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Analysis of Natural Recharge and Groundwater Dynamics in Alluvial Aquifer Systems

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ABSTRACT: Proper knowledge of groundwater recharge is essential for the management and protection of valuable groundwater resources. Natural groundwater recharge is a very complex and dynamic phenomenon, and its determination involves a number of unresolved problems, thereby making direct measurement of natural recharge extremely difficult. Modeling is a very useful tool to analyze groundwater systems and gain new insights. In the present study, an analytical recharge model was used to analyze the spatial and temporal variations of groundwater recharge/discharge. Seven years (1998–2004) daily groundwater level data and other relevant data were obtained from an alluvial aquifer system in Japan. The recharge/discharge rates were estimated at seven sites using the selected model. In order to examine groundwater-surface water dynamics, regression analyses were performed between the rainfall and groundwater levels at the seven sites as well as between the river stage and groundwater levels at these sites. The monthly recharge analysis indicated very limited number of monthly recharge events, which significantly varied from site to site and year to year. At most sites, the groundwater discharge was found to be predominant during the 1998–2004 period. The results of the regression analysis indicated that both the rainfall and the Monobe River stage are major sources of recharge. The aquifer was found to be hydraulically connected with the Monobe River. It is concluded that the analytical recharge model and regression analysis are effective tools for analyzing complex hydrogeologic processes.

Keywords: Recharge Analysis, Analytical Modeling, Groundwater Dynamics, Alluvial Aquifer.

INTRODUCTION

Water is a vital ingredient for the sustenance of all living things, and for maintaining the health of ecosystems. It is anticipated that over the next 20 years, the world's population will increase from 6 billion to an estimated 7.2 billion, while the average supply of water per person is expected to drop by one-third (IWMI, 1999). If the current trend of exploitation continues, about two-third of the world's population will face moderate to severe water stress by 2025 compared to one-third at the present. Large water consumption leads to surface water drawdown, and thereby groundwater decline. On the top of it, overuse of groundwater has resulted in significant groundwater lowering in several parts of the world (e.g., Konikow and Kendy, 2005; Sahuquillo *et al.*, 2005; Bouwer, 2000; Shah *et al.*, 2000; Zektser, 2000). Undoubtedly, groundwater plays a central role in water resources planning and management in both developed and developing nations. Proper knowledge of groundwater recharge is essential for the management and protection of vital groundwater resources. However, natural groundwater recharge is very complex and dynamic, and its determination involves a number of unresolved problems, thereby making the direct measurement of natural recharge extremely difficult. Hydrogeologic processes being hidden and complex, modeling plays an important role in the analysis of groundwater systems. Analytical models are less data demanding, and hence are useful practical tools for analyzing complex groundwater systems. In the present study, an analytical recharge model developed by Su (1994) was employed to analyze the spatial and temporal variations of groundwater recharge/discharge in an alluvial aquifer system of Japan. The availability of adequate field data in this basin enabled the authors to investigate surface water-groundwater dynamics as well.

OVERVIEW OF STUDY AREA

The Konan groundwater basin, which is comprised of alluvial aquifers, is located in Kochi Prefecture, Shikoku Island of Japan (Figure 1). It is bounded by the Monobe River (perennial) in the west and the Koso River (intermittent) in the east. Mountains demarcate the northern boundary and the southern boundary is demarcated by the Pacific Ocean. There are two intermittent rivers called the Karasu River and the Yamakita River. Land use mainly consists of agricultural land (paddy fields, greenhouses and fisheries), industry and built-up land, with three hills. This constitutes a total area of 2200 ha, of which approximately 1502.5 ha is paddy fields, 488.0 ha upland, and 186.5 ha is under greenhouse cultivation. January and February are the coldest months and July–August are the hottest months. The average daily maximum temperature is 37°C in summer, and the average daily minimum temperature is –4°C in winter. The mean annual rainfall and evapotranspiration in the region are about 2600 mm and 800 mm, respectively. More than 50% of the total rainfall occurs during June through September. However, October through February is usually characterized as a dry period. The hydraulic conductivity of these aquifers ranges from 65–804 m/day, and is classified as high (Jha *et al.*, 1999).

