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Effect of climate change on sea water intrusion in coastal aquifers

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Abstract:

There is increasing debate these days on climate change and its possible consequences. Much of this debate has focused in the context of surface water systems. In many arid areas of the world, rainfall is scarce and so is surface runoff. These areas rely heavily on groundwater. The consequences of climate change on groundwater are long term and can be far reaching. One of the more apparent consequences is the increased migration of salt water inland in coastal aquifers. Using two coastal aquifers, one in Egypt and the other in India, this study investigates the effect of likely climate change on sea water intrusion. Three realistic scenarios mimicking climate change are considered. Under these scenarios, the Nile Delta aquifer is found to be more vulnerable to climate change and sea level rise. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS sea water intrusion; climate change; coastal aquifers; Nile Delta aquifer; ground water; sea level rise

INTRODUCTION

Climate is a dynamic system and is subject to natural variations at various time-scales, from years to millennia. Like any other system, if no excitations are imposed on the climate system, the average temperature of the globe will not change. However, the concentration of active greenhouse gases, mainly carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), has increased considerably during this century. Greenhouse gases allow solar radiation to pass through the atmosphere and hit the surface of the earth, but they intercept and store the infrared radiation emitted from the surface of the earth (Sherif, 1995). This phenomenon warms up the atmosphere and leads to what is perceived as global warming which is considered to be the cause of climate change. When a significant change in climate variables from one period to another occurs, it is referred to as climate change (Refsgaard *et al.*, 1989). On the other hand, climate variability is defined as the variation from year to year and generally occurs as a result of natural and/or man-made activities. Thus, global warming and climate change are intertwined. Were there no greenhouse gases in the atmosphere, the average temperature of the earth would be 30 °C cooler. Likewise, any increase in the concentration of greenhouse gases will be associated with a corresponding increase in the average global temperature. Measurements show that the average temperature of the earth has risen by 0·5–0·7 °C since the beginning of the twentieth century.

Many uncertainties involved in the calculation of global warming and ongoing efforts to control emissions of greenhouse gases notwithstanding, significant increases in the atmospheric concentration of greenhouse gases are expected in the next century (Mimikou, 1995). The rise of the global mean temperature is expected to be accelerated because of the growing concentration of other greenhouse gases (CH_4, N_2O and CFCs) and

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is likely to occur even before the doubling of the concentration of CO_2 (Berger, 1989). Simulation studies indicate that increase in the atmospheric concentrations of greenhouse gases in the atmosphere will cause an increase in the average temperature of the earth by 1·5–4·5 °C by the middle of the next century. Simulation models of general atmospheric circulation have shown an increasing trend in the global annual temperature, attributed largely to the increase in greenhouse gases in the atmosphere.

Global warming and climate change have a multitude of serious consequences. They change the character (both quantity and quality) of the components of the hydrological cycle in space, time and frequency domains. The objective of this study is to investigate the effects of climate change on sea water intrusion in coastal aquifers. The climate change was mimicked using three realistic scenarios.

CLIMATE CHANGE AND GROUNDWATER

Groundwater constitutes the sole source of freshwater supply in many countries around the world, especially in arid and semi-arid regions where surface water is scarce. Groundwater resources are affected by global warming in various ways. Excess rainfall or runoff, which cannot be stored or used, ultimately finds its way to groundwater basins or to oceans. Climate change may include both increased and decreased rainfall. The geographical distribution of rainfall may change considerably and, hence, the recharge of aquifers will be affected.

For analysing the effect of climate change (Jacoby, 1990), groundwater resources may be divided into four categories. The first category includes confined aquifers with upper impermeable layers. The recharge of such aquifers is encountered only where the water-bearing formations outcrop at the surface. Renewability of such aquifers depends on the availability of rains at their surface exposure. The second category includes phreatic (unconfined) aquifers in wet regions, where rainfall is high and evaporation is low. Since precipitation exceeds evaporation and evapotranspiration throughout the year, such aquifers are highly renewable and will not be affected under the expected geographical redistribution of rainfall. The third category encompasses unconfined aquifers in dry and arid regions, where there is a shifting annual balance between precipitation and evapotranspiration. Such regions may be subject to drier weather under the expected trend in global warming. Therefore, the available groundwater will be less on one hand and, because of the expected decrease in rainfall and increase in the population, the demand for groundwater will be more on the other. The fourth category includes coastal aquifers, which are generally subject to sea water intrusion.

Thomsen (1989) evaluated the effects of climate variability and change on groundwater in Europe in terms of the expected increase or decrease in groundwater recharge depending on the regional distribution of rainfall, which was evaluated by global circulation models (GCMs). A study in Australia by Sharma (1989) revealed that a $\pm 20\%$ change in rainfall would result in a $\pm 30\%$ change in recharge beneath grasslands, while beneath pine plantation the corresponding change in groundwater recharge was $\pm 80\%$.

