EFFECTS OF CLIMATE AND LAND USE CHANGES ON GROUNDWATER RESOURCES IN COASTAL AQUIFERS

S. PRIYANTHA RANJAN[1*], SO KAZAMA[2] , MASAKI SAWAMOTO[3]

[1]Department of Civil Engineering,
Graduate School of Engineering,
Tohoku University
Aoba yama 06,
Sendai, 980-8579,
Japan.
Email: ranjan@kaigan.civil.tohoku.ac.jp

[2] Graduate School of Environmental Studies,
Tohoku University
Aoba yama 06,
Sendai, 980-8579,
Japan.
Email: kazama@kaigan.civil.tohoku.ac.jp

[3]Department of Civil Engineering,
Graduate School of Engineering,
Tohoku University
Aoba yama 06,
Sendai, 980-8579,
Japan.
Email: sawamoto@kaigan.civil.tohoku.ac.jp

* Corresponding Author

S. PRIYANTHA RANJAN
Department of Civil Engineering,
Graduate School of Engineering,
Tohoku University
Aoba yama 06,
Sendai, 980-8579,
Japan.

Tel: +81-22-217-7459 (office)
+81-90-3641-1196 (residence)
Fax: +81-22-217-7458
Email: ranjan@kaigan.civil.tohoku.ac.jp

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Abstract

To estimate the freshwater loss in coastal aquifers due to salinisation, a numerical model based on the sharp interface assumption has been introduced. The developed methodology will be useful in areas where limited hydrological data is available. This model will elaborate on the changes in fresh groundwater loss with respect to the climate change, land use pattern and hydrologic soil condition. The aridity index has been introduced to represent the variations in precipitation and temperature. The interesting finding is that the deforestation leads to increase groundwater recharge in arid areas, because deforestation leads to reduce evapotranspiration even though it favors runoff. The combined climate and land use scenarios show that when aridity index is less than 60, the agricultural lands give higher groundwater recharge than other land use patterns for all hydrologic soil conditions. Calculated recharge was then used to estimate the freshwater-saltwater interface and percentage of freshwater loss due to salinity intrusion. We found that in arid areas, the fresh groundwater loss increases as the percentage of forest cover increases. The combined effects of deforestation and aridity index on fresh groundwater loss show that deforestation causes the increase of the recharge and existing fresh groundwater resource in areas having less precipitation and high temperature (arid climates).

Keywords: Salinity intrusion, Freshwater loss, Climate change, Land use

1. Introduction

Freshwater is a scarce resource. According to the World Meteorological Organization, only 2.5 percent of the total water volume on earth is fresh water and the remainder is saline. The largest available source of freshwater still lies under ground and the availability of surface water becomes limited in many areas in the world. To meet the ever increasing water demand in the world, groundwater is being extensively used to supplement the available surface water. When considering the water resource in areas bordering seas, coastal aquifers are very important resource of freshwater. The use of coastal aquifers as operational reservoirs in water resources systems requires the development of tools that facilitate the prediction of the aquifer behavior under different conditions. Since groundwater systems in coastal areas are in contact with saline water, one of the major problems is the prediction of the saltwater body motion in the aquifer. Already at this moment, many coastal aquifers in the world, especially shallow ones, experience an intensive salt water intrusion caused by both natural as well as man-induced processes. The quantitative understanding of the patterns of movement and mixing between freshwater and saltwater, as well as the factors that influence these processes, are necessary to manage the coastal groundwater resources. Studies on the freshwater-saltwater interface either in steady or transient conditions have become necessary in designing and planning of groundwater systems in coastal areas.

In nature the freshwater-saltwater interface seldom remains stationary. Large scale recharging into the aquifer as well as withdrawals from the aquifer, result in the movement of the interface from one position to another. The movement will be advancing or retreating depending on whether the freshwater flow through the aquifer is decreased or increased. 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. This could mean a reduction of fresh groundwater resources. Changes in climatic factors, such as precipitation and temperature and the land use change are very important part of the hydrologic balance. It is imperative to understand the process when planning salinity management strategies. Under such circumstances it is important to study the rate of movement of the salinity interface and predict the shape of the interface profile due to changes in recharge or discharge of groundwater and related activities such as climate changes and change in land use pattern (Mahesha and Nagaraja, 1996, Lambrakis and Kallergis, 2001, Cartwright *et al*, 2004).

The main objectives of this study are to understand the dynamics of the freshwater- saltwater interface due to salinity intrusion and to evaluate the effects of climatic and land use changes on the fresh groundwater resources in coastal aquifers.

2. Materials and methods

2.1. Numerical modeling of the movement of freshwater – saltwater interface

Many models have been developed to represent and to study the problem of saltwater intrusion. These models range from relatively simple analytical solutions to complex numerical models. 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. After introducing Ghyben - Herzberg principle, several analytical solutions were published to describe various forms of boundary conditions of cross sectional systems. Glover (1959) presented an approximated analytical solution considering the seepage flow at the seaward boundary. Van Der Veer (1977) presented an analytical solution to determine the steady position of the interface, accounting the fresh groundwater flow towards the sea. Bear (1979, 1999) provides excellent mathematical descriptions of the problems related to seawater intrusion in coastal aquifers.

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.

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 result in the following system of differential equations (Bear, 1979).

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

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

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, 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 in fresh and salt water regions. Storage coefficients in fresh and salt water regions are given by S_f and S_s respectively. δ is defined as $\delta = \rho_f / (\rho_s - \rho_f)$ and θ is the porosity of the aquifer media. α = 1 for unconfined aquifer and α = 0 for confined aquifer.

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 in order to obtain approximate solutions. The sharp interface models which solve the coupled freshwater and saltwater flow equations have been developed with different numerical techniques (Shamir and Dagan, 1971; Vappicha and Nagaraja, 1976). A finite element method solution with indirect toe tracking technique was presented by Wilson and Sa Da Costa (1982). Polo and Ramis (1983) discussed an unconditionally convergent finite difference approach to solve sharp interface problem. A sharp interface model which solves the coupled freshwater and saltwater flow equations has been developed and it was successfully applied to evaluate multilayered aquifer systems by Essaid (1986, 1990).