MATERIALS AND METHODS

Data Collection and Site Selection

The daily rainfall data of 7 years (1 January 1998 to 31 December 2004) were obtained from a nearby meteorological station. The daily river-stage data of the Monobe River at the Fukabuchi gauging station (at 3.8 km from the river mouth) for the 1998–2004 period were gathered from the Kochi Work Office, the Ministry of Construction. The daily groundwater-level data for 34 sites were obtained for the 1998–2004 period from the Kochi Prefecture Office. The aquifer hydraulic conductivities at 14 sites as determined by pumping test data analysis were obtained from Jha *et al.* (1999). Based on the availability and continuity of groundwater-level data and the availability of aquifer hydraulic conductivity data, seven sites (D-6, D-7, E-5, E-2, F-6, E-7 and E-4) were selected for the estimation of spatial and temporal variations of natural recharge for the 1998–2004 period; the location of these sites is shown in Figure 1.

ESTIMATION OF NATURAL RECHARGE

After getting the required data and selecting the sites, the Su model (Eqn. 1) was applied to calculate monthly recharge/discharge rates for the 1998–2004 period (Su, 1994, 1995),

$$R(x,t) = S_y \frac{\Delta h(x,t)}{\Delta t}\left(\frac{h(x,t)}{D}\right) - \left(\frac{S_y H_o^{\,2}}{2D}\right) \cos(\in x)\left(\in^2 k + \frac{K^2\lambda^2}{4T\,S_y}\right) \cdot \exp\left[\frac{K\lambda}{2T}x - \left(\in^2 k + \frac{K^2\lambda^2}{4T\,S_y}\right)t\right] \quad \dots (1)$$

Where,

$$\in = \frac{1}{L}\arccos\left[\left(\frac{H_L}{H_0}\right)^2 \exp\left(\frac{-K\lambda}{2T}L\right)\right] \quad \dots (2)$$

$R(x, t)$ is the recharge rate as a function of space and time $[L/T]$, S_y = specific yield, $\Delta h\,(x, t)$ = change in water table level during time Δt $[L]$, $h(x, t)$ = water table level during time t $[L]$, D = mean saturated thickness of the aquifer $[L]$, k = aquifer diffusivity $[L^2/T]$, K = mean hydraulic conductivity of the aquifer $[L/T]$, T = aquifer transmissivity $[L^2/T]$, λ = slope of the aquifer base, L = length of the aquifer [L], and H_o, H_L = water table heights above the aquifer base at upstream (i.e., $x = 0$) and downstream (i.e., $x = L$) ends of the aquifer.

The spatio-temporal variations of recharge/discharge were calculated using MS Excel software. In order to calculate natural recharge rate at a given site, monthly mean values of groundwater levels and the corresponding hydraulic conductivity were considered. While applying this model, monthly mean values of H_o and H_L were used, where H_o and H_L are respectively upstream and downstream groundwater levels from the aquifer base. These upstream and downstream groundwater levels were obtained using the geologic profile of the study area and the monthly groundwater levels at individual sites. Based upon the field experience, a representative value of specific yield for the Konan basin has been recommended as 15% (Jha *et al.*, 2003).

Analysis of Surface Water-Groundwater Dynamics

Surface water and groundwater are intricately related to each other; the changes in one system usually affect the other system. Therefore, it is necessary to examine the relationship between the groundwater and surface water fluctuations. In the study area, the Monobe River is a perennial river which is expected to contribute to groundwater recharge in the basin. Since the unconfined aquifer is prevalent in the basin, the recharge from direct rainfall could also be a significant source. As a result, firstly simple plots of monthly average groundwater level at different sites, together with monthly rainfalls were prepared. In addition, simple linear regression analyses were performed between monthly groundwater levels at individual sites and monthly cumulative rainfalls of a given year. Similarly, a separate regression analysis was also performed at the seven sites using the monthly groundwater-level data and the monthly Monobe River stage data.

