Effect of climate change on coastal fresh groundwater resources

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Abstract

Changes in key climatic variables could significantly alter groundwater recharge for aquifers and thus affect the availability of fresh groundwater in the region. This study assesses the implications of climate change for groundwater recharge and then the effect of change in groundwater recharge and sea level rise on the loss of coastal fresh groundwater resources in the selected water resources stressed areas; Central America, Southern Africa, Northern Africa, the Mediterranean and in the Southern Asia. To estimate the freshwater loss in coastal aquifers due to salinisation, a conceptual model based on the sharp interface assumption has been considered. The climate assessment uses Hadley Centre climate model, HadCM3 with higher emission scenario, SRES-A2. Among the five selected water resources stressed areas, the relationships of loss of fresh groundwater resources highlight a rough increase in loss of fresh groundwater resources except northern Africa region. The correlation between the change in precipitation, temperature and loss of fresh groundwater resource shows that the precipitation and temperature individually does not show a good correlation with loss of fresh groundwater resources. Therefore combined effect of precipitation and temperature has been considered through the aridity index. It concludes that aridity index versus loss of fresh groundwater resources exhibits a global negative correlation. The scattered plot of aridity index versus loss of fresh groundwater resource clearly shows a regional distribution. The aridity index is less than 15 in both central American and northern Africa regions which shows higher fresh groundwater loss. A wide range of aridity index (15 – 60) appears and the loss of fresh groundwater resources is comparatively less in Mediterranean region.

Keywords: coastal aquifers, fresh groundwater resources, climate change, SRES A2.

1. Introduction

Atmospheric carbon dioxide levels have recorded continual increases since the 1950s. This phenomenon may significantly alter global and local climate characteristics. The change in climate has a profound effect on hydrological cycle through precipitation, evapotranspiration, soil moisture etc. Studies on global warming and its effect on climatic change are being pursued as a multi-disciplinary problem, especially for hydrology and global water resources (Arnell, 1999, 2004; Hulme, 1999; Eckhardta and Ulbrichb, 2003; Hitz and Smith, 2004). Information on the local or regional impacts of climate change on hydrological processes and water resources over different areas in the world is becoming more interesting. Previous studies have usually suggested climate change scenarios coupled with hydrological models, and have generally used these to investigate the impact of climate change on water resources in different areas Among these assessments, DETR (1997) and Arnel (1999) indicated and mapped the areas experiencing water resource stress due to the future climate changes. Stressed countries are concentrated in southern and northern Africa, around the Mediterranean and in the Middle East, southern Asia and the Indian subcontinent, central America and large parts of Europe.

When considering the water resource in coastal zones, coastal aquifers are very important resource of freshwater, but salinity intrusion is one of the major problems there. Salinity intrusion replaces the freshwater in coastal aquifers by saltwater and leads to a reduction of available fresh groundwater resource. Change in groundwater recharge directly affects the changes in fresh groundwater resources. Subsequently, the salinisation of coastal aquifers will accelerate due to the reduction of groundwater recharge and it could mean a reduction of fresh groundwater resources.

The climate change studies, determined from different GCM scenarios, indicate that the global warming has clearly been increasing during recent decades and that the trend may worsen in the future. Considering the complex mechanics at work in the atmosphere and the uncertainty of the model structure, this study concerns the results from Hadley center GCM (HadCM3) with SRES A2 scenario, for the estimation of future climate changes. Among the scenarios in SRES storylines scenario A2 has the largest population in 2100 and the greenhouse gas concentrations used in the climate simulations SRES-A2 emission scenario assumes comparably strong increases (IPCC, 2001, Semmler and Jacob, 2004).