From equation (1) and (2), it is possible to derive a numerical model using implicit finite difference techniques. The continuous system described by above two equations are replaced by finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in both freshwater and saltwater head values at these points. Spatial discretization is achieved using a block entered finite difference grid which allows for variable grid spacing. 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 model accommodates the aquifers with spatially variable hydro-geological properties. The main hydro-geological inputs are hydraulic conductivity, porosity and the specific storage of the porous media. Temporal and spatial variations in groundwater recharge are also accounted as main inputs. The freshwater and saltwater mass balances can be simultaneously calculated using the initial freshwater and saltwater heads, porous media properties and groundwater recharge. The interface elevation h^i, can be determined for each grid point using equation (3).

2.2. Parameter estimation: Effect of hydro-geological properties and groundwater recharge on salinity intrusion

To investigate the effect of hydro geologic factors mainly, specific storage, porosity and hydraulic conductivity on the dynamics of the freshwater-saltwater flow systems, a horizontal strip through an unconfined aquifer has been simulated by changing the hydro geological properties while observing the system's transient responses. Both specific storage and porosity represent the volume of saltwater that must flow into the system from the sea to replace the freshwater removed from the system. The effect of the specific storage was evaluated by increasing the storage coefficient by orders of magnitude. The change in storage coefficient does not affect the location of the interface. The system responds in almost same manner for different specific storage values because most of the water to fulfill the changes in storage is coming from the drainage of water table rather than elastic storage.

The other factor which illustrates the storage of the aquifer is the porosity. To investigate the effect of porosity on the behavior of the flow system, the porosity was changed from 0.1 to 0.4 in increments of 0.1. The change in the porosity does not lead to change the position of the interface. It leads to a change in the time period in order to achieve the steady state of the interface. Fig. 1 shows the time taken to achieve the steady state interface at 500m away from the coastline. Reduction in porosity accelerates the movement of the interface and drives the system to steady state over a shorter time period and finally it reached to same interface depth for different porosities. Theoretically it can be explained as the freshwater heads fall to steady state more rapidly since less water must drain from the pores and the interface change more rapidly (Essaid, 1986).

<u>Approximate location of Fig. 1</u>

Another factor affecting the change of the position of freshwater-saltwater interface is hydraulic conductivity. The hydraulic conductivity was changed over the range of 10^{-3} m/s to 10^{-4} m/s. Those values are in the hydraulic conductivity range for clean sand or basalt aquifers (Freeze and Cherry, 1979). Fig. 2 explains that the changes in hydraulic conductivity have quite an impact on the steady position of the interface. The change in hydraulic conductivity makes the changes in the transmissivity and it affects the head gradients necessary to maintain the freshwater flux. This process showed that the model is more sensitive with respect to changes in hydraulic conductivity than other hydro-geological factors.

<u>Approximate location of Fig. 2</u>

The effect of groundwater recharge on the dynamics of the freshwater-saltwater interface can be understood most readily by considering a simple, finite ground water flow system in which the only source of recharge is from precipitation and all discharge is to the ocean. To represent the effect of groundwater recharge, the simulation runs were conducted with realistic annual recharge values between 50 mm/year and 100 mm/year with constant hydro-geological properties. A set of interface profiles for various recharge rates were obtained. Location of freshwater-saltwater interface profiles for above recharge rates are shown in Fig. 3. It shows that high recharge can reduce saltwater intrusion effectively. The saltwater will intrude further inland than now occurring unless the amount of additional recharge can push the seawater equilibrium surface seaward. This kind of simulations shows that any groundwater development activity in the catchments needs to be carefully planned with remedial measures in order to prevent the further intrusion of seawater in coastal regions. For the estimation of fresh groundwater loss in coastal aquifers, the effect of groundwater recharge in the watershed area is very important. The groundwater recharge is influenced by the climatic changes and land use changes.

Approximate location of Fig. 3

2.3. Model verification with field observation data

For this study, salinity intrusion has been observed in the lower part of Walawe River basin located in the southern coastal aquifer in Sri Lanka. The Walawe River basin is located in the southern part of Sri Lanka, between North latitudes 6^0 00’ and 6^0 40’ and East longitudes 80^0 40’ and 81^0 10’ (Fig. 4.a). The catchment area of the basin is 2442 km^2 and it is the major irrigation area in the dry topics of southern Sri Lanka. Walawe river flows from north to south with the total river length of 105 km.

Physiographically, Walawe River basin can be divided into three well defined areas viz. the coastal plains in the South, the middle region in the center and the hilly ranges in the small areas in North and North-East parts (Statkraft Groner, 2000). The 'Coastal Plains', covering major part of the southern region has elevation less than 6 m above mean sea level, parallel to the coast. The width of the coastal plains generally ranges from 2 km to 10 km. Coastal alluvial soils as well as laterites cover the area parallel to the coast. The unconsolidated alluvial formations occupy most of the area on the coastal plains. It includes the river sediments and fine to medium green quartzite sand, silty sands of the plains and grey to dark grey beach sands. Groundwater within the area is constrained by the unconsolidated alluvial and deltaic sediments, which were deposited by the Walawe River and its distributaries (Kulatunga, 1988). Fig 4.b shows the lithological section across the river, which was developed using available borehole log data.

<u>Approximate location of Fig. 4</u>

The salinity condition has been measured in three observation wells. These observation wells were selected at different distances from the coastline. These wells are located at different levels and at such a distance that in case of salinisation the eventual progression of the saline front can be observed. Salinity was measured using a portable salinity meter (model WQC-24). It detects the salinity in terms of electrical conductivity and the temperature and reproduces the salinity value as the direct measurement of *psu*. For the purpose of investigating the dynamics of the interface, we take the 50% seawater salinity contour as the equivalent sharp interface. Using the vertical salinity profiles of the observation wells, the depth to the sharp freshwater-saltwater interface was estimated as 13.5m, 21.5m and 34m in the observation wells located at 400m, 1km and 2km distances from coastline respectively.

