Oman. The catchment is characterized by its arid conditions and for most of the year there is no flow in the channels. However, occasional intense rainfall events can generate short-duration flash floods.

Average annual rainfall in the catchment is around 150 mm/year, with a range between 20 and 506 mm/year (Sherif *et al.* 2009, 2011).

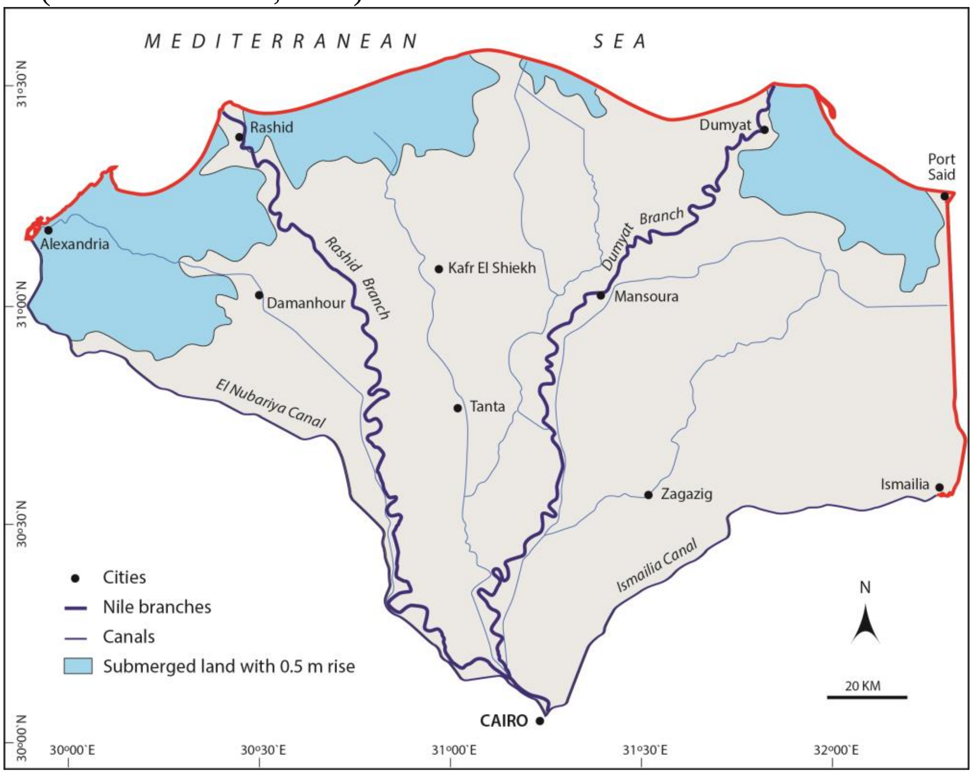

Figure 2. Submerged land in the coastal zone under the condition of 0.5 m seawater rise.