2. Methodology and data sources

2.1 Numerical modeling of salinity intrusion

Many models have been developed to study the problem of saltwater intrusion. They range from relatively simple analytical solutions to complex numerical models. Recently the studies involving the movement of freshwater and saltwater in coastal aquifer systems are classically studied using two different approaches (Reilly and Godman, 1985). In the first approach, freshwater and saltwater are assumed completely immiscible and a sharp interface exists between these two phases. In the other approach, the freshwater and saltwater are assumed to be in a dynamic equilibrium resulting from the flow and dispersion mechanisms within the aquifer. Since the main aim of this study, is to evaluate the long term overall behavior of the coastal groundwater systems due to the effect of global warming, we follow the sharp interface concept to estimate the salinity intrusion to coastal aquifers and hence to evaluate the loss of fresh groundwater resources in the aquifer.

Sharp interface models couple the freshwater and saltwater flow based on the continuity of flux and pressure. 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 (Bear*,* 1999).

$$\frac{\partial}{\partial x}\left[K_{fx}\left(h^f-h^i\right)\frac{\partial h^f}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{fy}\left(h^f-h^i\right)\frac{\partial h^f}{\partial y}\right]+q_f=S_f\frac{\partial h^f}{\partial t}-\theta\left[\left(1+\delta\right)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right]+\alpha\theta\frac{\partial h^f}{\partial t} \qquad (1)$$

$$\frac{\partial}{\partial x}\left[K_{sx}\left(h^i-z^b\right)\frac{\partial h^s}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{sy}\left(h^i-z^b\right)\frac{\partial h^s}{\partial y}\right]+q_s=S_s\frac{\partial h^s}{\partial t}+\theta\left[\left(1+\delta\right)\frac{\partial h^s}{\partial t}-\delta\frac{\partial h^f}{\partial t}\right] \qquad (2)$$

The location of the interface elevation (h^i) 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 ρ_f and ρ_s are specific weight in fresh and salt water respectively, h^f and, h^s are the piezometric heads of freshwater and saltwater regions, q_f and q_s are flow rate in fresh and salt water respectively. K_f and, K_s represent the hydraulic conductivity in fresh and salt water regions. Storage coefficients in fresh and salt water regions are given by S_f and S_s respectively. θ is the porosity of the aquifer media. α = 1 for unconfined aquifer and α = 0 for confined aquifer.

From equations (1) and (2), it is possible to derive a numerical model using implicit finite difference techniques. To solve the two simultaneous linear algebraic difference equations, the Strongly Implicit Procedure -SIP (Remson *et al*, 1971) was used as a suitable numerical technique. Empirical evidence suggests that for cases of flow in heterogeneous or anisotropic media, the strongly implicit procedure is much faster than the other methods. Also the strongly implicit method does not depend upon the complexity of the problem (Essaid 1986). The sharp interface model has been utilized to simulate the movement in freshwater saltwater interface due to the change in groundwater recharge and sea level change as a result of global warming.

2.1.1. Fresh groundwater loss due to salinisation

The concept of interface between freshwater and saltwater can be used to estimate the amount of fresh groundwater resources in coastal aquifers. Increase in groundwater recharge leads to move the salinity interface seaward and decrease in recharge leads to move it landward. This movement of salinity interface due to the changes in recharge creates the changes 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, 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%.

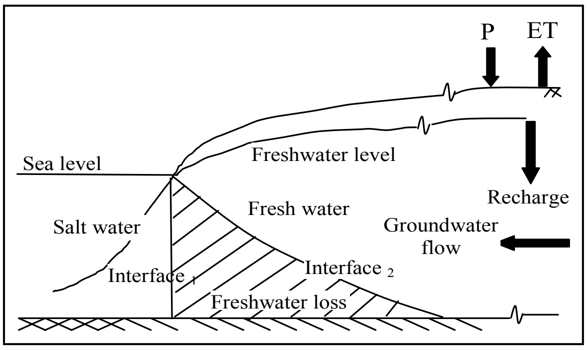

Fig. 1. Loss of fresh groundwater resource due to salinisation

2.3 regions with water resource stress

Five major coastal regions, experiencing water stress have been considered for this study; Central America (CAM) Southern Africa (SAF) and Northern Africa / Sahara (SAH), around the Mediterranean (MED) and in the Southern Asia (SAS) have been selected to assess the change in fresh groundwater resource due to salinity intrusion as a result of global warming (Fig 2). Furthermore, these regions can be categorized into different climate groups and different rates of sea level rise.