A single-layer approach for modeling aquifers, allows all minor variations to be incorporated into a single hydro-stratigraphic unit (Bear, 1999). The study area is simulated as a single-layer unconfined aquifer. The simplified model developed, has assumed homogeneous aquifer properties and the hydraulic conductivities of the aquifer have been estimated based on available data. In the study area (Fig. 4), the hydraulic conductivity is estimated to be varied between 10^{-4} m/s to 10^{-3} m/s. Average annual groundwater recharge in the Walawe basin is around 80 mm/year (Ranjan, 2002) and a steady state simulation with this average annual recharge was used to generate the situation prior to steady state. For the calibration process, a wide range of values for each parameter has to test to estimate the most suitable value. The parameter estimation process shows that the hydraulic conductivity is the main hydro-geological factor affecting the movement of salinity interface. Therefore, the model was calibrated by adjusting hydraulic conductivity values to match the steady interface location with the field observed value at observation wells. Comparison of the observed data with modeling results has been found to be in reasonable agreement (Fig. 5).

Approximate location of Fig. 5

3. Groundwater recharge

Since recharge is one of the main factors affecting the movement of freshwater-saltwater interface, the possible changes in groundwater recharge due to changes in climatic conditions such as precipitation and temperature and the land use change were aimed to evaluate. Even though groundwater recharge is the major source of freshwater across much of the aquifers, particularly in arid and semi-arid regions, but there has been very little research on the potential effects of climate change on groundwater recharge. Changing land-use and land-management practices can also alter the hydrological system. The concept of water balance provides a framework for studying the hydrological behavior of a catchment. It is useful for assessing how changes in catchment conditions can alter the partitioning of rainfall into different components. The simple water balance for any catchment can be written as:

$$R = P - ET - RO \tag{4}$$

Where R is the groundwater recharge, P is the precipitation, RO is the surface runoff and ET is the evapotranspiration. All variables have dimensions [L/T].

The water balance method of estimating recharge as precipitation minus evapotranspiration minus runoff is very sensitive to measurement errors due to the involvement of large number of observation parameters. The data requirement to estimate the groundwater recharge using water balance technique is large. If the groundwater recharge can be represented as a function of limited available parameters such as annual precipitation, mean annual temperature and land use pattern, it is possible to reduce the errors in estimation. Hence, a methodology for estimation of the long-term average spatial patterns of actual evapotranspiration, surface runoff and groundwater recharge has to be developed. Such kind of methodologies can be used in areas with limited meteorological data and also in ungauged basins.

Land use change has a direct effect on hydrologic processes through its link with the evapotranspiration regime on one hand and on the other hand it has an enormous impact on the initiation of surface runoff. Three main land use types were considered in this study; forest, agricultural crops and grass or pasture. Precipitation is the primary source of groundwater and it is the largest term in the water balance equation, and varies both temporally and spatially. For most of the hydrological applications, it is appropriate to assume that precipitation is independent of vegetation type and evapotranspiration and surface runoff are closely linked with land use characteristics (Calder, 1998, Zhang 2001). A large number of land use impact studies on water resources have been carried out for watersheds with a focus on water scarcity, flood, erosion and water management. (Bultot *et al.*,1990; Krause, 2002; Batelaan *et al*, 2003).

3.1. Evapotranspiration

Since the evapotranspiration is one of the major inputs in the water balance equation, the effect of the land use on evapotranspiration has to be mainly evaluated to estimate the groundwater recharge with different land use patterns. The crop evapotranspiration is a simple representation of the physical and physiological factors governing the evapotranspiration process, taking vegetation parameters into account. The crop evapotranspiration can be estimated as a multiplication of reference crop evapotranspiration (ET_o) and crop coefficient (K_c).

$$ET_{crop} = ET_0 \times K_c \tag{5}$$

Several methods exist for the empirical estimation of reference evapotranspiration (ET_0). Based on the data requirement, these methods are classified as temperature based methods, pan evaporation, radiation and combination methods. Combination methods such as the Penman Equation require air temperature, relative humidity, wind speed and radiation information reflecting meteorological parameters influencing evapotranspiration. In the most of those methods, the large amount of parameters to be considered in estimation of evapotranspiration accumulates measurement errors and the lack of data for the necessary parameters leads the final estimation of groundwater recharge erroneous. Most of the areas with limited meteorological data sources, the estimation of groundwater recharge became practically impossible. When considering data requirements of each estimation method, the only alternative available for the consumptive use operation is the temperature based method. A widely used temperature based theoretical method to calculate reference crop evapotranspiration is SCS Blaney Criddle method (Shuttleworth, 1992). The SCS Blaney Criddle method is simple, using measured data on temperature only. This method presents the temperature as the main physical factor governing the evapotranspiration process, together with annual percentage of monthly sunshine hours.

SCS Blaney Criddle method gives

$$ET_0 = K_t \times \left(T \times \frac{p}{100} \right) \tag{6}$$

$$K_t = 0.0173\, T - 0.314 \tag{7}$$

Where T is the mean monthly temperature (^{0}F) and p is percentage of daylight of the year occurring during a particular month.

In the crop coefficient approach, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for within the crop coefficient (K_c). The crop coefficient serves as an aggregation of the physical and physiological differences between crops. It represents an integration of the effects of four primary characteristics that distinguish the crop from each other. These characteristics are; crop height, Albedo (reflectance), canopy resistance and the evaporation from soil. The crop coefficient values referred by FAO were used for the study (Doorenbos and Pruitt, FAO,1977 ,Wright, 1982).

3.2. Surface runoff

The surface runoff can be estimated using the Soil Conservation Service Curve Number (SCS-CN) method. SCS-CN model developed by United States Department of Agriculture (USDA) computes direct runoff through an empirical equation that requires the rainfall and a watershed coefficient as inputs. The watershed coefficient is called the curve number (CN), which represents the runoff potential of the land cover and soil complex. The runoff curve number method for the estimation of direct runoff from storm rainfall is well established in hydrologic engineering. Its popularity is rooted in its convenience and simplicity. In addition, the method does not consider the time distribution of rainfall, rainfall intensity and rainfall duration when it is used to calculate direct runoff. Only rainfall volume is considered. (Steenhuis *et al*, 1995, Boughton, 1989). The standard SCS CN method is based on the following relationship between rainfall depth, *P*, and runoff depth RO*;*

$$RO = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{8}$$

where *P* is the precipitation and the *S* represents the potential maximum retention after runoff begins. The retention factor is related to the soil and land use condition of watershed through the curve number and it is determined by;

