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ORIGINAL ARTICLE

Dynamic analysis of the infiltration rate of artificial recharge of groundwater: a case study of Wanglong Lake, Pingtung, Taiwan

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Abstract Although Pingtung plain is an agriculturally developed region, its limited hydrologic conditions have restrained the maximization of its surface water resources. Due to the lack of proper management and sustainable utilization, groundwater has been overdrawn, causing serious land subsidence and seawater intrusion. The present paper presents a pilot study for artificially recharging groundwater using high-infiltration basins. Results of the geometric factor show that the large basin is ca. 6.8 times the size of the small one, with the infiltration volume almost approaching 1 m^3/day/m^2. In the groundwater variation, the MW-2 is located immediately below the infiltration basin; therefore, its water level rises more rapidly than that of MW-3. As for the infiltration volume, results of the experiment used the same basin since 2002, which shows that the volumes gradually decreased from 12,136 to 5,555 m^3/day. This is particularly evident in 2005 when volume decrease was at a maximum ca. 2,000 m^3/day. Finally, the infiltration rate decreased from 22.76 to 7.15 m/day. The difference in infiltration rate between 2003 and 2005 has a maximum variation from to 15.2 to 10.33 m/day. In 2003, the addition of sand caused the infiltration rate to fall to a minimum ca. 5.3 m/day. By extending the recharge time, the infiltration rate fell gradually similar to those identified from 2005 to 2007.

Keywords Pingtung plain · Artificial recharge of groundwater · Infiltration rate · Land subsidence

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Introduction

Pingtung Plain, located in the southern region of Taiwan, has a regional area of ca. 1,210 km^2. It has a large amount of annual rainfall; by measurement, 90% of the annual precipitation falls during the rainy season (May to September), while only 10% occurs during the dry season (October to April). This uneven distribution in monthly rainfall presents a major problem for planners involved in the protection and utilization of water resources in the area.

Groundwater represents the primary freshwater source for aquaculture water diluting and flushing along the coastal areas of southwestern Taiwan. The process of obtaining groundwater, however, has resulted in environmental and geological hazards including land subsidence, soil salinization and seawater intrusion. To address these problems, local government initiatives have been launched to investigate the potential of exploiting new water