RESULTS AND DISCUSSION

Spatio-Temporal Variations of Natural Recharge/Discharge

Recharge/discharge rates were calculated at the seven sites (D-6, D-7, E-7, E-5, F-6, E-4 and E-2) for the 1998–2004 period. Results obtained are shown in Figures 2(a–g). D-6, D-7 and E-7 are located in the eastern part of the study area, which are in close proximity of an industry. Figures 2(a, b, c) show the variation of monthly recharge/discharge rates at Sites D-6, D-7 and E-7 during seven years (1998–2004). It is apparent from these figures that the discharge rate predominates over the recharge rates at these three sites for all the seven years. This may be due to the heavy pumping for the industrial purpose. In addition, the well logs of these sites revealed that they are confined sites (i.e., observation wells at these sites are tapping the confined aquifer), which are mainly recharged through the outcrops. This could be another reason for the dominating discharge over recharge at these wells. Land slope also augments the discharge rate of these sites. For Site D-6 [Figure 2(a)], the discharge rate during the year 1998 was comparatively less compared to other years which may be due to the heavy annual rainfall of 3765 mm in 1998. The discharge rate at Site D-6 was maximum throughout the year 2001 due to the least annual rainfall of 2082 mm apart from the least annual rainfall of 1942 mm in 2002. For Site D-7 [Figure 2(b)], the year 2003 experienced heavy discharge throughout the year compared to other years.

Site E-5 is located in almost middle portion of the Konan groundwater basin. Figure 2(d) shows the recharge/discharge rate at Site E-5 for the seven years.