Fig. 2. Selected water resource stressed areas (Aller et at , 1999)

2.4. Estimation of loss of fresh groundwater resource to due climate changes

The study uses climate change scenarios developed from Hadley Centre climate simulations (HadCM3). The climate data is available at a spatial resolution of 2.5^0 of latitude by 3.75^0 of longitude. In this coarse resolution, study areas only represented by a few grids and the grids in the seaward boarder have been selected to represent the regional climate for the evaluation. We use a water balance model, which calculates the components of the water balance at a monthly time-step, treating each cell as a separate catchment. The estimated monthly recharge, for the period 2000-2099, has been employed to calculate the average annual fluctuation in freshwater- saltwater interface in coastal aquifers in selected five regions. Mean average change in freshwater-saltwater interface has been used to estimate the annual variation in loss of fresh groundwater resources due to salinity intrusion in theses aquifers and the percentage loss was estimated as explained in section 2.1.1. The model is run to simulate 100 years of changes in fresh groundwater resource at a monthly time step, although annual totals only are saved as output.

3. Results

Future fluctuations of loss of fresh groundwater resource clearly indicate a trend of long-term increase, except in northern Africa / Sahara region. Over the 100 years period, the linear regression between loss of fresh groundwater resource (percentage loss) versus time shows different regional scale relationships for five selected regions. As shown in Fig 3a, inter-annual mean fluctuation of loss of fresh groundwater resource display short term trends in Mediterranean and southern Asian regions, while showing long term trends in other three regions. The Mediterranean region shows short term increments and gives overall long term increase of 0.028 percentage of loss of fresh groundwater resource per year. Southern Asian region also shows two remarkable short term variations and on overall long term change trends with a gradient of 0.075 percent increase in loss of fresh groundwater resources per year. The central American and southern African regions indicate long term changes of 0.015 and 0.027 percent increase in loss of fresh groundwater resources per year. In northern Africa / Sahara region, a slight negative gradient can be observed; a gradient of 0.002 percent decrease in loss of fresh groundwater resources per year. This remarks an increase in availability of fresh groundwater resource in coastal zones in northern Africa and Sahara region.

Considering the selected five water resources stressed regions, change in groundwater recharge allows the changes in the available fresh groundwater resource over future 100 years, providing new insight into temporal succession of fluctuations in climate factors, especially precipitation. Precipitation is the primary source of groundwater recharge and it is the largest term in the water balance equation, and varies both temporally and spatially. Hence, changes corresponding to the future precipitation emphasized the fluctuations of loss of fresh groundwater resources. It can be noticed that the annual variation of loss of fresh groundwater resource is well matched with the changes in precipitation and reproduces the relative changes (Fig 3b). The increases and decreases in precipitation are followed by a succession of reduction and increments in loss of fresh groundwater. These changes can be clearly identified in southern Asian region and Mediterranean region, which show large fluctuations in inter-annual precipitation. However, northern Africa / Sahara region shows that the precipitation will be increased in the future. The changes in temperature also show trends of increasing in annual mean temperature in all five areas (Fig 3c). However, we do not see a clear relationship between increases in temperature and loss of fresh groundwater resource.

4. Discussion

4.1 Regional variations with respect to aridity index

To evaluate the correlation of climate factors with the loss of fresh groundwater resource in each region, the change in precipitation and temperature have been considered. Figure 4a shows the correlation between the change in precipitation and changes in loss of fresh groundwater resource, while Fig. 4b shows the correlation between the change in temperature and changes in loss of fresh groundwater resource. It indicates that, only the Mediterranean and southern Asian region give good correlation between the precipitation and the loss of fresh groundwater resource, with a correlation coefficient of 0.92 and 0.78 respectively.