CLIMATE CHANGE AND SEA LEVEL RISE

The expected increase in the global temperature will warm, to some extent, the land surface, oceans and seas. The warming will also affect atmospheric pressure. Variations in the atmospheric pressure will cause inverse variation in the sea level. With a one millibar decrease in atmospheric pressure, the sea level rises by 10 millimetres. A series of depressions in atmospheric pressure can cause a considerable rise in water levels in shallow ocean basins (Theon, 1993).

Sea water level may also rise for two reasons. First, warmer oceans would expand; and secondly, melting ice sheets and glaciers would add to the total volume of water in the oceans (Theon, 1993). The data obtained from tidal gauges indicate that the sea level has risen by 10–20 cm over the past century. It is estimated that about 25% of the rise has resulted from thermal expansion of the oceans. The rest must be the result of both melting ice sheets and glaciers on the land surface and depressions in atmospheric pressure. The predicted increase in the sea level is in the range of 0·5–1·5 m within the next 50–150 years (Buddemeneir, 1988). A projected global sea level rise of $1{\cdot}1 \pm 0{\cdot}6$ m by the year 2080 AD is ascribed to a combination of thermal expansion of ocean water and melting of glaciers and ice sheets.

SEA LEVEL RISE AND SEA WATER INTRUSION

According to the Ghyben–Herzberg relationship, a one metre height of free water table above mean sea level ensures 40 m of freshwater below sea level. Likewise, a 50 cm rise in sea level causes a 20 m reduction in the freshwater thickness, as shown in Figure 1. The last statement is typically true away from the sea boundary, where the water tables and/or piezometric heads are more affected by pumping and recharge activities rather than the increase or decrease in the sea water level. Under conditions of climate change, the rate of sea level rise is sufficiently slow so that gorundwater heads at and in the vicinity of the coast will increase in parallel rather than remaining at their present position. However, the increase in the groundwater table near the sea boundary will not be associated with a similar increase in groundwater levels at the land side, as shown in Figure 1. The gradient of the water table and/or the piezometric head will decrease and hence more intrusion will result. Near the sea boundary, the thickness of the freshwater body may be slightly reduced because the free water table will rise as well, while significant reduction will be more encountered inland. Deep coastal aquifers with mild hydraulic gradients are more vulnerable under conditions of climate change and sea level rise.

The Ghyben–Herzberg relationship is based on the sharp interface assumption, which is not realistic especially when the width of the dispersion zone is large. The width of the dispersion zone may vary from a few metres to several tens of kilometres, as, for example, in the case of the Nile Delta aquifer (Sherif *et al.*, 1988). In the dispersion zone the flow of water and the transport of salt ions are coupled. The density of the mixed water in the dispersion zone varies from the density of freshwater at the land side to that of sea water at the seaside. The flow of water is governed by the hydraulic gradient, while the transport of salt ions is dominated by dispersion and diffusion processes (Sherif *et al.*, 1990a).

Sea water rise will impose an additional pressure head at the seaside boundary of the aquifer. The process of sea water intrusion depends on many hydraulic, geometric and transport parameters. Each aquifer has its own conditions and the sharp interface approach cannot generally be applied. Quantitative prediction of the expected sea water intrusion can only be evaluated through numerical models which account for the dispersion zone.

STUDY CASES

The Nile Delta aquifer in Egypt and the Madras aquifer in India were employed to investigate the effect of climate change on sea water intrusion. The two selected aquifers have different scales and different geometric and hydraulic parameters. The sea water intrusion in the aquifers was simulated under two different sea

