Annual Journal of Hydraulic Engineering, JSCE, Vol 49, 2005, February

# EFFECT OF SEA LEVEL RISE ON THE LOSS OF FRESH GROUNDWATER RESOURCES: CASE STUDIES OF WESTERN AMERICAN COAST AND BAY OF BENGAL

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Effect of sea level fluctuations on the movement of the freshwater saltwater interface was analyzed by means of a sharp interface model. The simulation was carried out over 100 years period for two case studies based on available data; western coast of America and the Bay of Bengal and adjacent continental shelf. The position of freshwater-saltwater interface was estimated and it reflects the effect of long term average sea level rise on the position of interface. Using the location of the interface, the related loss of freshwater resources was estimated in both areas and results show that volumetric freshwater losses due to sea level rise is 1%- 5% of the aquifer volume in western American coast and 1%-3% in Bay of Bengal. The effects and influences of the loss of fresh groundwater resources were discussed, considering the groundwater use and groundwater recharge and adaptation proposals were introduced for both areas.

***Key Words :*** *Salinity Interface, freshwater loss, coastal aquifers, sea level rise*

## 1. INTRODUCTION

When considering the water resource in areas bordering seas, coastal aquifers are very important resource of freshwater. Greater than 75 percent of the human population lives within 60 km of the coast[1)]. Since groundwater systems in coastal areas are in contact with saline water, one of the major problems is the prediction of the motion of the saltwater body in the aquifer. The quantitative understanding of the patterns of movement and mixing between freshwater and saltwater are necessary to manage the coastal groundwater resources. The movement of the freshwater-saltwater interface could result in change of fresh groundwater resources in coastal aquifers.

Coastal aquifers within the zone of influence of mean sea level can be threatened by sea level rise. Sea level is rising worldwide and it is important to recognize the impacts of sea level rise in relation to coastal aquifers. Sea level rise takes place progressively. The time characteristic of sea level rise is in the order of decades. Available references indicate that sea level is rising approximately 2.0mm/year. Although it seems to be a relatively small amount of change, a small increase in sea level leads to devastating effects[2)].

Only a few quantitative studies on saltwater intrusion in coastal aquifers induced by sea level rise are available[3) 4) 5)]. In these studies, modeling has remained rather tractable because of the assumptions made. The main objective of this study is to evaluate the effects of sea level rise on fresh groundwater resources in coastal aquifers. We try to evaluate the effects of changes in sea level on the movement of freshwater-saltwater interface and the quantification of the movement of interface to estimate the loss of fresh groundwater resources in two different coastal aquifers in western America and Bay of Bengal regions which have entirely different trends of sea level rise and different climatic and socio-economic zones.

## 2. METHODOLOGY

### (1) Modeling of the freshwater-saltwater interface using sharp interface concept

Many models have been developed to represent and to study the problem of saltwater intrusion. The first concept about freshwater-saltwater interface, now widely cited as the Ghyben – Herzberg principle, is based on the hydrostatic equilibrium between fresh and saline water. Recently the studies involving the movement of fresh groundwater and saltwater in coastal aquifer systems are classically studied using two different approaches; sharp interface and disperse interface approaches[6]. In sharp interface approach, freshwater and saltwater are assumed completely immiscible and a sharp interface exists between these two phases. Since sharp interface models couple the freshwater and saltwater flow based on the continuity of flux and pressure, it has been selected to simulate the effect of sea level rise on the position, shape and the behavior of the interface. The sharp interface models have been developed with different numerical techniques[7) 8) 9) 10)]. In this approach, together with Dupuit approximation, for each flow domain the equation of continuity may be integrated over vertical direction and come up with following system of differential equations [11) 12)].