$$S = (\frac{1000}{CN} - 10) \times 25.4 \qquad (9)$$

where *CN* is the curve number and *S* is in millimeters

For convenience, *S* is expressed in terms of CN, which is a dimensionless watershed parameter ranging from 0 to 100. The SCS has developed tables of initial curve number (CN) values as a function of the watershed soil type, land use condition and antecedent moisture condition (AMC). The list of soils is prepared by the SCS and soils are classified in one of four different categories, ranked A to D on the basis of their runoff potential. Class A soils mostly consist of deep, well- drained sands and gravels with low runoff potential and high infiltration and water transmission rates. Class B soils have moderately fine to moderately coarse textures and are considered to have moderate infiltration rates. Class C soils have moderately fine to fine textures with slow infiltration and water transmission rates. Class D soils are primarily clay soils or soils with clay pans that have slow infiltration with slow rates of water trans-mission. Melesse and Shih (2002) discussed the difference in runoff depth for four types of hydrologic soil groups in details. The curve number table from the National Engineering Handbook (USDA, 1972) contains curve number values for three antecedent moisture conditions. The AMC I is the lower limit of moisture representing a dry condition, AMC II is the average condition of moisture, and AMC III is the upper limit of moisture representing a wet condition. Usually in the literature, the curve number for antecedent moisture condition is given as average curve number. For this study, the average moisture condition was considered and curve number with AMC II was taken into account for each land use pattern.

3.3. Estimation of groundwater recharge

The water balance methodology based on SCS Blaney Criddle method and curve number technique was used to estimate the groundwater recharge using average annual precipitation, average mean temperature, land use and hydrologic soil group. There are several assumptions that have to be considered; the annual precipitation is uniformly distributed over the year considering equal monthly precipitation for each month and the mean temperature is uniform over the year. In the estimation of evapotranspiration using SCS Blaney-Criddle method, the reference evapotranspiration (ET_0) varies with the daily sun shine hours. Daily sunshine hours vary with the location of the interested area, mainly with the latitude of the area. Considering the pattern of the change in mean sunshine hours, the average pattern for the percentage of monthly sunshine hours was selected for the estimation of evapotranspiration. In the estimation of runoff, it is assumed that the monthly rainfall is a single storm event in the particular month.

The estimation of the groundwater recharge in different soil conditions including climate changes and land use pattern was carried out considering annual precipitation range from 500 mm to 3000 mm and mean temperature range from 5^0C to 20^0C, the annual groundwater recharge was estimated for three major land use patterns; forest, agricultural crops and grass/pasture for four main hydrologic soil groups A to D.

3.4. Aridity Index

The estimated groundwater recharge for each land use pattern and soil group mainly depends on two climatic effects; precipitation and temperature. With the change of precipitation and temperature, the groundwater recharge can be graphically represented using the climatic indexes such as Aridity index.

Aridity indexes are quantitative indicators of the degree of water deficiency present at a given location. A variety of aridity indexes have been formulated. Although the term *Aridity Index* refers to the spatially averaged climatic factors, it has been applied at continental and sub-continental levels and is most commonly relate to distributions of natural vegetation and crops. 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 because their data requirements were minimal (Oliver and Fairbridge, 1987).

Aridity index is defined by;

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

Where T is the mean annual temperature (^{0}C) and P is the mean annual precipitation in millimeters.

3.5. 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. The movement of salinity interface due to the changes in recharge/discharge leads to change in available fresh groundwater resources in the aquifer. As illustrated in Fig. 6, 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 (the whole aquifer fills with saltwater), the freshwater loss will be 100%. If the groundwater recharge is zero, then the whole catchment tends to fill with saltwater and freshwater loss will be 100%.

<u>Approximate location of Fig. 6</u>

4. Results and discussion

4.1. Quantification of the impacts on groundwater recharge

The combinations of precipitation and temperature are used to estimate the aridity index and the estimated annual groundwater recharge is presented as a function of Aridity index, land use and hydrologic soil group (Fig. 7). Using these graphs, the annual groundwater recharge can be estimated as a function of annual precipitation, mean annual temperature, land use and hydrologic soil condition for any watershed.

The Fig.7 shows that, while considering all four types of hydrologic soil groups, when the aridity index is less (less than 60), the contribution to groundwater recharge from agricultural lands is higher than other land use patterns. Soil group A, which has well draining hydrologic conditions has the maximum groundwater recharge for a given aridity index and land use. Since this kind of soil has less possibility to create surface runoff, most of the precipitation infiltrates to the soil and contributes to groundwater recharge.

The conversion of forests to agricultural lands (deforestation) leads to reduce the evapotranspiration even though it favors the runoff. In the areas having less precipitation and high temperature (arid areas), the influence of evapotranspiration is greater than the influence of runoff to change the groundwater recharge. Also small rainfall events do not create runoff unless the amount of rainfall exceeds the maximum potential retention. Therefore when the aridity index is less (less precipitation and high temperature), the effect of surface runoff is less due to reduced precipitation and the evapotranspiration is the leading factor to decide the amount of groundwater recharge. So, the crop lands have less evapotranspiration and it gives larger recharge while the forest with higher evapotranspiration gives less recharge in arid areas. For higher aridity indexes (over 60), the forest has more contribution to recharge than other crops in well draining soil conditions. This is due to the high precipitation which leads to higher runoff in agricultural lands than in forests. In such climates, the evapotranspiration has less impact than surface runoff for groundwater recharge. Similar pattern of recharge is shown in the lands having moderately drained soils (type B), but the amount of recharge is less for same aridity index, because of the higher surface runoff.

The surface runoff is higher in the lands with poor drained soil (soil group C and D). It is clear that when soil has the low infiltration rate, a considerable amount of precipitation runs off without contributing to the recharge. The infiltrated water also evaporates and it leads to further decrease the groundwater recharge. In such soil types, the groundwater recharge is very small for any type of land use pattern, even for higher aridity index. Agricultural crop lands which have low evapotranspiration lead to a relatively higher recharge and the forest cover which has higher evapotranspiration gives low groundwater recharge. The introduction of forest covers in catchments increases the evapotranspiration, whereas agricultural crops lead to a decline of evapotranspiration.