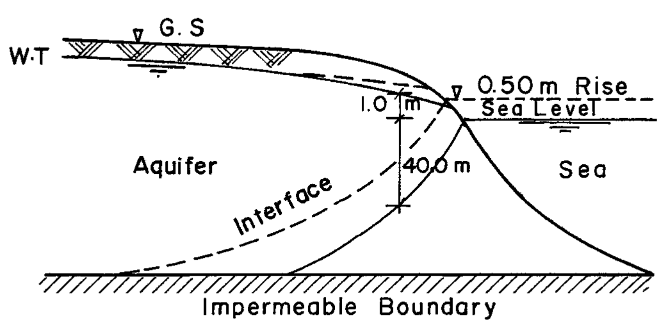

Figure 1. Sharp interface and sea level rise

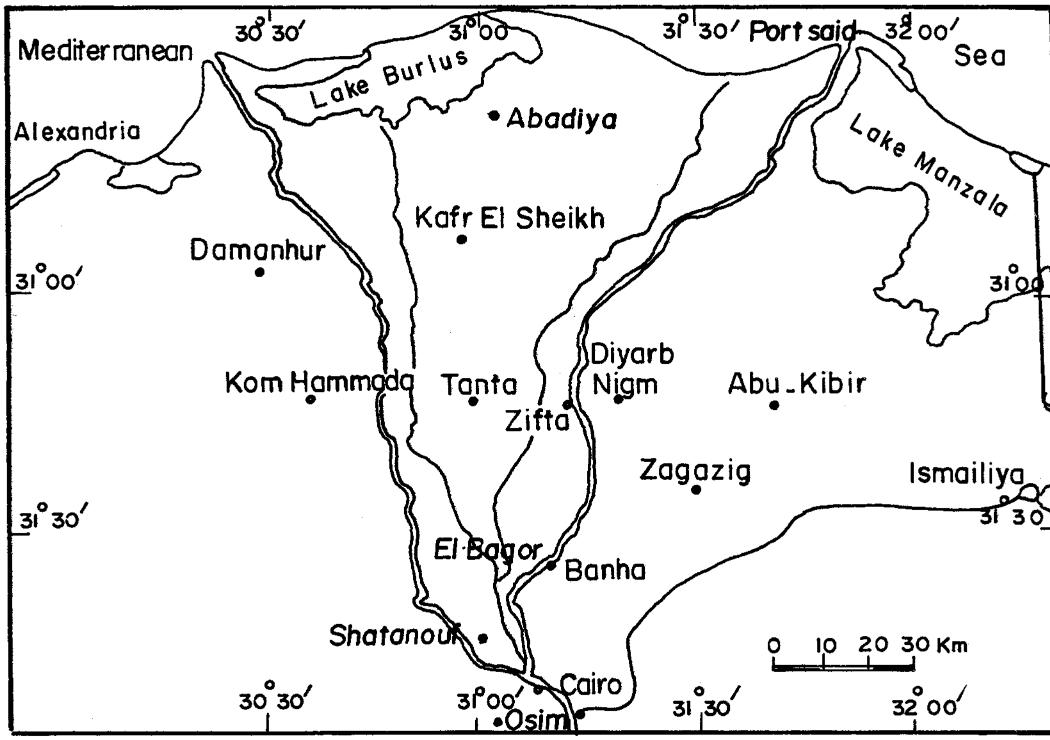

Figure 2. The Nile Delta aquifer

water levels, as well as under the condition of excessive pumping which may be encountered as a result of the expected shortage of surface water. All simulations were conducted in a two-dimensional vertical section using the 2D-FED model (Sherif *et al.*, 1988).

The Nile Delta aquifer

Physical setting. The Nile Delta, along with its fringes, occupies an area of 22 000 km^2. It lies between latitudes 30°05′ and 31°30′ north, and longitudes 29°50′ and 32°15′ east. At a distance of 20 km north-west of Cairo (Delta Barrage), and at an elevation of 17 m above the sea level, the Nile Valley begins to open out into a triangular alluvial delta with a base length of 275 km along the Mediterranean Sea between Alexandria and Port-Said, as shown in Figure 2. The level of the delta land ranges between 17 m above sea level to the south, to less than 1 m on the northern boundary (Farid, 1985).

The Nile Delta region lies within the Great Desert belt. It also occupies a portion of the arid belt of the Southern Mediterranean region. The desert fringes on both sides of the delta give elevated temperatures. The average temperatures in January and July in Cairo are 12 °C and 31 °C, respectively. The minimum and maximum temperatures in Cairo are 3 °C and 48 °C, respectively. Rainfall over the Nile Delta is scarce and occur mostly in winter. The maximum average annual rainfall along the shores of the Mediterranean is 180 mm, decreasing very rapidly inland to about 26 mm in Cairo.

The Nile Delta aquifer fills a vast underground bowl situated between Cairo and the Mediterranean Sea. It is a leaky aquifer, with an upper semi-permeable boundary and lower impermeable boundary. The aquifer is recharged by infiltration from a network of irrigation conduits, excess irrigation water and the limited precipitation that percolates through the upper clay layer. It may also be recharged by flow coming from the Nile Valley aquifer.