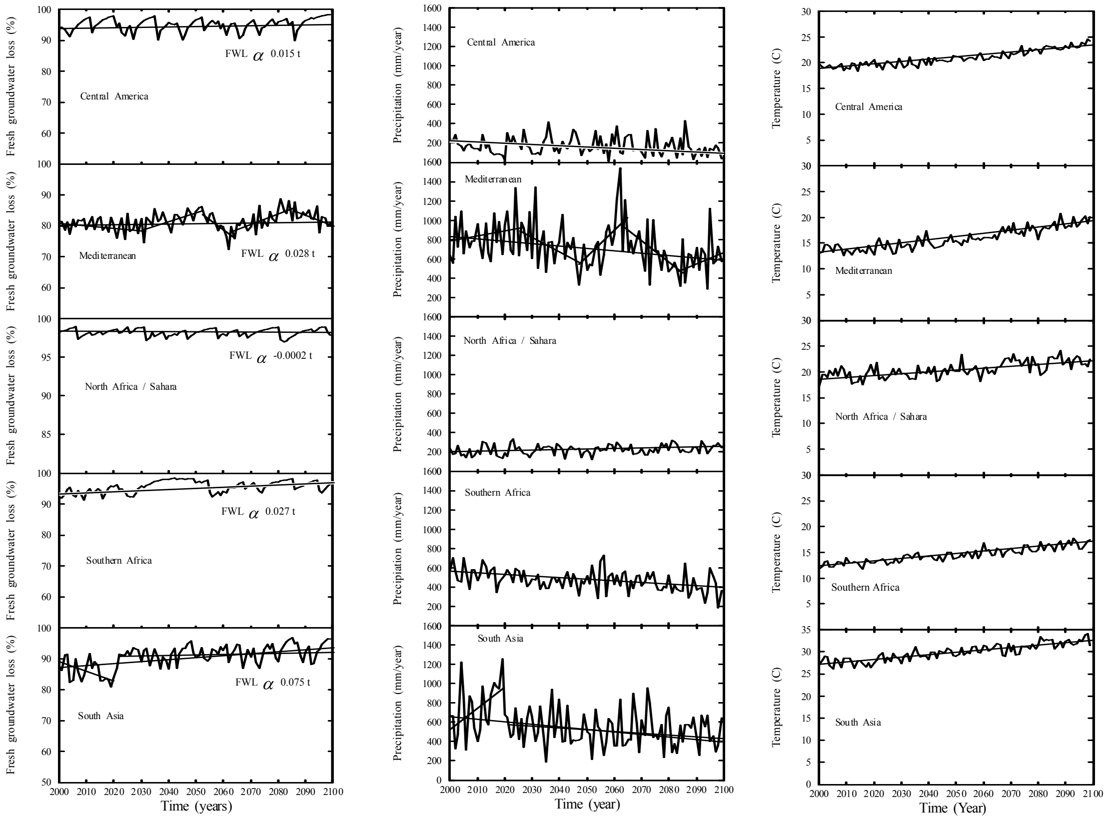

Fig 3. Average annual variation of (a) loss of fresh groundwater resource, (b) precipitation and (c) temperature

The Mediterranean and southern Asian region show wide range in change in precipitation (over ± 400 mm/year) and it leads to vary the loss of fresh groundwater resource in wide range, whereas the change in precipitation and relevant change in fresh groundwater resource is very small in north African region. In the Mediterranean region, which is affected with Mediterranean climate, receives precipitation primarily due to mid-latitude cyclones during winter season and it varies widely. Also in southern Asian region which has tropical and monsoon climate, the main source of precipitation is monsoon rain and the annual precipitation varies widely. In the southern Asian area, the Himalayas play a critical role in the provision of water to continental monsoon Asia and seasonal variability in precipitation can be observed. Johns et al (2003) shows that the spatial patterns in change in both temperature and precipitation are very similar in similar latitudes. He also explained that the annual precipitation increases in high latitudes while the precipitation increases in winter across most mid-latitude regions and the temperature increases are greater at high latitudes. However, the correlation between temperature and change in fresh groundwater resources is very poor in all regions. In overall point of view, the correlation coefficients emphasize that the precipitation and temperature individually do not show a good correlation with the loss of fresh groundwater resources. Therefore the combined effect of precipitation and temperature has to be considered for the analysis.