$$\frac{\partial}{\partial x}\left[K_{fx}\left(h^f-h^i\right)\frac{\partial h^f}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{fy}\left(h^f-h^i\right)\frac{\partial h^f}{\partial y}\right]+q_f$$

$$=S_f\frac{\partial h^f}{\partial t}-\theta\left[(1+\delta)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right]+\alpha\theta\frac{\partial h^f}{\partial t} \qquad (1)$$

$$\frac{\partial}{\partial x}\left[K_{sx}\left(h^i-z^b\right)\frac{\partial h^s}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{sy}\left(h^i-z^b\right)\frac{\partial h^s}{\partial y}\right]+q_s$$

$$=S_s\frac{\partial h^s}{\partial t}+\theta\left[(1+\delta)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right] \qquad (2)$$

The location of the interface elevation is given by

$$h^i=\frac{\rho_s}{\rho_s-\rho_f}h^s-\frac{\rho_f}{\rho_s-\rho_f}h^f \qquad (3)$$

where $\rho_f$ and $\rho_s$ are specific weight and $h^f$ and $h^s$ are the piezometric heads in fresh and salt water, regions. $z^b$ is the elevation of confining layer. $q_f$ and $q_s$ are flow rate in fresh and salt water respectively. $K_f$ and $K_s$ represent the hydraulic conductivity and $S_f$ and $S_s$ are storage coefficients in fresh and salt water regions respectively. $\theta$ is the porosity of the aquifer media and $\delta$ is defined as $\delta=\rho_f/(\rho_s-\rho_f)$ $\alpha$ =1 for unconfined and $\alpha$ =0 for confined aquifers.

### (2) Numerical modeling of sharp interface

Except for very simple systems, analytical solutions of those two coupled non linear partial differential equations are rarely possible. Various numerical methods must be employed to obtain approximate solutions. One of the approaches is the finite-difference method. From above equations, it is possible to derive a numerical model using implicit finite difference techniques. Spatial discretization is achieved using a block centered finite difference grid which allows for variable grid spacing. To solve the two simultaneous linear algebraic differential equations, the Strongly Implicit Procedure -SIP[13)] was used as a suitable numerical technique.

### (3) Model simulation

For the convenience of modeling process, each case used a reference 2km × 2km horizontal strip from the unconfined aquifer by changing the sea level rise. To identify the factors affecting the dynamics of the freshwater-saltwater interface, a sensitivity analysis was conducted. It shows that hydraulic conductivity is the main governing hydro-geological factor affecting the movement of the interface and the model is very sensitive with respect to changes in hydraulic conductivity. Distribution of hydraulic conductivity was estimated considering the soil properties and geological properties of the area based on USGS[14)] and WISE/ISRIC[15)] data sets. The hydraulic conductivity in both coastal aquifers ranges from $10^{-2}$m/s to $10^{-5}$m/s such as highest hydraulic conductivity with coarse gravelly aquifers and lowest with fine textural sandy aquifers. Sensitivity analysis also shows that saltwater intrusion is far more sensitive to groundwater recharge and high recharge rate in the aquifer can reduce the seawater intrusion effectively. Groundwater recharge of the study areas were estimated using water balance method as the difference between precipitation and evapotranspiration (Fig.1). Evapotranspiration was estimated using Hamon's equation based on temperature data. Average annual precipitation and temperature data were obtained from the NOAA-EPA Global Ecosystem data base, which has a spatial resolution of $0.5^0\times0.5^0$ [16)]. Seasonal change in recharge with change in climate were not considered as a scenario in this modeling but should be considered in future studies.

### (4) Simulation of sea level rise

Responses to sea-level change were simulated through modifications in the seawater boundary. Simulating sea level rise requires an introduction of increase in the hydrostatic pressure term, which computes vertical variations in pressure along the seawater boundary. Sea-level rise scenarios were simulated as gradual increases. Gradual sea-level rise was modeled as a series of short uniform step increases in pressure occurring annually along the seawater boundary. The step increases were represented by uniform increases in the magnitude of hydrostatic pressure values along the seawater boundary nodes and model was run over 100 years.