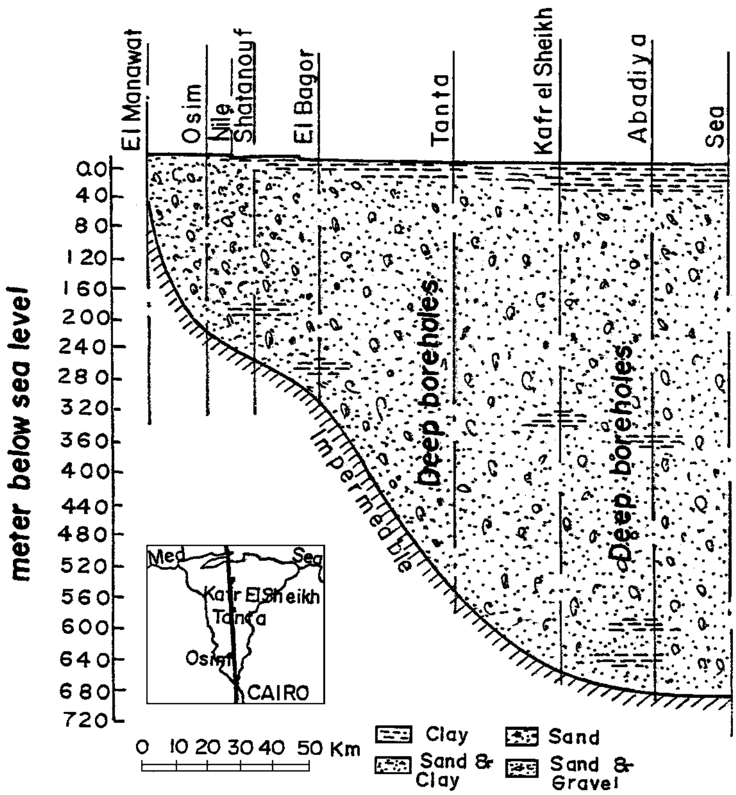

Figure 3. Cross-section in the Nile Delta aquifer

Study domain and hydraulic parameters. A vertical cross-section in the middle Delta was considered, as shown in Figure 3. The geometric characteristics of the aquifer were evaluated from about 18 deep boreholes, tapping the bottom, in the Delta (Farid, 1980). A hydrochemical investigation was also conducted in the same study to evaluate the chloride–bicarbonate ratio $[Cl/(CO_3 + HCO_3)]$ as a criterion for recognition of sea water intrusion. Based on field observations, chemical analysis and previous studies, it was assumed that sea water would not migrate inland beyond Shatanuf, which is 150 km from the Mediterranean. Under this assumption a domain of 150 km in length was used. Based on field data, the thickness of the upper semi-pervious layer was taken as 40 m between the coast and Om-Sin, which is about 17 km inland. From Om-Sin to Kafr-Elsheikh, 52 km from the sea, it varied from 40 to 15 m, after which the thickness of the semi-pervious layer was taken as constant. The bottom boundary of the Nile Delta aquifer is impermeable. The depth of the aquifer varies between 680 m at the coast and 240 m inland at Shatanuf. The slope of the bed of the aquifer varies from one reach to the other and is not precisely defined between the locations of the deep boreholes, as shown in Figure 3. The slope of the aquifer bed was taken as constant at $2{\cdot}93 \times 10^{-3}$.

Owing to uncertainties associated with field data concerning the hydraulic parameters, a calibrated value of 100 m d^{-1} for the hydraulic conductivities K_{xx} and K_{zz} was considered representative of the aquifer. The vertical hydraulic conductivity for the upper semi-pervious layer, K'_{zz}, was set equal to 0·05 m d^{-1} (Sherif *et al.*, 1988). The piezometric head at the land boundary was set equal to 14·0 m above sea level. At the sea boundary the piezometric head was taken as 0·60 m above sea level (GWRI, 1988). The free water table level was known for some stations (borehole locations), and between them it was assumed linear. No data were available on dispersivity. Based on similar studies, the longitudinal and transversal dispersivities, α_l and α_t, were assumed to be 100·0 and 10·0 m, respectively.

The study domain was divided into five subdomains. Each subdomain was then subdivided into a number of triangular elements with smaller areas in the regions where the variation in concentration gradient was relatively high. A high resolution grid was also required near the shore boundary. The domain was finally represented by a non-uniform grid with 4020 nodes and 7600 triangular elements. The convergence criterion was set equal to 10^{-5} to ensure accuracy of simulation, with specific reference to the process of solute transport. Any slight variation in the piezometric heads would have a significant effect on the concentration distribution (Sherif *et al.*, 1990b).

Effect of climate change. Measurements indicate that the water level in the Mediterranean Sea has increased by an average value of 2·5 mm per year during the last 70 years (Alnagger *et al.*, 1995). Meanwhile, the coastal region is subject to land subsidence, with an average value of about 4·7 mm per year. Therefore, the relative difference in land and sea level is approximately 70 cm per century (Alnagger *et al.*, 1995). It is also known that the elevation of the coastal area varies between −0·5 and +2·0 m relative to sea level. Low elevation lands in the delta are not uniformly encountered along the coast. Investigations show that about 4000 km^2 of the low elevation delta lands will be submerged by sea water if the trend in global warming and sea level rise continue to the end of the next century. The groundwater resources beneath such low lands will be lost as a result.