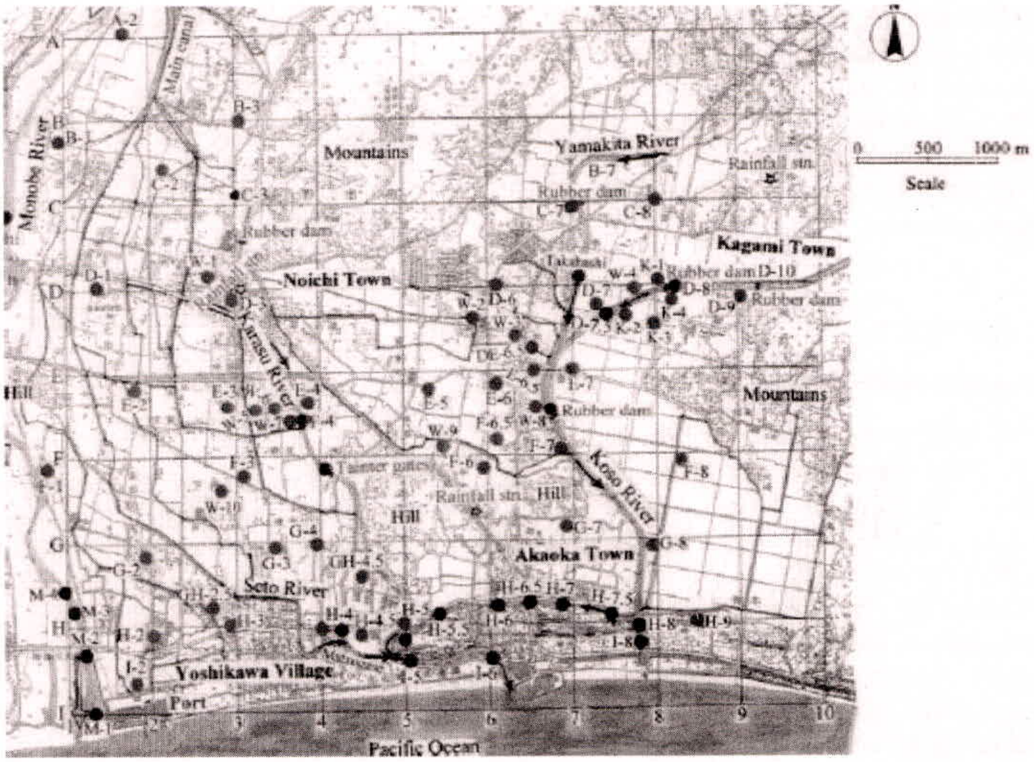

Fig. 1: Map of the study area with the location of observed sites

Due to pumping for the agricultural purpose, the discharge rate is prevalent during most months of a year. The recharge during March–April for all the years, and during June–July and September–October for some years may be due to the absence/reduction of pumping during these periods. Reduction of pumping during these periods may be due to the absence of greenhouse cultivation. Maximum recharge rate was found to be 118 mm during the year 1998 due to heavy annual rainfall of 3765 mm. Compared to Sites D-6, D-7 and E-7, the discharge rates are less for Site E-5. Figure 2(e) illustrates recharge/discharge rates at Site F-6 for the seven years, which are somewhat similar to those at Site E-5. The recharge and discharge rates of this site are almost similar to that of Site E-5, except for the year 2003. Maximum recharge rate was found to be 124 mm during the year 1998 and maximum discharge rate was found to be 274 mm in the month of March, 2003.

Since the Karasu River is an intermittent river, the contribution to groundwater recharge is very little at Site E-4. This well is located in the unconfined part of the Konan basin and is very near to agricultural fields and greenhouses. Due to heavy pumping for the agricultural purpose, the discharge rate is predominant during most years [Figure 2(f)], except for March–April in the year 1999. Due to the absence of greenhouse cultivation during April, there is no pumping in this period. Mainly because of this reason, the recharge rate is high compared to other months of different years. Site E-2 is located close to the perennial river called Monobe River. Hence, this site should have a significant influence of the Monobe River stage also as is revealed from the regression analysis. However, the recharge rate is very less at this site also [Figure 2(g)], which is attributed to the pumping for agricultural and domestic purposes. Maximum recharge rate was found to be 118 mm in the month of April during the year 1999. Recharge rate was dominant only in the month of April, this may be also due to the absence of greenhouse cultivation during March–April, except in the year 2003. Discharge rate for different years do not have a similar pattern owing to the varying pumping rates for meeting water demands in domestic, agricultural and industrial sectors.

From the above results and discussion, it is clear that over-exploitation of groundwater is very much pronounced in the study area. Even though the rainfall and the Monobe River stage are considerably contributing to the groundwater recharge, the monthly recharge is less and not discernible for much of the year. The main reasons for such a recharge characteristic are heavy pumping for industrial, domestic and agricultural purposes and the relatively large topographic slope.

Rainfall-Groundwater Dynamics

Interrelation between surface water and groundwater can be illustrated with the help of simple plots of rainfall and groundwater levels for a given period. Monthly mean groundwater-levels at different sites for the year 1998 and 2004 are illustrated in Figure 3 along with the monthly rainfall bargraphs at a nearby rainfall station. These plots suggest that the response of groundwater to significant rainstorms is rapid and considerable at most sites. The rise and decline of groundwater levels vary appreciably with sites and time. Moreover, the analysis of monthly groundwater-level data for the period 1998–2004 revealed that the groundwater level has a decreasing trend during dry periods (October to February). It also indicates that more than 50 mm rainfall is needed to cause a significant rise in the water table.

Results of Regression Analyses

Table 1 summarizes the results of the linear regression analyses of monthly rainfall and the monthly groundwater levels at the seven sites. It can be seen from Table 1 that Site D-6 is highly influenced by rainfall during 2003 and 2004 years. Sites E-2, E-4, E-5 and F-6, however, are influenced by rainfall during 1999, 2000, 2003 and 2004 years. Thus, except for Site E-7, all other sites are greatly influenced by rainfall. In other words, the rainfall contributes very little to groundwater recharge at Site E-7, which might be due to the confined nature of this site. Table 1 also reveals that the correlation between rainfall and groundwater levels at different sites is not significant in 1998 and 2001 years. From this table, we can conclude that the source of recharge in the study area is not only rainfall, but there exists some other sources also.