Considering all four types of hydrologic soil groups, Fig. 7 shows that agricultural crops are the best land use cover to achieve maximum groundwater recharge for all type of soils with small aridity index. For soil type A and B, forests are better when the aridity index is higher. Aridity index is higher in humid area whereas it is smaller in arid and semi arid areas. With respect to effective groundwater recharge, agricultural crops are the best vegetation cover in arid and semi arid areas.

Approximate location of Fig. 7

4.2. Effects of land use, deforestation and climate changes on salinity intrusion

It is important to understand the effects of the combination of climatic changes and land use change on the groundwater recharge and the effect of corresponding groundwater recharge on the salinity intrusion. Those effects can be understood by considering a simple groundwater flow system and changing the groundwater recharge according to the different combinations of climatic factors and land use scenarios.

Simulation runs were conducted with selected annual groundwater recharge values and hydraulic conductivity values. The hydraulic conductivity values, within the range of 10^{-2} m/s and 10^{-4} m/s have been selected for this evaluation. Depth to the freshwater-saltwater interface at one kilometer distance from coastline, for different annual recharge rates and hydraulic conductivities are shown in Fig. 8. It shows the relationship between groundwater recharge rate and saltwater intrusion in coastal aquifers with typical range of hydraulic conductivities for sandy coastal aquifers. This result can be linked with the graphs shown in Fig. 7. From the Fig. 7, the groundwater recharge can be estimated using aridity index and land use pattern. The estimated groundwater recharge and the relevant hydraulic conductivity can be used to find salinity interface in the coastal aquifer.

<u>Approximate location of Fig. 8</u>

4.2.1. Deforestation

To evaluate the effects of land use change for the loss of fresh groundwater resource, the deforestation concept have been taken into account. Here the deforestation is defined based on the availability of forests and agricultural lands in the catchment. If the whole catchment is covered with agricultural crop land, the deforestation is defined as 100%, whereas the whole catchment is covered with forests, the deforestation is 0%. Intermediate values are defined based on the percentage of forest cover and the agricultural land cover in the catchment. For example, if the 75% of the catchment area is covered with forests and 25% of the area with agricultural crops, then the deforestation is defined as 25% for that catchment.

4.2.2.. Combination of deforestation and climate change

Groundwater recharge was estimated for different deforestation ratios for the range of aridity index and for each hydrologic soil group. The estimated recharge was applied to simulate the freshwater-saltwater interface with two hydraulic conductivity values; upper and lower boundary of the hydraulic conductivity for sandy/basalt coastal aquifers. The simulated salinity interface profiles were used to estimate the available freshwater resource of aquifers and the relative change of the salinity interface profiles were used to calculate the percentage loss of the fresh groundwater resources in the aquifer. Percentage loss of fresh groundwater resource due to the movement of salinity interface for the combinations of deforestation and climatic changes for four hydrologic soil groups A to D and two hydraulic conductivity values 10^{-2} m/s and 10^{-4} m/s are presented in Fig. 9 and Fig. 10. These figures show that catchment property of well drained soil condition and aridity index of 60 causes around 89% of fresh groundwater loss for 25% deforestation and fresh groundwater loss reduces to 87% for 75% deforestation in aquifers having hydraulic conductivity of 10^{-2} m/s. These results conclude that deforestation causes the increase of the groundwater recharge and existing fresh groundwater resource in areas having low aridity index (arid and semi arid climates). The freshwater loss is relatively high in areas having poor drained hydrologic soil types (soil type C and D).

<u>Approximate location of Fig. 9 and Fig. 10</u>

5. Conclusions

Numerical modeling can be considered to be a tool to enhance the knowledge of the saltwater intrusion process. In this study, saltwater intrusion was simulated through a numerical model based on sharp interface approach. The model further simulates the loss of fresh groundwater resource in coastal aquifers with respect to climate and land use changes.

The sensitivity analyses highlight that the model is very sensitive with respect to changes in hydraulic conductivity and groundwater recharge. To evaluate the factors affecting the groundwater recharge, the water balance technique has been employed in order to establish the groundwater recharge as a function of annual precipitation, mean annual temperature, land use pattern and hydrologic soil condition. The aridity index has been introduced to represent the variations in precipitation and temperature scenarios. Aridity index is higher in humid areas whereas it is lower in arid areas. In the arid climate, the effect of surface runoff is less due to small precipitation and evapotranspiration is the leading factor to decide the amount of groundwater recharge. Therefore in arid areas, the agricultural lands have less evapotranspiration and it gives higher recharge whereas the forest with higher evapotranspiration gives less recharge. Results further conclude that, when aridity index is less (less than 60), the agricultural lands give high groundwater recharge whereas the forests give low groundwater recharge for all soil conditions. With respect to groundwater recharge, agricultural lands are the best land use pattern in arid and semi arid areas. The combined effects of deforestation and aridity index on fresh groundwater loss conclude that, deforestation causes the increase of the recharge and existing fresh groundwater resource in areas having less precipitation and high temperature (arid climates).

The developed methodology will be useful in areas with limited hydrological data. The results from this study would assist the planners and decision-makers to come up with better land use and water resources management concepts ensuring its long term sustainability for natural and anthropogenic impacts.

Acknowledgements

The authors would like to acknowledge the Grant-in-Aid for Scientific Research by Prof. Nobuo Mimura, Ibaraki University, Japan and Prof. Masaki Sawamoto, Tohoku University, Japan.