**(5) Loss of fresh groundwater resources**

The concept of interface between freshwater and saltwater can be used to estimate the amount of fresh groundwater resources in coastal aquifers. The movement of salinity interface due to the changes in sea level rise leads to change in available fresh groundwater resources in the aquifer. As illustrated in Fig. 1, when the aquifer is totally filled with freshwater (interface 1), the freshwater loss can be considered as zero and the movement of salinity interface landward (interface 2), leads to reduce the freshwater amount in the aquifer. When the salinity interface coincides with piezometric head (whole aquifer fills with saltwater), the freshwater loss will be 100%.

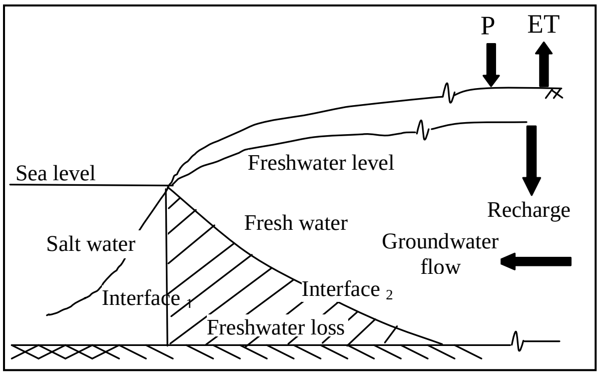


Fig.1 Loss of fresh groundwater resource due to salinisation

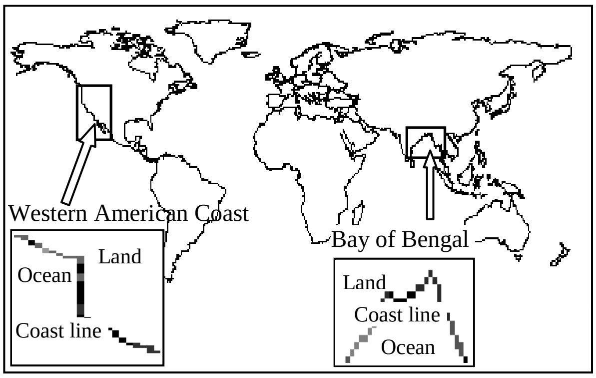


Fig.2 Study area; Western American Coast and Bay of Bengal

## 3. STUDY AREA

According to the available historical sea level data, two different case studies were considered to evaluate the effects and influences of sea level rise on groundwater resources (Fig. 2). The selected two study areas have lot of variations in most of the factors. Not only the sea level rise but also climatic factors such as pattern and amount of rainfall and social factors like population and groundwater use are different in these two study areas.

**(1) Case I: Western American Coast**

In most of the basins in the western coast alluvial-valley, tuffs were deposited along with the basin-fill sediments. Unconsolidated sediments are the main groundwater-yielding deposits in the area. The maximum thickness of unconsolidated permeable deposits in the valleys ranges from approximately 300 to 1,700 m. The areas are rich in surface as well as groundwater resources and even though groundwater recharge is less, it is uniform throughout the year due to the uniform precipitation. Because most of American coastal wetlands are less than one meter above sea level, a large fraction of the coastal wetlands could be threatened by sea level rise[17)]. Based on data of rise in sea level projected by particular scenarios at the particular locations in USA, recent estimates suggest that sea level may be rising 2.0 mm/yr in western coast of America [18)].

**(2) Case II: Bay of Bengal**

Most of the lands in Indian sub continent near the Bay of Bengal consist of low elevation deltas and flood plains. The area mainly comprises crystalline bedrock overlaid by sedimentary layers near the coast. The sedimentary cover mainly composed of sandstone, limestone and clay. Eolian dune sand and beach sands occur along a narrow coastal strip a few hundred meters wide. The groundwater in these coastal aquifers occurs under shallow water table conditions[19)]. Groundwater is the primary potable water source for the most of the coastal regions of the area and the groundwater recharge varies between wide ranges throughout the year[20)]. Past observations on the mean sea level along the Indian coast in the Bay of Bengal indicate a long-term rising trend of about 0.8-1.0 mm/yr on an annual mean basis. However, the recent data suggests a rising trend of greater rate sea level rise along Indian coastline and Bay of Bengal [21)].