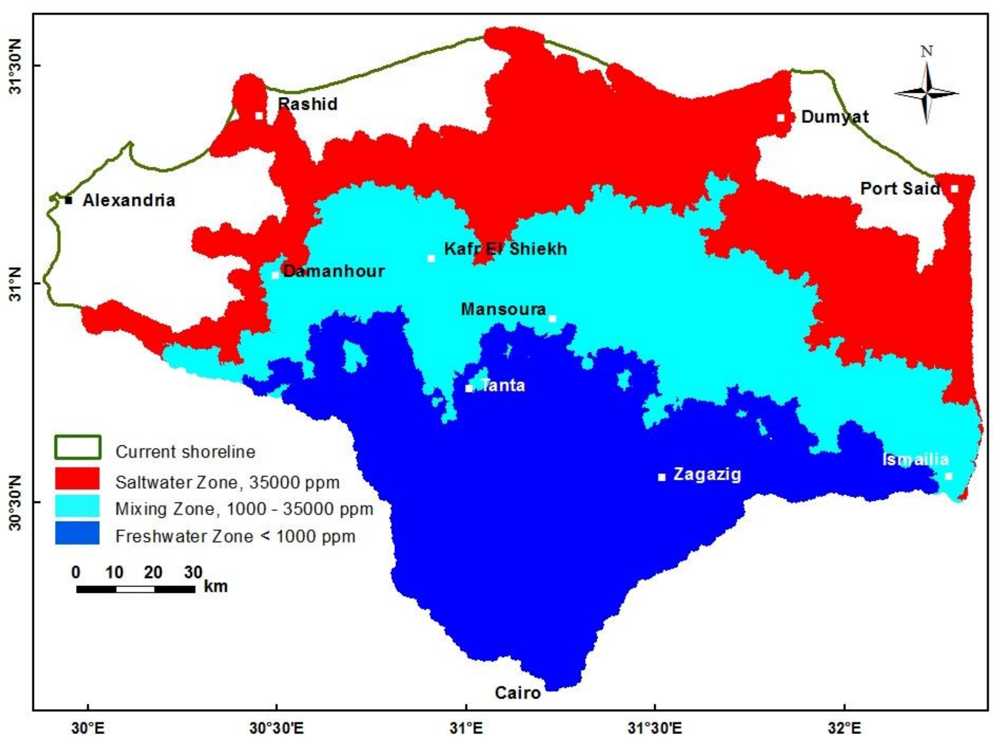

Figure 3. Seawater intrusion under the condition of 0.5 m seawater level rise and groundwater water pumping of 4.6 billion m^3/year.

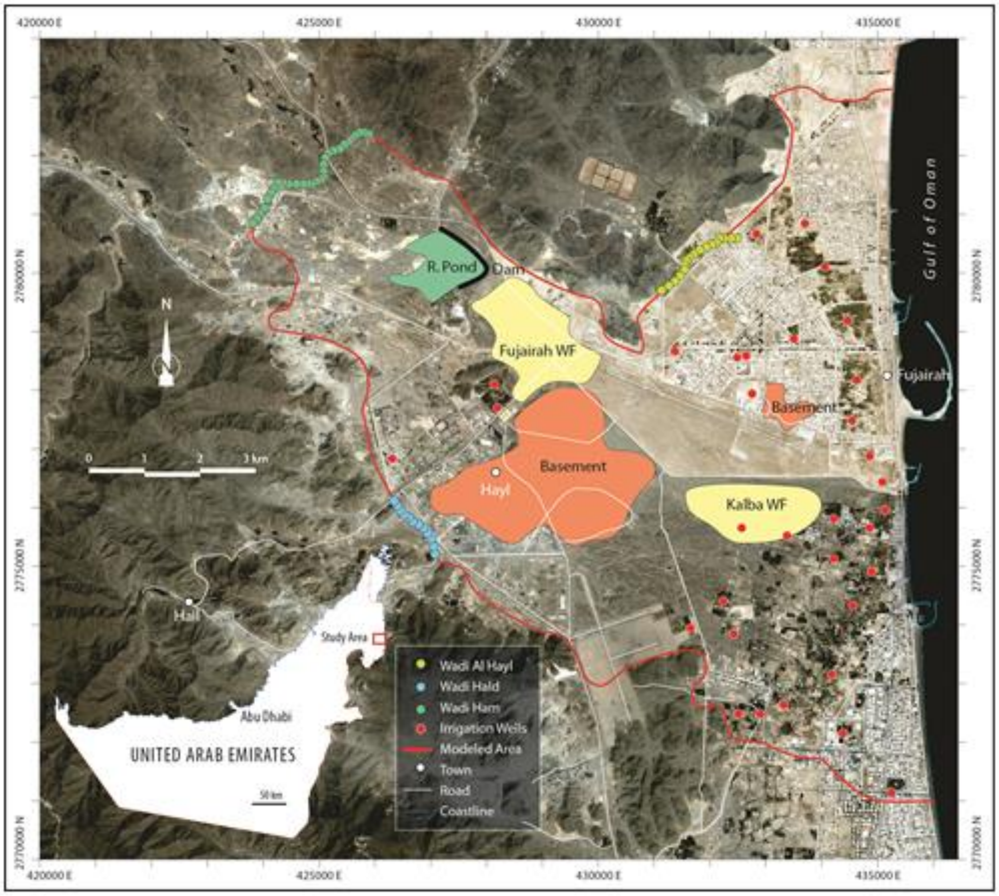

Figure 4. Land satellite image of Wadi Ham area and the study domain.