References

1. Batelaan, O., De Smedt, F., Triest, L., Regional groundwater discharge: phreatophyte mapping, groundwater modelling and impact analysis of land-use change, *Journal of Hydrology,* 275 (2003), 86-108
2. Bear, J., 1979, Hydraulics of Groundwater, McGraw-Hill, New York.
3. Bear, J., Cheng, A.H.D., Sorek, S., Ouazar, D., and Herrera, I., 1999, Seawater Intrusion in Coastal Aquifers- Concepts, Methods and Practices, Kluwer Academic Publishers, pp 145-151.
4. Boughton, W.C., A review of the USDA SCS curve number method, *Australian Journal of Soil Research*, 27 (1989), 511-23.
5. Bultot, F., Dupriez, G.L., Gellens, G., Simulation of land use changes and impacts on the water balance—a case study for Belgium. *Journal of Hydrology*, 114 (1990), 327–348.
6. Calder, I.R., Water resources and land use issues, SWIM paper-3, Int. Water Management Inst., Colombo, Sri Lanka, (1998) pp 7-8.
7. Cartwright, N., Li, L., and Nielsen, P., Response of the salt–freshwater interface in a coastal aquifer to a wave-induced groundwater pulse: field observations and modeling, *Advances in Water Resources*, 27(3) (2004), 297-303.
8. Doorenbos, J. and Pruitt, W. O., 1977. Crop water requirements. *Irrigation and Drainage Paper No. 24,* FAO, pp144.
9. Essaid, H.I., A comparison of the coupled freshwater- saltwater flow and the Ghyben-Herzberg sharp interface approaches to modeling of transient behavior in coastal aquifer system, *Journal of Hydrology*, 86 (1986), 169-183.

10. 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 (1990), 431 -1455.

11. Freeze, R.A., Cherry, J.A., 1979, Groundwater, Prentice Hall International, London, (Chapter 2).

12. Glover R.E., The pattern of freshwater in a coastal aquifer, *Journal of Geophysical Research,* 64(1959), 439-470.

13. Krause, P., Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model, *Physics and Chemistry of the Earth,* 27 (2002), 663–673.

14. Kulatunga, N., Hydrology of a Metamorphic Terrain: A Case Study from Hambantota, Sri Lanka., *Journal of the Geological Society of Sri Lanka*, Vol. 1 (1998), 140-148.

15. Lambrakis, N., Kallergis, G., Reaction of subsurface coastal aquifers to climate and land use changes in Greece: modeling of groundwater refreshing patterns under natural recharge conditions, *Journal of Hydrology*, 245 (2001, 19-31

16. Mahesha, A., Nagaraja, S.H., Effect of natural recharge on sea water intrusion in coastal aquifers, *Journal of Hydrology*, 174 (1996), 211-220.

17. Melesse, A.M., and Shih, S.F., Spartially distributed storm runoff depth estimation using Landsat images and GIS, *Computer and Electronics in Agriculture*, 37 (2002), 173-183.

18. Oliver J. E., Fairbridge R W., (Editors), 1987, The encyclopedia of Climatology, Encyclopedia of earth sciences, Volume XI, Van Nostrand Reinhold Publishers, New York, pp 103-107.

19. Polo, J.F., Ramis, F.J.R., Simulation of Salt-fresh water interface model, *Water Resources Research*, 19 (1983), 61-68.
20. Ranjan S.P., 2002, Evaluation of groundwater resources in Walawe river basin, Sri Lanka, Master Thesis, Asian Institute of Technology, Thailand, pp52-54.
21. Reilly, T.E., Goodman, A.S., Quantitative analysis of fresh-salt water relationship in groundwater systems- A historical perspective, *Journal of Hydrology*, 80 (1985), 125-149.
22. Remson, I., Hornberger, G.M., Molz, F.I., 1971, Numerical methods in subsurface hydrology: with an introduction to the finite element method, Wiley Interscience Publishers, Canada, (Chapter 5).
23. Shamir, U., Dagan, G., Motion of Saltwater interface in a coastal aquifers: A numerical solution, *Water Resources Research*, 7 (1971), 644-657.
24. Shuttleworth, W.J., 1992. Evaporation. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, pp. 4.1– 4.53
25. Statkraft Groner, 2000, Third Water Supply and Sanitation Project, Water Resources Management- Annex D, Groundwater, Walawe Ganga Basin, pp7-12.
26. Steenhuis, T.S., Winchell, M., Rossing, J., Zollweg, J.A., Walter, M.F., SCS runoff equation revised for variable source runoff areas, *Journal of Irrigation and Drainange Engineering, ASCE,* 121/3 (1995), 234-238.
27. US Department of Agriculture, Soil Conservation Service. 1972, Hydrology, National Engineering Handbook, Section 4, US Government Printing Office, Washington DC, pp 10.1-10.24.

28. Van Der Veer, P., Analytical solution for steady interface flow in a coastal aquifer involving a phreatic surface with precipitation., *Journal of Hydrology*, 34 (1977), 1-11.

29. Vappicha, V.N., Nagaraja, S.H., An approximate solution for the transient interface in a coastal aquifer, *Journal of Hydrology*, 31 (1976), 161-173.

30. Wilson, J.L., Sa Da Costa, A., Finite element Simulation of Salt-fresh water interface with indirect toe tracking, *Water Resources Research*, 18 (1982), 1069-1081.

31. Wright, J. L., New Evapotranspiration Crop Coefficients. *Journal of Irrigation and Drainage Division*, ASCE, 108 (1982), 57-74

32. Zhang, L., Dawes, W.R., Walker, G.R., Response of mean annual evapotranspiration to vegetation change at catchment scale. *Water Resources Research*, 37 (2001), 701-708.

Figure Legends

Fig. 1. The position of the interface at steady state conditions due to different values of porosity

Fig. 2. Change in the interface with hydraulic conductivity (K)

Fig. 3: Movement of interface with groundwater recharge (R)

Fig. 4. Study Area : Walawe River Basin, Sri Lanka

Fig. 5. Comparison of observed and simulated salinity interface

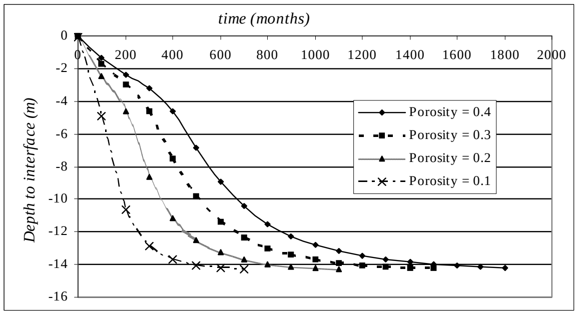
Fig. 6. Loss of fresh groundwater resource due to salinisation

Fig. 7. Relation between Aridity Index and groundwater recharge for land use patterns for hydrologic soil groups (a) A, (b) B, (c) C and (d) D.