To investigate sea water intrusion under conditions of climate change, three scenarios were considered. In all scenarios, the shore line was maintained at its current location. The effect of the submergence of low lands by sea water was not considered. Salinities under different scenarios were then compared with those under the current conditions presented by Sherif *et al.* (1988). A comparison between the salinity distribution with depth resulting from Sherif *et al.* (1988) and field measurements at Kafr El-Sheikh is given in Figure 4.

In scenario 1, all hydraulic and transport parameters were kept constant. The water level in the Mediterranean was raised by 0·2 m, while the free water table was kept unchanged. Initially, vertical equipotential

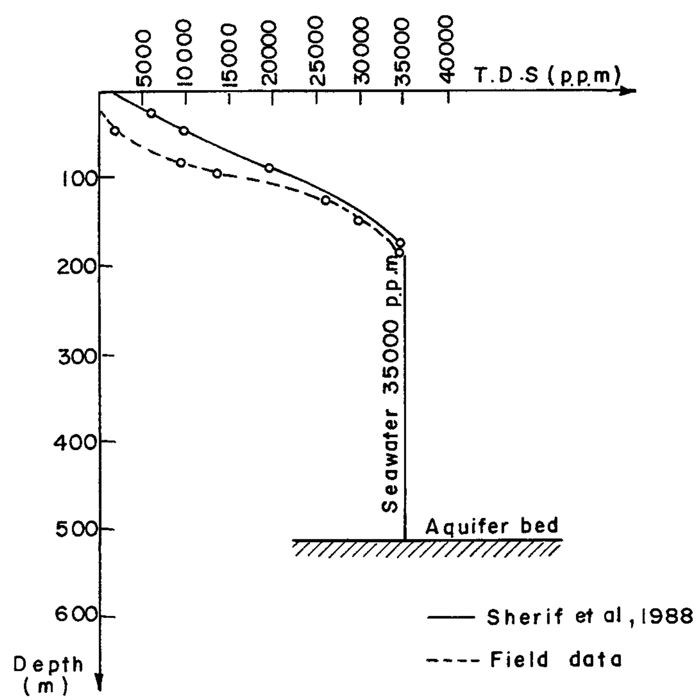

Figure 4. A comparison between the salinity distribution with depth as resulted from Sherif *et al.* (1988) and field measurements at Kafr El-Sheikh

lines were assumed. Like solute concentration, the piezometric head was not known *a priori*; it was adjusted through iterations according to the water mass balance of the system. Under this condition, the equiconcentration line 35·0 kg/m^3 (35 000 ppm) advanced slightly while the equiconcentration line 5·0 advanced by a distance of 2·0 km, measured along the bottom boundary. The equiconcentration line 1·0 advanced inland by a distance of 2·5 km, as shown in Figure 5a.

In scenario 2, the sea water level was raised by 0·5 m and all other parameters were kept to their basic values. The equiconcentration line 35·0 migrated inland by 1·5 km compared with current conditions, while the equiconcentration line 5·0 moved inland by a distance of 4·5 km measured along the bottom boundary, as shown in Figure 5b. The equiconcentration line 1·0 advanced inland by a distance of about 9·0 km. Low equiconcentration lines were affected more by the sea level rise than were higher ones.

Climate change may create a shortage of surface water, resulting in additional demands for groundwater resources. To investigate the effect of additional pumping from the Nile Delta aquifer the piezometric head on the land side was lowered by 0·5 m (as a result of additional pumping) and other parameters were kept unchanged in scenario 3. Under this scenario, the equiconcentration line 35·0 advanced inland a distance of 6·0 km (compared with current conditions) measured along the bottom boundary. The equiconcentration line 5·0 intruded to a distance of 11·5 km, measured along the same boundary. The width of the dispersion zone increased considerably, as shown in Figure 5c. Any additional pumping from the Nile Delta aquifer would cause a significant increase in sea water intrusion. The effect of additional pumping is more significant than the effect of sea level rise.

The Madras aquifer

Physical setting. The city of Madras, now called Channai, is the capital city of Tamil Nadu in India and is situated on the coast of the Bay of Bengal, as shown in Figure 6a. The climate is tropical, with a maximum mean temperature of 38·5 °C. Madras is the fourth largest city in India with a population of over 4·0 million. Many big industries have been established in and around the city. Demand for water for drinking, industrial and agricultural purposes is satisfied by three major well fields, viz. Minjur, Panjetty and Tamaraipakkam (Rouve and Stoessinger, 1980). Water is pumped from these wells and is supplied by a system of pipe lines to meet industrial and drinking needs. The well field at Tamaraipakkam is far away from the coast and therefore not subject to sea water intrusion. The wells in the Minjur and Panjetty are relatively close to the coast and may be subject to sea water intrusion under uncontrolled pumping.