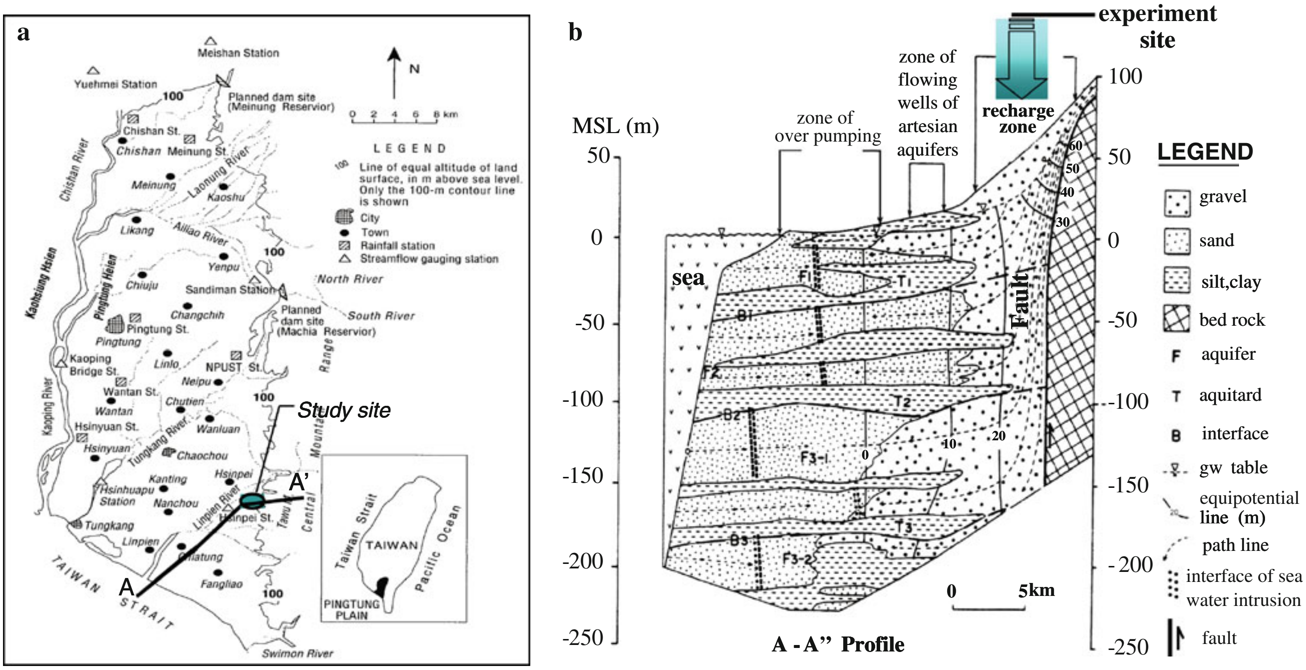

Fig. 1 Location of study area in Pingtung plain, Taiwan (Ting et al. 2002)

resources and developing artificial recharging of groundwater schemes.

One such scheme aims to transfer excess surface water, which can be conserved for use during the dry season, into an aquifer during the rainy season. Wanglong Farm, in the upstream of Siangtan Bridge over Linpien River in the Pingtung Plain, was chosen as a pilot research area (Fig. 1a). Hence, the present paper presents a pilot study for the artificial recharging of groundwater using high-infiltration basins.

Infiltration basin studies discussing artificial recharge design and application have already been published. These studies focused on, among others, groundwater quality variation (e.g., Vengosh and Keren 1996), geochemistry of aquifer recharge (e.g., Van Breukelen et al. 1998; Johnson et al. 1999; Stuyfzand 2002), the problem of clogging (e.g., Zare et al. 2002), water reuse and recharge (e.g., Carlson et al. 1982; Leach et al. 1980; Rice and Bouwer 1984; Legg and Sagstad 2002; Yun-Zheng and Jian-long 2006), and site selection and maintenance (e.g., Lluria 2002; Rastogi and Pandey 2002). Nowadays, these environmental problems can be alleviated by artificial groundwater recharge (Ting 1997) in Taiwan's Pingtung Plain. These schemes not only optimize surface water retention during wet or flood periods, but also conserve groundwater resource, thereby promoting the achievement of sustainable development of water resources in the plain (Ting et al. 2002).

Methodology

Geometric scale of the recharge site

The objective of the pilot study is to gain a better understanding of the artificial recharge of groundwater system, including infiltration velocity, recharge of quantity and water table variation. In doing so, the influence of the quantity of introduced water on groundwater recharge dynamics can more easily be understood.

The groundwater recharge program should begin in a small and simple manner (Bouwer 1999). In the first stage, a smaller infiltration basin 11.5 × 11.5 m in size with a depth of 2.7 m was excavated on 2 October 2001 (Fig. 2a). In the second stage, a larger basin 30 × 30 m in size with a depth of 2.5 m was excavated on 24 October 2001 (Fig. 2b). A 3 × 3 m sediment trap was also constructed at the entrance of the water supply from the Er-Fon irrigation channel.

Groundwater dynamics analysis

China Technical Consultants Incorporated (CTCI) Foundation (2002) constructed four groundwater observation wells in the site along the direction of the water flow (Fig. 3a). The first well (MW-1) is in the upstream region of the pilot experiment basin, MW-2 is in the midst of basin, and the rest of the wells (MW-3–4) are at the downstream of the basin. The observation wells were all