The review of rainfall records in the study area over the last 10 years has shown that the average annual rainfall dropped to less than 80 mm. Within the catchment area, the ground surface elevation varies from 60 above mean sea level (amsl) to about 950 amsl at the mountain peaks. The land use consists of arid region indigenous vegetation, irrigated farm lands and housing areas. Groundwater is used in the irrigation of cultivated areas along the Wadi streams and also in the vicinity of the coast line. Due to the current developments, the water demands for both domestic use and agriculture needs increased while the available groundwater has decreased and its quantity has deteriorated. The seawater intrusion in the coastal aquifer of Wadi Ham constitutes a major constraint against the sustainable development in the region.

Hydrogeological setting and boundary conditions of Wadi Ham Aquifer

Based on interpretation of the above data, two aquifers can be identified; namely the Quaternary aquifer which is composed of Wadi gravels and constitutes the main aquifer and the fractured Ophiolite which is of low groundwater potentiality. The gravel layer is highly permeable and tends to be unconsolidated at the ground surface. Values of the hydraulic conductivity of the unconsolidated gravels tend to be high, typically from 6 to 17 m/day and in the range 0.086-0.86

m/day for the cemented lower layers (Electrowatt, 1981 and ENTEC, 1996). The primary porosity of unconsolidated gravels is very high when compared to the cemented gravels. The storage coefficients typically range from 0.1 to 0.3. The width of the Wadi is about 2.0 km, the saturated thickness various between 10 and 40 m and the transmissivity varies between 100 and 200 m^2/d. Towards the shore line, the saturated thickness varies between 50 and 100 m and the transmissivity value ranges between 1000 and 10,000 m^2/d. The hydraulic conductivity ranges from 2 to 250 m/d (IWACO, 1986).

The study domain comprises an area of 117.81 km^2 with a length of 11.9 km east to west and 9.9 km north to south (Fujairah to Kalbha). The study area and the aquifer boundaries were delineated by digitizing the remote sensing image of Wadi Ham as shown in Figure 4. The model domain includes the Gulf of Oman and the ophiolite sequence rock out crops. The ophiolite outcrops are separated as inactive or no flow area. The area of separated outcrop is about 6.56 km^2. The area occupied by the Gulf of Oman in the model domain was considered as a constant head boundary cells with a defined sea level (0.0 m) throughout the simulation period. The model area of lower plains of Wadi Ham is composed of Recent Pleistocene Wadi gravels. This layer is underlain by the consolidated rocks of the Semail formation (Ophiolitic sequence).

Based on the available geological information, the top layer is gravel and sand and the bottom layer is of ophiolite. The bottom layer of ophiolite is impermeable in nature and hence, a one layer model of Wadi gravel and sand is considered. The DEM of the SRTM in a resolution of 3 arc seconds was used for the identification of the top boundary of the model domain. The base of the whole aquifer system was built by an interpolation of isolines and cross-sections.

Results of the simulation

FEFLOW was calibrated and validated to simulate the groundwater conditions and seawater intrusion in the area of Wadi Ham. Details related to calibration and validation of the model are given in Sherif et al., 2014. Due to the relatively steep slope of the land surface in the vicinity of the shore line, a seawater rise of 0.5 m may not cause significant land submergence and hence the inland migration of the shore line will not be significant. The retardation factor was taken as 1.0. The molecular diffusion coefficient was set equal to 0.1. The value of the longitudinal dispersivity was initially varied between 80 and 10 m while the ratios between the longitudinal and lateral dispesivities and longitudinal and vertical dispersivities were set as 0.1 and 0.01. Cells representing the Gulf of Oman in the study domain were considered to have a constant concentration with salinity of 35,000 mg/l. Otherwise, a freshwater salinity of 200 mg/l was assigned to all other cells as initial conditions. The evapotranspiration concentration boundary condition was not considered because the extinction depth was assumed 2 m and the evapotranspiration from the water table was found negligible. A longitudinal dispersivity of 20 m provided the best match with the available limited measured groundwater concentrations and was, hence, considered as representative for the medium.

Increasing the pumping rates by 50% caused a significant landward movement of the transition zone as shown in Figure 5. Under this scenario, and by the year 2020, the Kalbah well field will be fully intruded by brackish and saline water. The volume of freshwater in the coastal aquifer of Wadi Ham will reduce to 124.2 MCM, while the volumes of the brackish and saline water will increase to 189.1 and 293 MCM, respectively. The results indicate that any increase in the groundwater pumping would cause a tangible acceleration in the seawater intrusion process. In general, the southeastern area of the study domain is more vulnerable and its groundwater quality is more responsive to pumping activities, Figure 5.