The results of the linear regression analysis between monthly Monobe River stage and the monthly groundwater levels at individual sites for the 1998–2004 period are summarized in Table 2. It is apparent from this table that Site E-2 is highly influenced by the changes in the river stage during 1999 and 2003 years followed by Sites E-4, E-5 and F-6 during 1999 and 2003 years; Sites E-5 and F-6 also show a strong correlation with the river stage in the year 2002. This table also reveals that except in 2001, groundwater levels in the most sites are considerably influenced by the Monobe River stage. This finding clearly suggests that the Monobe River is in hydraulic connection with the aquifer (i.e., Konan groundwater basin).

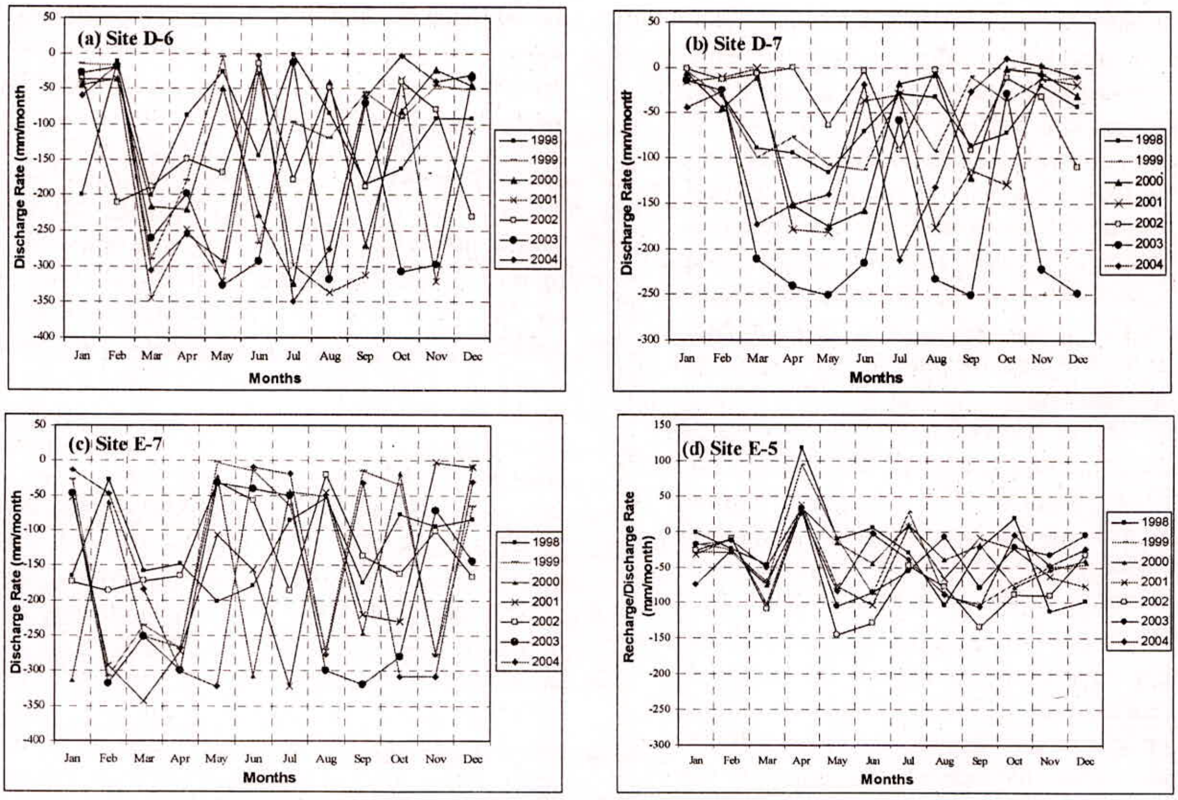

Fig. 2(a–d): Variation of groundwater recharge/discharge during 1998–2004 at four sites