## 4. RESULTS AND DISCUSSION

The two selected areas have been simulated with sea level rise of 2.0 mm/yr for western American coast and 0.9 mm/yr for Bay of Bengal. Saltwater intrusion in each hydro-geologic system was evaluated through analyzing the vertical salinity

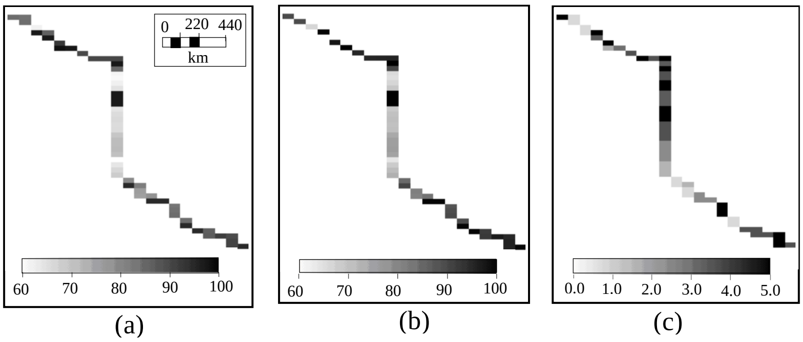


Fig.3 Loss of fresh groundwater resources in western American coast (a) with natural seawater intrusion (without considering sea level effect), (b) with the effect of sea level rise and (c) Difference between (a) and (b) (additional fresh groundwater loss due to sea level rise)

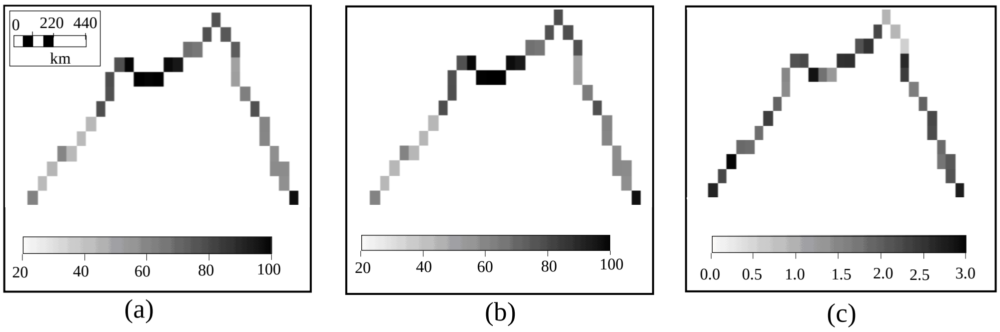


Fig.4 Loss of fresh groundwater resources in Bay of Bengal (a) with natural seawater intrusion (without considering sea level effect), (b) with the effect of sea level rise and (c) Difference between (a) and (b) (additional fresh groundwater loss due to sea level rise)

profile over 100 years period. The simulations were carried out with respect to sea level rise and without considering sea level rise. Uniform groundwater recharge in each pixel, which has a spatial resolution of $0.5^0 \times 0.5^0$ have been taken into account to model 2km wide coastal aquifer. The loss of fresh groundwater resource in 2km wide coastal aquifer, due to salinity intrusion has been estimated in each simulation. Each quadrilateral represents the percentage loss of fresh groundwater resource in 2km × 2km aquifer volume. Fig.3a and Fig.4a show the percentage loss of fresh groundwater resource due to salinity intrusion in both case studies, without considering sea level rise. It shows the loss of fresh groundwater resource in coastal aquifers under natural conditions. Fig.3b and Fig.4b represent the percentage loss of fresh groundwater resource considering the effect of sea level rise. Fig.3c and Fig.4c show the difference between the situations of (a) and (b), which gives the additional fresh groundwater loss due to sea level rise. The additional freshwater loss due to sea level rise in western American coast is around 1% to 5% of the aquifer volume and it is larger than that of Bay of Bengal which shows the freshwater loss of 1% to 3% of aquifer volume.