Study domain and hydraulic parameters. The aquifer formation on the east coast consists of unconsolidated and semi-consolidated sand, silt and alluvial gravel. A geological cross-section of the aquifer, taken through the Minjur and Panjetty fields approximately in the east–west direction, is shown in Figure 6b. The aquifer is confined by clays, nearly homogeneous and isotropic in nature, with an average thickness of about 30·0 m. The upper and lower boundaries of the aquifer are impermeable clay layers (Rouve and Stoessinger, 1980).

The aquifer has an effective porosity of 0·35 and an average hydraulic conductivity of $3{\cdot}0 \times 10^{-3}$ m s^{-1} (Rouve and Stoessinger, 1980). No measurements are available about dispersivities. Based on a similar study in California (Pinder and Gray, 1977), longitudinal and transversal dispersivities were set equal to 66·6 and 6·6 m, respectively. The molecular diffusion D^* was taken as $1{\cdot}0 \times 10^{-6}$ m^2 s^{-1}. It was assumed that no rainfall infiltrated directly into the aquifer. In the case of the Madras aquifer, actual recharge takes place over a region far away from the pumping area. There is no correlation between the time variation of rainfall and groundwater fluctuations in the Minjur area. Based on numerical simulations, it was found that the pumping fields at Panjetty and Minjur were independent of each other (Rouve and Stoessinger, 1980). Therefore, only Minjur, which is near to the shore, was considered. Because the depth of the aquifer, which is in direct hydraulic contact with the sea, is only 30·0 m, the limit to which the influence of hydrodynamic dispersion can extend is about 3·0 km, at which a boundary of freshwater concentration was assumed. A study domain of 2600 m × 30 m was considered. The domain was represented by 400 triangular elements and 246 nodes.