Fig. 8. Variation of depth to salinity interface with groundwater recharge rate at 1.0 km away from the coast

Fig. 9. Change in fresh groundwater loss in coastal aquifers with deforestation and climatic changes (Aridity Index) for hydraulic conductivity of 10^{-2} m/s for hydrologic soil groups (a) A, (b) B, (c) C and (d) D.

Fig. 10. Change in fresh groundwater loss in coastal aquifers with deforestation and climatic changes (Aridity Index) for hydraulic conductivity of 10^{-4} m/s for hydrologic soil groups (a) A, (b) B, (c) C and (d) D.



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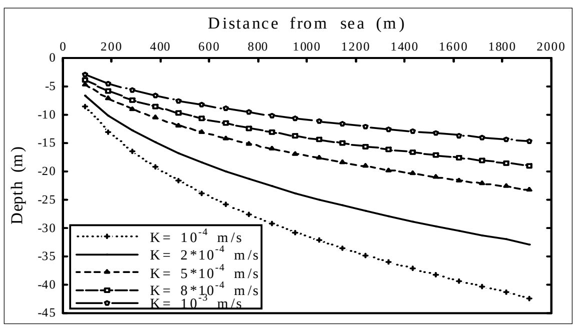


Fig. 2. Change in the interface with hydraulic conductivity (K)

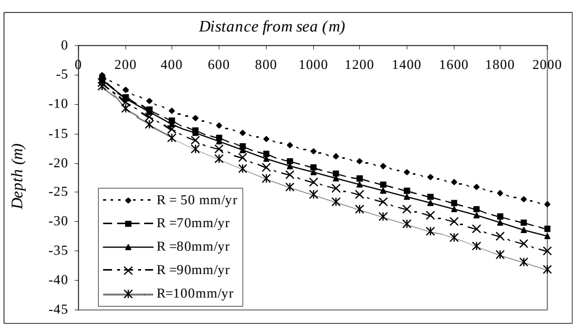


Fig. 3: Change of interface with groundwater recharge (R)

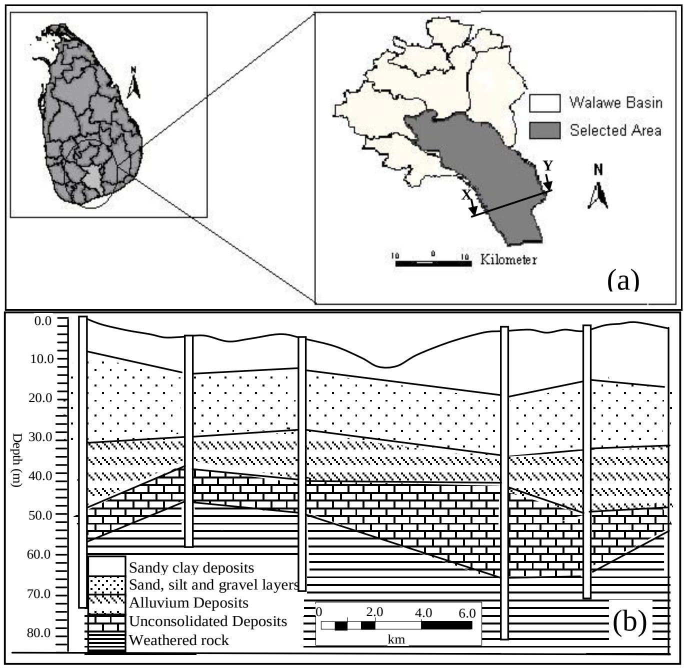


Fig. 4.(a) Walawe River Basin and (b) Lithological section along X-Y

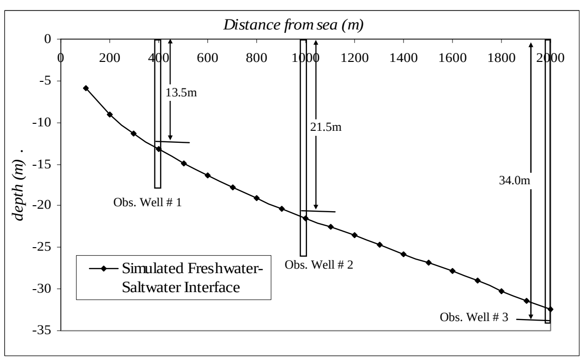


Fig. 5. Comparison of observed and simulated salinity interface

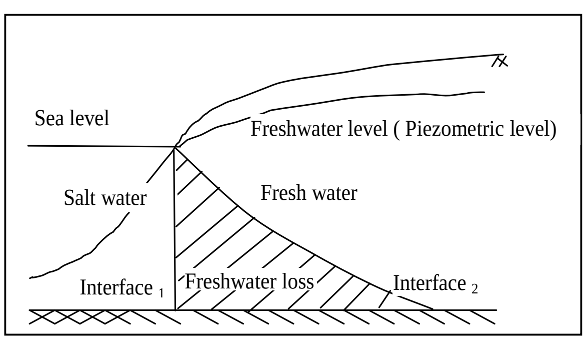
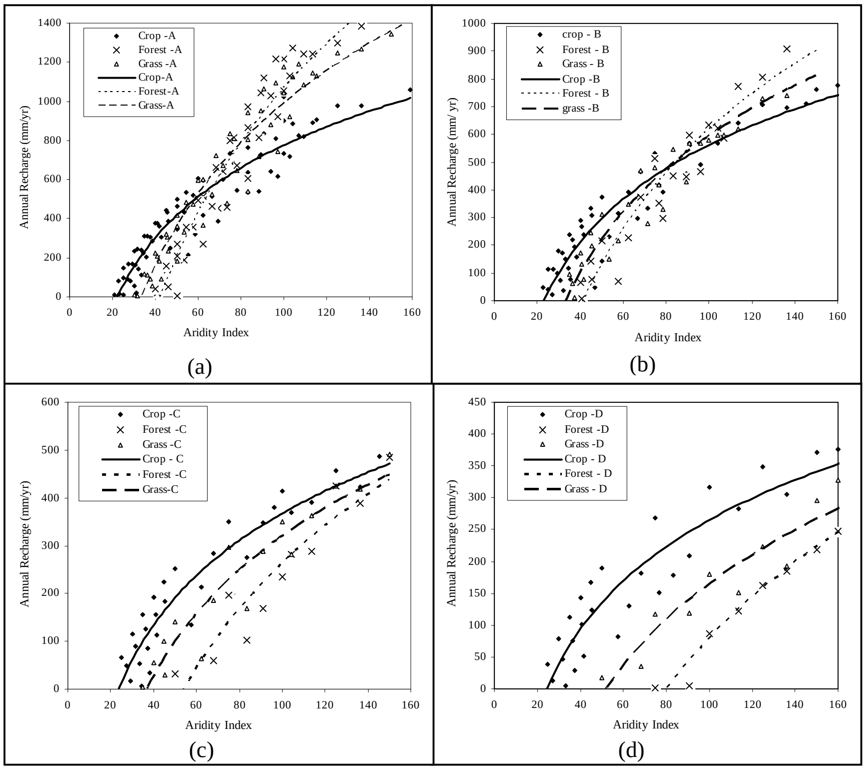