**(1) Effects of sea level rise on freshwater supply**

Even though the freshwater loss is less in Bay of Bengal than western American coast, the influences of the loss of water resources is more effective in Bengal area which has high population. It is severe in the regions with less land and surface water resources. Most of the areas in Bay of Bengal, groundwater is the main water resources. Although this area has favorable hydro-geological conditions, various constraints limit the availability of fresh groundwater. These mainly include the salinity intrusion. Considering the prediction of water demand and population growth, the groundwater use in Bengal area is estimated approximately as 40l/cap/day[17)]. The loss of fresh groundwater resources due to sea level rise over 100 years period in 2km × 2km aquifer in Bay of Bengal coastal area can be estimated as $4\times10^6 m^3$ to $12\times10^6 m^3$ and this amount of fresh water would be sufficient to serve around 2700 to 8000 populations to satisfy their water demand. Therefore, it can be simply predicted that around 2700 to 8200 people will be directly influenced by the loss of freshwater due to sea level rise in 2km × 2km area in Bengal region. In western American area the groundwater use is higher than that in Asian countries due to higher living standards. In the state of Washington it is reported as 460 l/cap/day[14)]. Based on this demand, the number of affected people due to loss of fresh groundwater in a 2km × 2km area in western American coast can be estimated as 250 to 1200. A comparison of the situation of water resources in both regions is shown in Table 1.

Table 1. Comparison of two case studies.

| | Case study area | |
|---|---|---|
| | Western American Coast | Bay of Bengal coast |
| Avg. Annual Precipitation | 1180 mm | 1900 mm |
| Avg. Ann. groundwater recharge | 524 mm | 960 mm |
| Sea level rise | 2.0 mm/year | 0.9 mm/year |
| Fresh groundwater loss due to sea level rise (percentage of aquifer volume) | 1% - 5% | 1% - 3% |
| Groundwater use | 460 l/cap/day | 40 l/cap/day |
| Affected people in 2km*2km area by loss of freshwater due to sea level rise | 250-1200 | 2700-8200 |

### (2) Impacts of reduction in groundwater recharge

The seasonal change in groundwater recharge was not taken into the consideration in the simulation process. Even though recharge was not taken into account for this analysis, loss of fresh groundwater will be affected by not only sea level rise, but also changes in natural recharge. According to the climate change predictions, IPCC[2)] reported that temperature would increase throughout the most of the regions in tropical Asian region, including Bay of Bengal area and the rainfall indicated a tendency for an increase in wet season and decrease in dry season. Karl et al found that temperature increased greatly over the western part of the American continent and a reduction in annual precipitation of 10%-20% [22)]. According to these climate change trends, it can be expected a decrease in groundwater recharge in both case study areas.

The effect of change in groundwater recharge was simulated considering reduction of groundwater recharge as percentage of present recharge. In this estimation, two simulations were carried out with same hydro geological properties (hydraulic conductivity value) and two different recharge and sea level rise. Considering the distribution of estimated annual groundwater recharge in each pixel, the present groundwater recharge was estimated as the average value of the annual groundwater recharge of both areas. It is 524 mm/year for western American coast and 960 mm/year for the Bay of Bengal. Fig.5 shows the change in the loss of fresh groundwater resource due to change in groundwater recharge with and without the effect of sea level rise in western American coast and Bay of Bengal regions with hydraulic conductivity of $10^{-3}$m/s. It shows that the fresh groundwater loss with the effect of sea level rise and without the effect of sea level rise, increase with the reduction of groundwater recharge. If the groundwater recharge reduces by 20% of the present recharge in each area, it affects around 2.7% increment from the present value of the loss of fresh groundwater resource with the effect of sea level rise and 2.35% without the effect of sea level rise in Bay of Bengal, while it is 1.85% and 1.5% in western American coast. It shows that the reduction in groundwater recharge severely affects to reduce the fresh groundwater resource in Bay of Bengal region than in western American coast, because groundwater recharge is the main factor to control salinity intrusion in Bay of Bengal area, and the stress of the reduction of groundwater recharge on salinity intrusion is higher in this area. The stress of the reduction of groundwater recharge is less, but the effect of sea level rise is greater in the western American area. The seasonal variation in groundwater recharge will significantly affect the change in loss of fresh groundwater resource in the Bengal region which has a wide range of variation in groundwater recharge over the year.