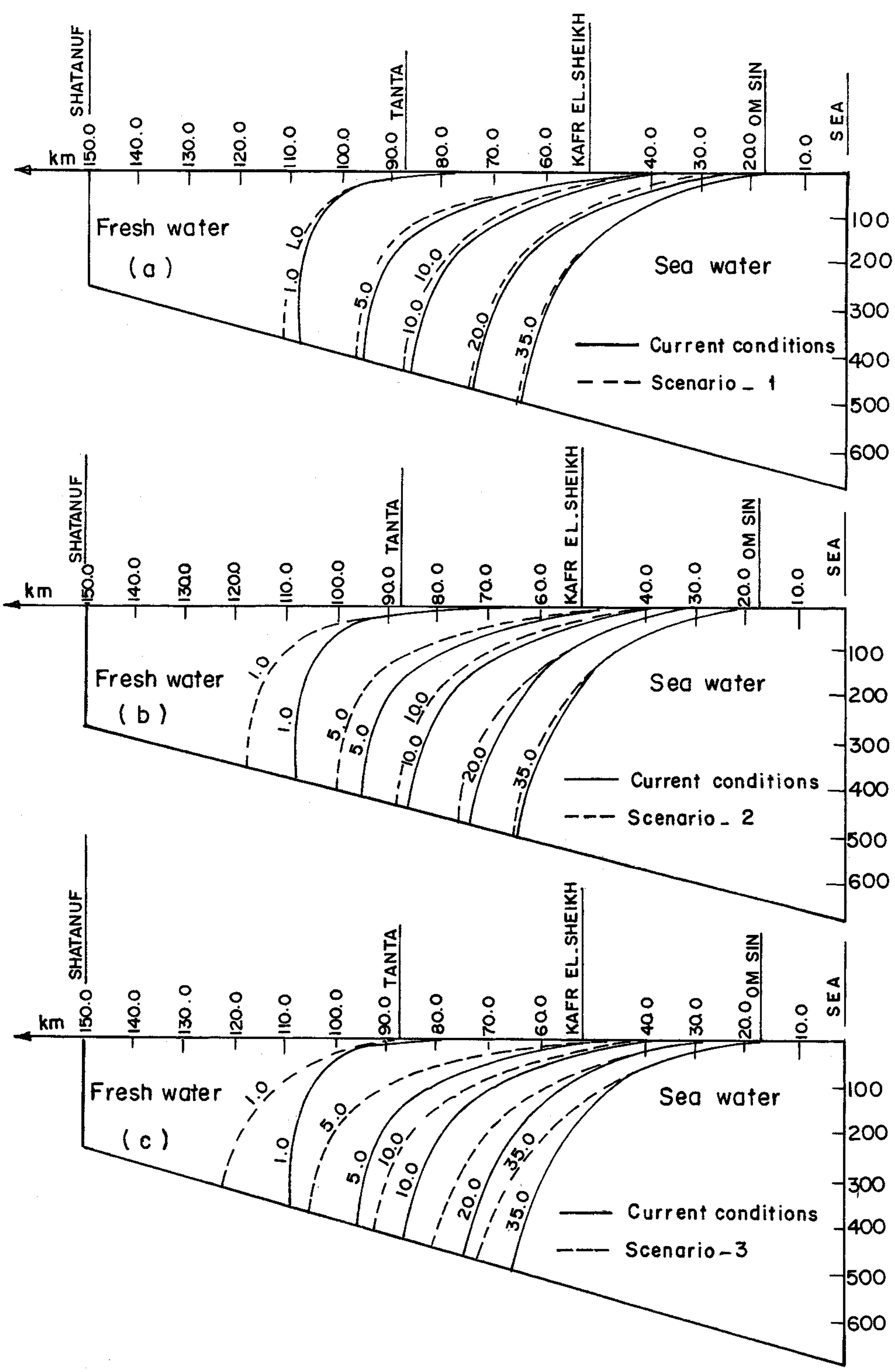

Figure 5. Sea water intrusion in the Nile Delta aquifer under different scenarios. (a) Comparison between scenario 1 and current conditions; (b) comparison between scenario 2 and current conditions; and (c) comparison between scenario 3 and current conditions

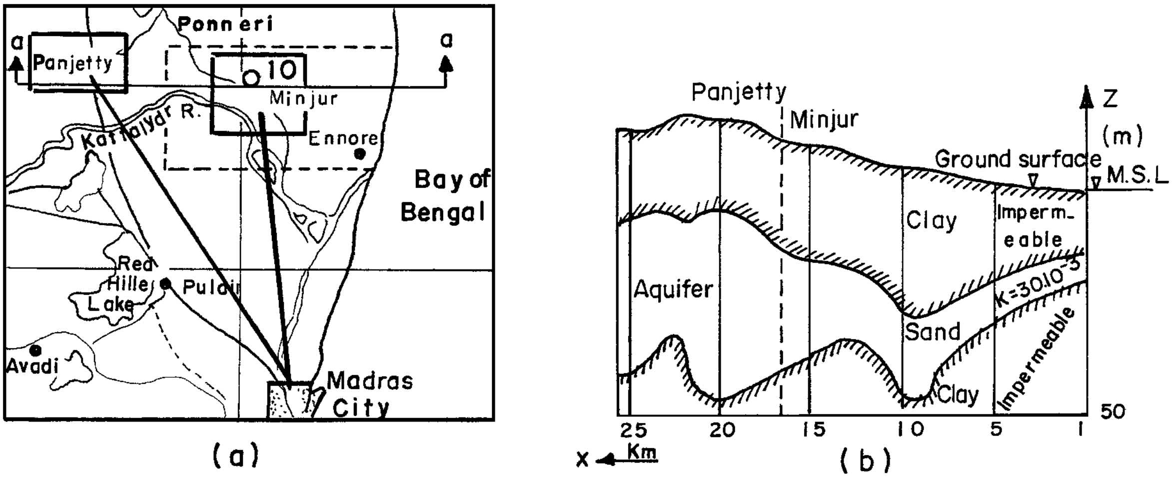

Figure 6. The Madras aquifer. (a) Minjur and Panjetty well field, and (b) geological cross-section in Madras aquifer

The piezometric head at the land side (2600 m from the shore line) under actual pumping conditions is 1·0 m above the mean sea level.

Effect of climate change. To investigate the effect of climate change on sea water intrusion in the Madras aquifer, three scenarios were considered. The resulting equiconcentratin lines were then compared with those under the current conditions as presented by Sherif *et al.* (1988). In scenario 1, the water level in the Bay of Bengal was raised by 0·2 m, while all other parameters were kept constant. The piezometric head was fixed only at the land boundary, while for the rest of the study domain it was naturally adjusted with the condition of sea level rise through iterations. The effect of this scenario on equiconcentration lines was limited, as shown in Figure 7a. For example, compared with the current conditions the equiconcentration line 1·0 (1000 ppm) moved inland by a distance of 102 m, while the equiconcentration line 17·5 (17 500 ppm) moved by a distance of 36 m.

In scenario 2, where the sea water level was raised by 0·5 m and all other parameters were kept unchanged, the width of the dispersion zone increased considerably. Lower equiconcentration lines were more affected than were the higher ones, as shown in Figure 7b. The equiconcentration line 1·0 migrated inland by a distance of 500 m more than under current conditions. On the other hand, the equiconcentration line 17·5 moved inland to a distance of about 60 m, while the equiconcentration line 35 moved inland to a distance of 41·0 m measured along the bottom boundary from the sea side.