Fig. 6. Loss of fresh groundwater resource due to salinisation



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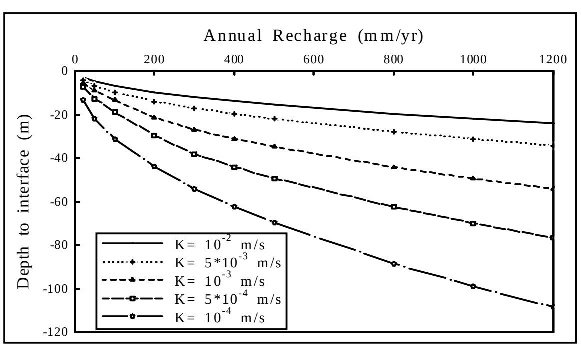

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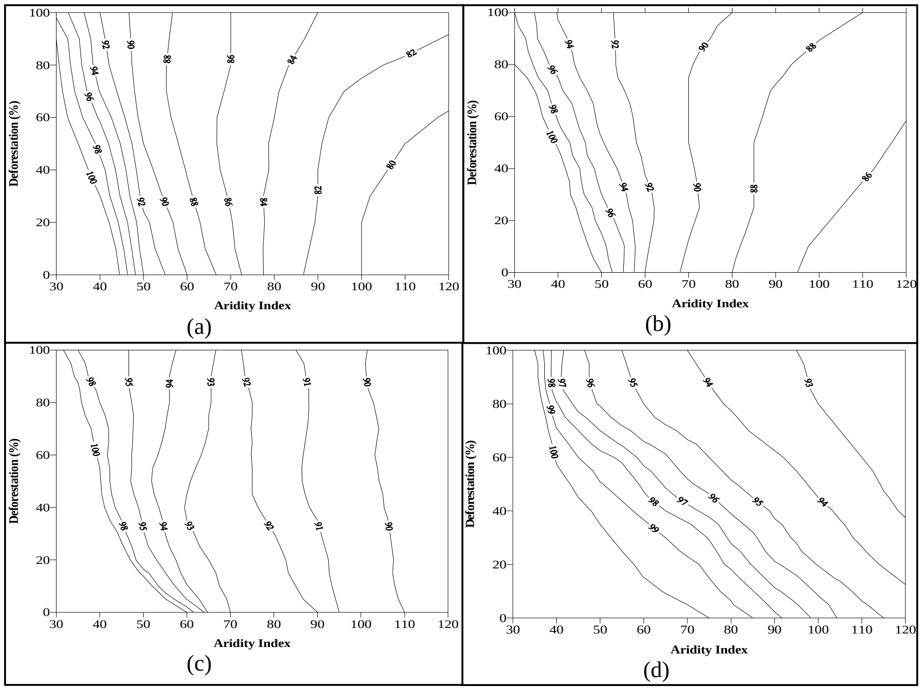

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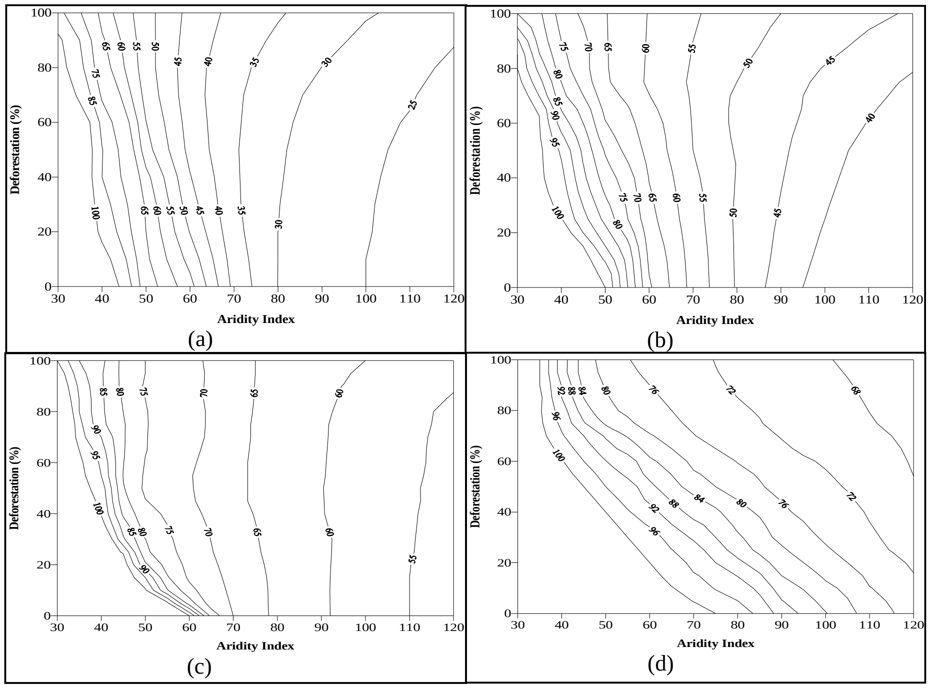

Fig. 10. Change in fresh groundwater loss in coastal aquifers with deforestation and climatic change (Aridity Index) for hydraulic conductivity of 10 $^{-4}$ m/s for hydrologic soil groups (a) A, (b) B, (c) C and (d) D