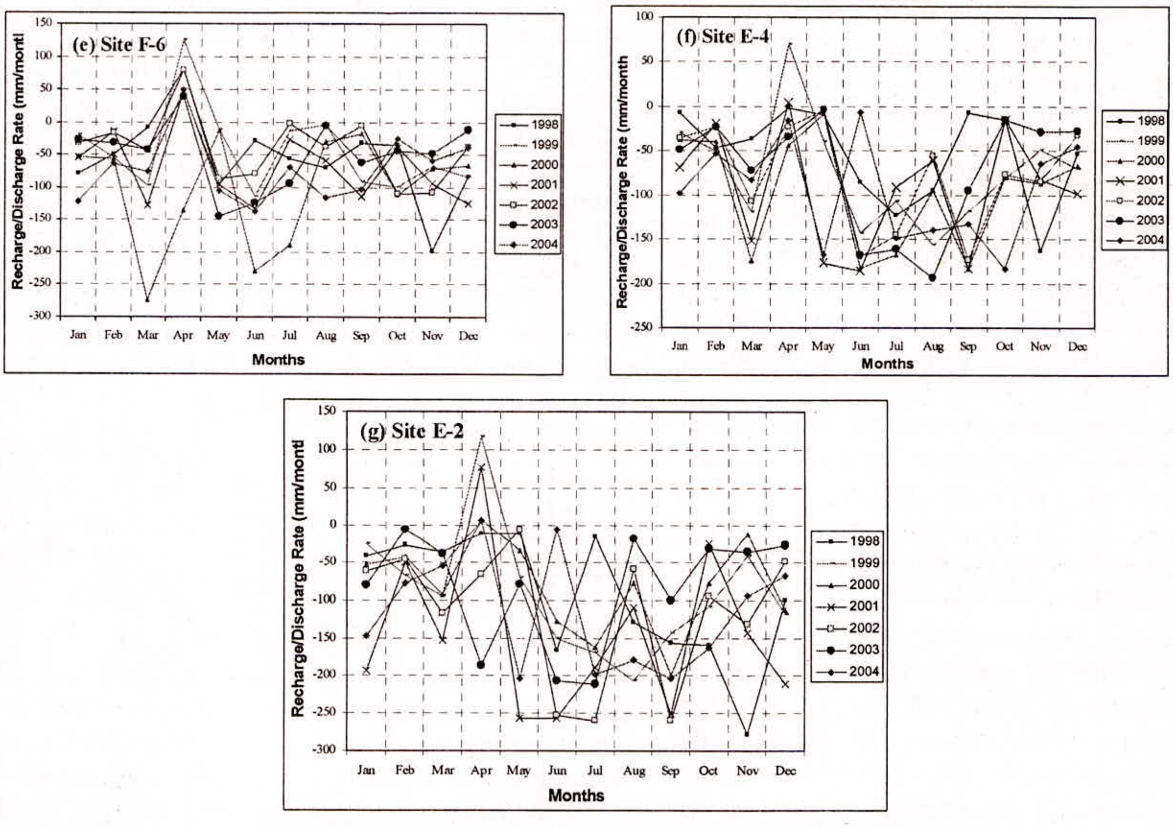

Fig. 2(e–g): Variation of groundwater recharge/discharge during 1998–2004 at three sites