To represent the relationships between combined effects of regional climate factors (mainly precipitation and temperature) and loss of fresh groundwater resource, a well-known climatic index; aridity index has been used. Aridity indexes are quantitative indicators of the degree of water deficiency present at a given location and it expresses the effect of water and energy in the region. Although the term *Aridity Index* specifically refers to the specified purposes, it has been applied at continental and sub-continental levels. Aridity index was a ratio between mean annual precipitation and mean annual temperature (Lang's index) and a modified version done by E. de Martonne in 1925 is widely used and it also called as “Martonne index” (Oliver and Fairbridge, 1987, Pahari and Murai, 1999).

Martonne’s aridity index is defined by;

$$AI = \frac{P}{T + 10} \tag{4}$$

Where T is mean annual temperature (^{0}C) and P is mean annual precipitation (mm)

As shown in Fig 4c, the aridity index versus loss of fresh groundwater relationship exhibits a global negative correlation. The correlation coefficients imply that the changes in climate and loss of fresh groundwater resource have good correlation in the central American, Mediterranean, southern African and southern Asian regions, which give correlation coefficient of 0.65, 0.87, 0.62 and 0.8 respectively. In the northern Africa / Sahara region, the correlation between climate and loss of fresh groundwater resource leads to poor results. However the variations in climate and impacts on fresh groundwater resource are very small and it appears to be inconsistent estimates of changes in regional precipitation and temperature in northern Africa / Sahara region.

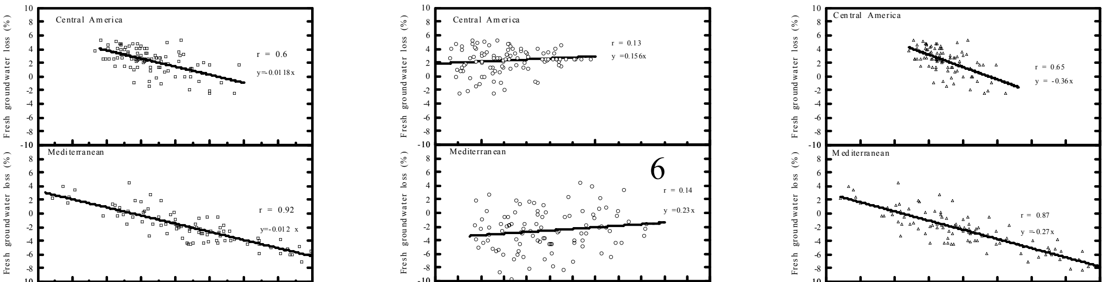

Fig. 4. Correlation between (a) precipitation versus loss of fresh groundwater resource (b) temperature versus loss of fresh groundwater resource and (c) aridity index versus loss of fresh groundwater resource

The regional variation of the absolute value of the aridity index and volumetric loss of fresh groundwater resource (fresh groundwater loss per unit area) can be identified from the scatter plot in Fig. 5. It clearly shows that the distribution of aridity index versus loss of fresh groundwater resources is characterized by scattered distribution in different ranges according to the climatic zones. The low aridity index, which gives relatively higher loss of fresh groundwater resource, can be observed in central America and northern Africa / Sahara regions. In both areas, the aridity index is less than 15, but the highest loss of fresh groundwater resource can be observed in northern Africa / Sahara region. Central American region located in tropical climate zone and northern Africa / Sahara region has desert areas and the precipitation is very low in both regions, having average annual precipitation less than 200 mm/year. In north African and Sahara region, the rainfall may become more intense, but there will be more extreme events with average monthly temperatures above 30°C during the warmest months and extremes above 50°C (IPCC,1998). The aridity index varies through wide range from 15 to 60 in Mediterranean region and the loss of fresh groundwater resource also less in this area. The changes in precipitation on different regions of the Mediterranean can be classified according to the current and projected distributions of rainfall.