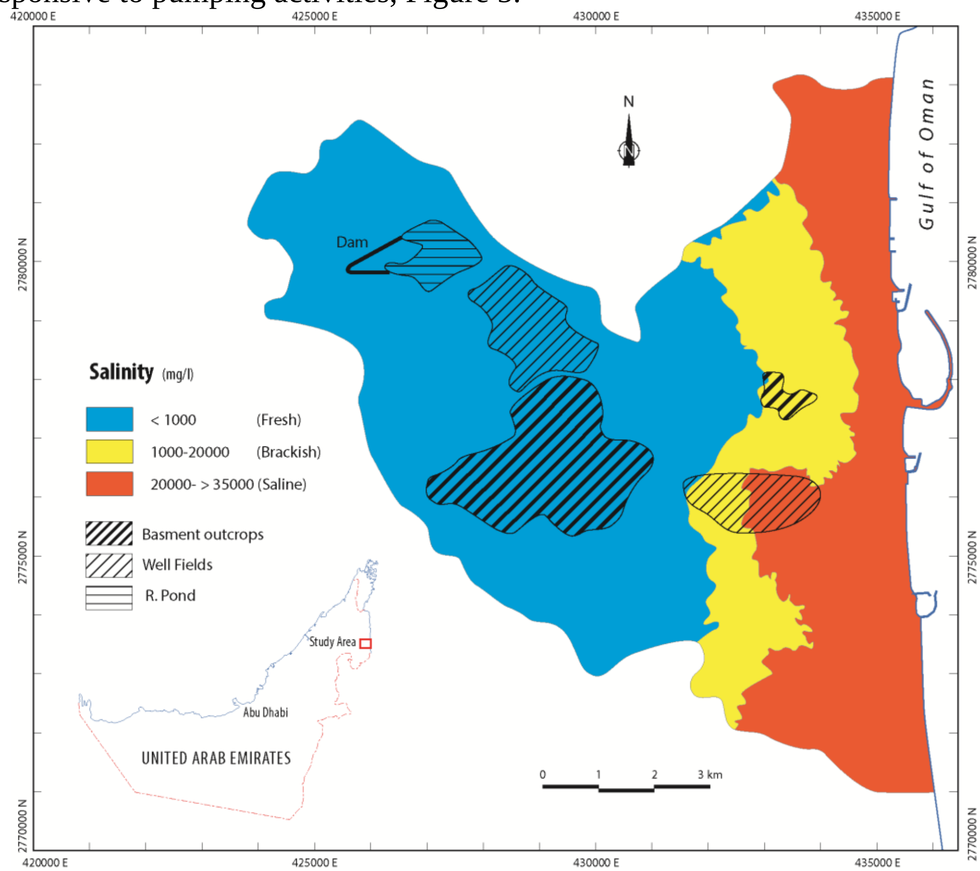

Figure 5. Seawater intrusion in Wadi Ham under the condition of 50% increase of groundwater pumping.

Conclusions

The climate change is expected to have a number of undesirable impacts on groundwater resources in coastal aquifers. The increase of the seawater level may cause significant loss of fertile lands due to land submergence and the shifting of the shore line. In addition, climate change would accelerate the seawater intrusion due to the increased hydraulic heads at the seaside and the excessive pumping to meet the possible shortage in surface water resources in arid and semi-arid regions.

This papers investigated the possible impacts of climate change in two coastal aquifers located in arid regions; namely, the Nile Delta aquifer, Egypt, and the Wadi Ham aquifer, United Arab Emirates. FEFLOW was employed and all simulations were conducted in the areal view. The two aquifers are significantly different in scale and geological and hydrogeological conditions. Due to the flat nature of the topography of the Nile Delta, large areas will be lost under the condition of 0.5 m rise in the seawater level. In addition, the seawater and the transition zone will migrate further inland and the freshwater zone will shrink to about one third of the total area of the Delta. For the case of Wadi Ham, the landside shift of the shoreline will be insignificant. However, due to the increase of groundwater pumping, the seawater intrusion is expected to accelerate and the groundwater quality and well fields in the vicinity of the shore line will be affected.

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