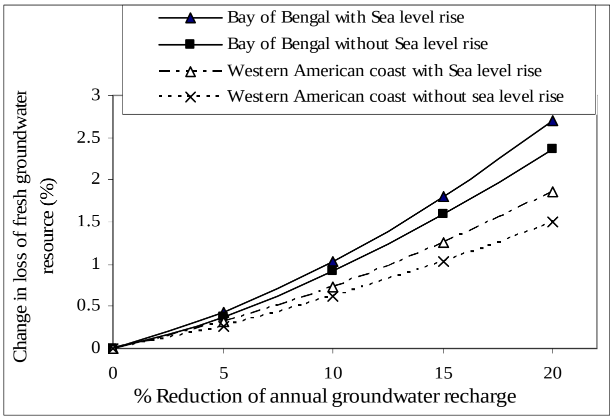


Fig.5 Change in loss of fresh groundwater resource with the reduction of groundwater recharge

The adaptation procedures for the loss of fresh groundwater resources due to sea level rise can be evaluated based on number of affected people, freshwater demand and the reduction in groundwater recharge in both cases. In western American region, the reduction of per capita water use will be lead to utilize the available fresh groundwater resource for more populations. Water policies can be redirected towards reducing water demand and recycling and reuse. Another approach can be adapted using price intensives to encourage water savings. In Bay of Bengal area, the water demand is in the lower margin and cannot be reduced, but water wastage can be prevented. Also the efficiency of the water use such as the efficiency of the distribution networks and irrigation efficiency can be increased. Since reduction of groundwater recharge affects severely on the loss of freshwater in both cases (see Fig.5), another adaptation procedure is increasing the groundwater recharge to achieve a higher and uniform recharge throughout the year. Taking these into account, intrusion of seawater can be counteracted by technical counter measurements such as creating recharge areas or artificial recharge by deep well infiltration of freshwater in that area.

## 5. CONCLUSIONS

The effect of sea level changes on the distribution of saltwater and freshwater in the western American coastal plain and Bay of Bengal has been analyzed using finite difference model. Vertical profile of the interface was simulated in both case studies. Rising sea level causes the interface to be shallower and to extend farther landward. Freshwater loss due to sea level rise over 100 years is estimated in each case study using a conceptual aquifer strip of 2km width. It shows that the percentage fresh water loss due to sea level rise varies between 1%-5% of the aquifer volume in western coast of America and 1%-3% in Bay of Bengal.

The results further show that, even though the effect of sea level rise is higher in high latitudes than mid latitudes and equatorial areas, the influences of the loss of fresh groundwater resource is more severe in mid latitude and equatorial areas which has arid and semi arid climates, large diversity of seasonal climate, high population density and higher demand for groundwater resource. The combined influence of the reduction in groundwater recharge and the sea level rise shows that there is an increase in the loss of fresh groundwater resource with the reduction of groundwater recharge due to future climate change. These results suggest that sea level rise could be a significant problem and hence it needs to be considered within the policy process in terms of mitigation as well as adaptation.

**ACKNOWLEDGEMENT**: The authors would like to acknowledge the Grant-in-Aid for Scientific Research by Prof. Nobuo Mimura and the Feasibility Study Foundation of NISE by Dr. Harasawa.