In scenario 3, the piezometric head at the land side was lowered by 0·2 m and other parameters were kept unchanged. This case was considered to account for additional pumping which is likely to be practised under conditions of climate change. The sea water (equiconcentration line 35) intruded inland to a distance of 260 m measured along the bottom boundary from the sea side. The equiconcentration line 1·0 moved inland to a distance of about 590 m more than the case for current conditions, as shown in Figure 7c. Like the case of the Nile Delta aquifer, additional pumping from the Madras aquifer prompts sea water intrusion. However, because of its distant location compared with the expected intrusion, pumping from the Minjur will not be affected.

CONCLUSIONS

This paper investigated the possible effect of climate change on sea water intrusion in coastal aquifers. Under conditions of climate change, the sea water levels will rise for several reasons, including variations in

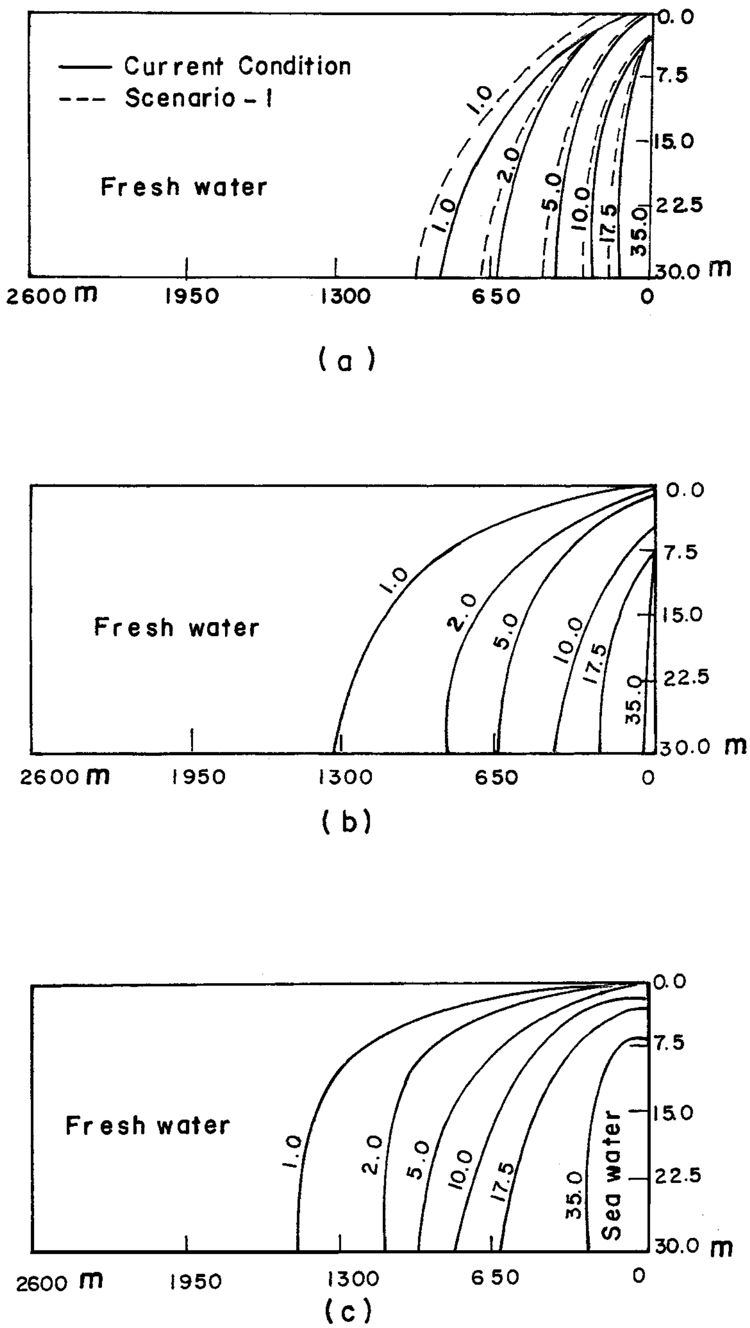

Figure 7. Sea water intrusion in the Madras aquifer. (a) Scenario 1; (b) scenario 2; and (c) scenario 3

atmospheric pressures, expansion of warmer occasions and seas and melting of ice sheets and glaciers. The rise in sea water levels will impose additional saline water heads at the sea side and therefore more sea water intrusion is anticipated.

A 50 cm rise in the Mediterranean Sea level will cause additional intrusion of 9·0 km in the Nile Delta aquifer. The same rise in water level in the Bay of Bengal will cause an additional intrusion of 0·4 km. The

Nile Delta aquifer is more endangered under the conditions of climate change and sea level rise. Additional pumping will cause serious environmental effects in the case of the Nile Delta aquifer.

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