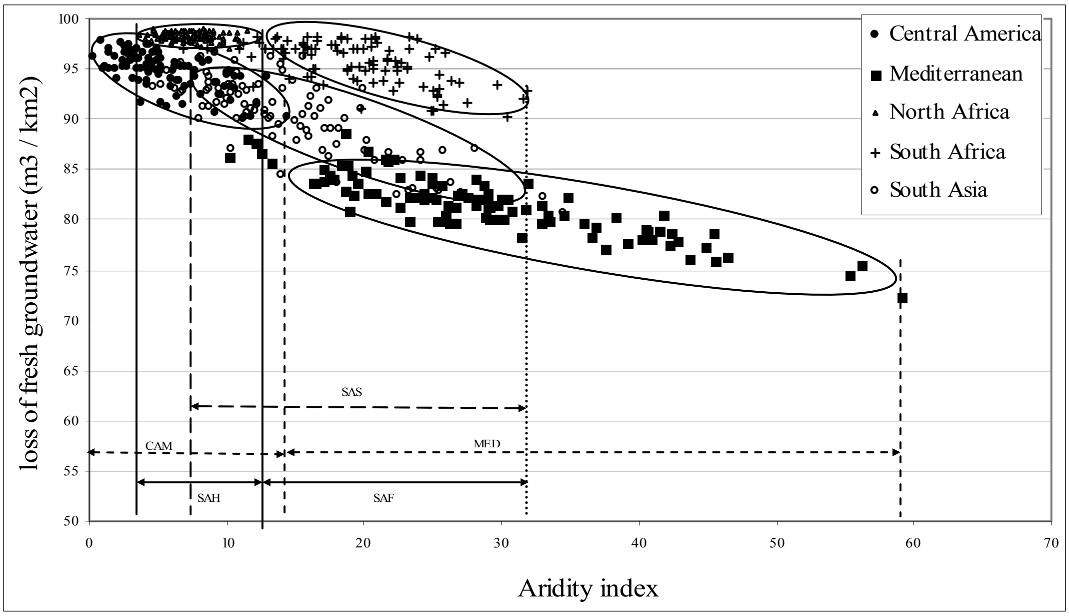

Fig. 5. The scatter plot of the change in aridity index and loss of fresh groundwater resource in different climate regions

5. Conclusions

The investigation of the relationship between climate change and loss of fresh groundwater resource is important for understanding the characteristics of the different regions and for forecasting ongoing changes. Among the five selected water resources stressed areas, the relationships between precipitation, temperature and the loss of fresh groundwater resource highlight the complexity of the hydrological consequences, but still indicate a rough increase in loss of fresh groundwater resources except northern Africa and Sahara region.

The correlation between the change in precipitation versus changes in loss of fresh groundwater resource and the change in temperature versus changes in loss of fresh groundwater resource may lead to poor results. These correlations might be positive or negative at the continental scale, which indicates the high complexity of the feedback of precipitation and temperature changes on the hydrological cycle at the regional scale. The correlation coefficients are emphasized that the precipitation and temperature individually does not show a good correlation with loss of fresh groundwater resources and the combined effect of precipitation and temperature has been considered for the further analysis. The aridity index has been used to evaluate the combined effect of regional climate condition. The evaluation concludes that aridity index versus loss of fresh groundwater resources exhibits a global negative correlation. The scattered plot of aridity index versus loss of fresh groundwater resource shows a regional distribution in the scattering points. The aridity index is less than 15 in both central American and northern Africa / Sahara regions which shows higher fresh groundwater loss. A wide range of aridity index of 15 – 60, appears and the loss of fresh groundwater resources is comparatively less in Mediterranean region.

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