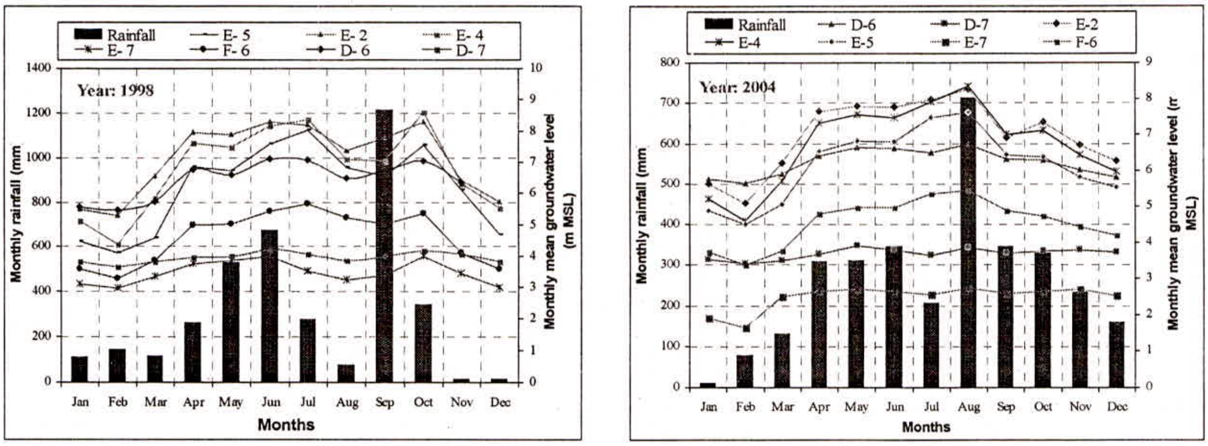

Fig. 3: Well hydrographs at the seven sites and bargraphs of rainfall for 1998 and 2004

Table 1: R^2 Values for the Regression between Monthly Rainfall and Monthly Groundwater Levels at the Seven Sites for the 1998–2004 Period

Site	*Values of Coefficient of Determination (R^2)*						
	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*
D-6	0.27	**0.44**	**0.45**	0.21	**0.50**	**0.67**	**0.64**
D-7	0.20	**0.55**	**0.54**	0.09	0.35	0.36	**0.70**
E-2	0.31	**0.73**	**0.73**	0.27	**0.48**	**0.69**	**0.60**
E-4	0.18	**0.74**	**0.74**	0.28	**0.48**	**0.64**	**0.66**
E-5	0.18	**0.78**	**0.78**	0.25	**0.48**	**0.66**	**0.63**
E-7	0.18	0.22	0.22	0.02	0.02	0.11	**0.44**
F-6	0.25	**0.74**	**0.74**	0.29	**0.53**	**0.61**	**0.62**

Table 2: R^2 Values for the Regression between the Monthly Monobe River Stage and Monthly Groundwater Levels at the Seven Sites for the 1998–2004 Period

Site	*Values of Coefficient of Determination (R^2)*						
	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*
D-6	**0.43**	**0.63**	**0.61**	0.30	**0.67**	**0.78**	**0.69**
D-7	**0.43**	**0.65**	**0.41**	0.01	**0.48**	**0.65**	**0.70**
E-2	**0.51**	**0.75**	**0.64**	0.30	**0.60**	**0.86**	**0.60**
E-4	**0.51**	**0.81**	**0.63**	0.31	**0.44**	**0.79**	**0.67**
E-5	**0.42**	**0.84**	**0.62**	0.30	**0.71**	**0.79**	**0.63**
E-7	**0.78**	0.11	0.14	0.21	0.02	0.01	**0.51**
F-6	**0.43**	**0.83**	**0.66**	0.35	**0.74**	**0.74**	**0.66**

CONCLUSIONS

The growing water scarcity and water pollution in both developed and developing nations have resulted in more and more dependence on groundwater resources leading to groundwater lowering and other associated environmental problems. Proper knowledge of groundwater recharge is essential for the management of invaluable groundwater resources. Analytical models being less data demanding offer a useful practical tool for analyzing complex groundwater systems. In this study, an analytical recharge model was used to analyze the spatial and temporal variations of groundwater recharge/discharge. Seven years (1998–2004) daily groundwater level data and other relevant data were obtained from an alluvial aquifer system in Japan. The recharge/discharge rates were estimated at the seven sites for the seven years using the selected analytical model. For analyzing the groundwater-surface water dynamics, regression analyses were performed between the monthly rainfalls and monthly groundwater levels at the seven sites as well as between the monthly river stage and monthly groundwater levels at these sites.

The recharge and regression analyses indicated very limited number of recharge events, which considerably varied from site to site and year to year. At most sites, the groundwater discharge was found to be predominant during the 1998-2004 period. This analysis also revealed that the groundwater at Sites D-6, D-7 and E-7 is under confined conditions. The regression analysis indicated that both the rainfall and the Monobe River stage are major sources of recharge together with the flow from adjoining areas. The aquifer system was found to be in hydraulic connection with the Monobe River. Finally, it is concluded that the analytical recharge model coupled with regression analysis are very effective tools for analyzing complex hydrogeologic processes.

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