**REFERENCES**

1) Michener, W.K., Elizabeth, R., Keith, L., Bildstein, K.L., Brinson, M. and Gardner, L.R., Climate change hurricanes and tropical storms and rising sea level in coastal wetlands, *Ecological Applications*, 7, pp 770-801, 1997.
2) IPCC, The Regional Impacts of Climate Change: An Assessment of Vulnerability; *A Special Report of IPCC Work group*, Cambridge University Press, UK. Pp517, 1998.
3) Meisler, H., Leahy P.P., and knobel L.L.,, Effect of Eustatic Sea-Level Changes on Saltwater-Freshwater Relations in the Northern Atlantic Coastal Plain. *U.S. Geological Survey-Water-Supply Paper No.2255*, 28 pp, 1984.
4) Oude Essink and G.H.P., Impact of sea level rise in the Netherlands, *Seawater intrusion in coastal aquifers; Concepts, Methods and Practices,* edited by J.Bear et al Kluwer Acad., pp 507-530, 1999.
5) Kooi, H. and Groen, J., Modes of seawater intrusion during transgressions, *Water Resources Research,* Vol 36/12, pp 3581-3589, 2000.
6) Reilly, T.E. and Goodman, A.S., Quantitative analysis of fresh-salt water relationship in groundwater systems- A historical perspective, *J. of Hydrology* ,80, 125-149, 1985.
7) Wilson, J.L. and Sa Da Costa, A., Finite element Simulation of Salt-fresh water interface with indirect toe tracking, *Water Resources Research*, 18, 1069-1081, 1982.
8) Polo, J.F. and Ramis, F.J.R., Simulation of Salt-fresh water interface model, *Water Resources Research*, 19, 1983.
9) Essaid, H.I., A Multilayered sharp interface Model of coupled freshwater and saltwater flow in coastal systems: Model development and application, *Water Resources Research*, 26, 431 -1455, 1990.
10) Mahesha, A., Nagaraja, S.H., Effect of natural recharge on sea water intrusion in coastal aquifers, Journal of Hydrology, 174, 211-220, 1996.
11) Bear, J., Hydraulics of Groundwater, McGraw-Hill, New York, 1979.
12) Bear, J., Cheng, A.H.D., Sorek, S., Ouazar, D., and Herrera,I., Seawater Intrusion in Coastal Aquifers- Concepts, Methods and Practices, 1999.
13) Remson, I., Hornberger, G.M. and Molz, F.I., Numerical methods in subsurface hydrology: with an introduction to the finite element method, pp389, 1971.
14) USGS groundwater data, (http://water.usgs.gov/pubs/circ /2004/circ1268/htdocs/table05.html)
15) WISE data, A homogenized soil profile data set for global and regional environment research, *International Soil Reference and Information Centre*, ISRIC, 2002.
16) NOAA-EPA , Global Ecosystems database, (http://www. ngdc. noaa.gov/seg/cdroms/ged_iia/dataset/a04/lw. Html)
17) Hoffman, J.S., D. Keyes, and J.G. Titus. *Projecting Future Sea Level Rise*. U.S. Env Protection Agency, 1983..
18) Ryan, H. F. and Noble, M., Sea level response to ENSO along the central California coast: how the 1997–1998 event compares with the historic record, *Progress In Oceanography,* Vol 54, pp 149-169, 2002.
19) Gnanasundar, D., and Elango, L., Groundwater quality assessment of a coastal Aquifer using geo-electrical techniques, *Journal of Environmental Hydrology,* vol.7, 1999. (http://www.hydroweb.com)
20) UN, Guidebook to water resources, use and management in Asia and the Pacific. *Water Resources Series*, No.74, 1995.
21) Lal, M. and Aggarwal, D. Climate change and its impacts in India, *Asia-Pacific Journal of Env & Development*, 2000.
22) Karl, T.R., R.W. Knight, Easterling, and R.G. Quayle, Indices of climate change for the United States. *Bulletin of the American Meteorological Society,* **77**, 1996.

**(Received September 30, 2004)**