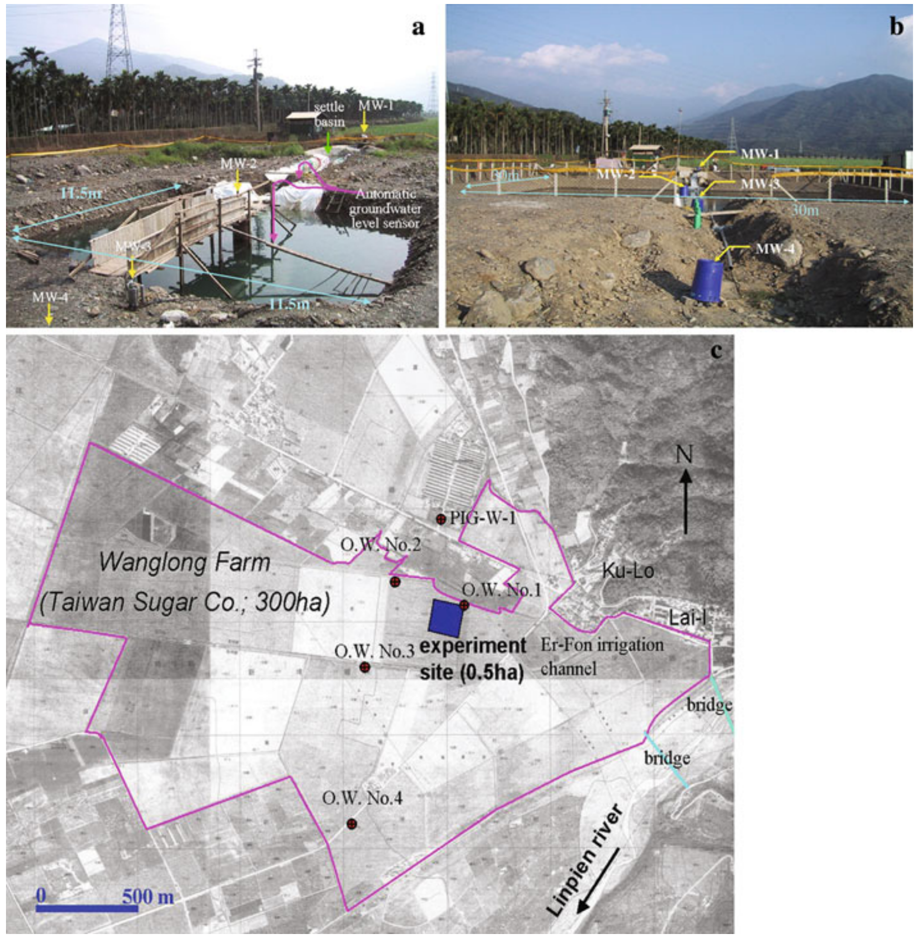

Fig. 2 Recharge experiment site

embedded at 64-m depth and constructed with a 30-m well screen located 32–62 m underground (Fig. 3b).

Mechanisms affecting infiltration rate

The Infiltration rate standard chart issued by Pérez-Parício and Carrera (1998) (Fig. 4) shows that the initial fall in the infiltration rate was caused by the sediment being expended, which then disintegrated after moisturization. The infiltration rate subsequently increased as a result of pore air dissipation because air was dissolved in the water. Gradually, the infiltration rate decreased as a result of sediment pore clogging. This clogging may be a result of the deposition of sediments carried by the water in suspension or caused by algal growth, sediment colloidal swelling, microbial activity or soil dispersion, among others.

Description of the pilot study site

Geology

The geological formation related to groundwater occurrence in the area and a brief description of the deposits found present certain geological characters (Fig. 1b). The recharge zone shows that the unconsolidated sediments constituting the main aquifer in the plain belong to the order alluvium that covers the major part of the recharge zone. Hence, it has been eroded twice by the consequent streams and the inclination of terrace surface. The terrace deposits possess permeable water-bearing properties and are composed of coarse material (Fig. 1b).

The rock formation, probably belonging to the Suao Group of Eocene–Oligocene age, is distributed on the western flank of the Central Mountain Range east of the plain. It forms a thick sequence of black slate intercalated with beds of coarse or fine-grain quartzose sandstone.

The fault is a high-angle reverse fault (Yen and Tien 1986; Meng 1967); there is a geologic boundary between the slate belting to the east and the western foothills to the west. The fault possesses a straight Piedmont line along the central mountain and has proved heterotaxy and fracture filling during the Pleistocene orogeny. In the recent decade, fault activity has therefore not occurred yet (Hsu et al. 1985). The fault is suspected to be active because it is covered by recent sediment. The geology of the upper fault mainly consists of shale and argillite; the lower fault is typically alluvium, which mainly consists of

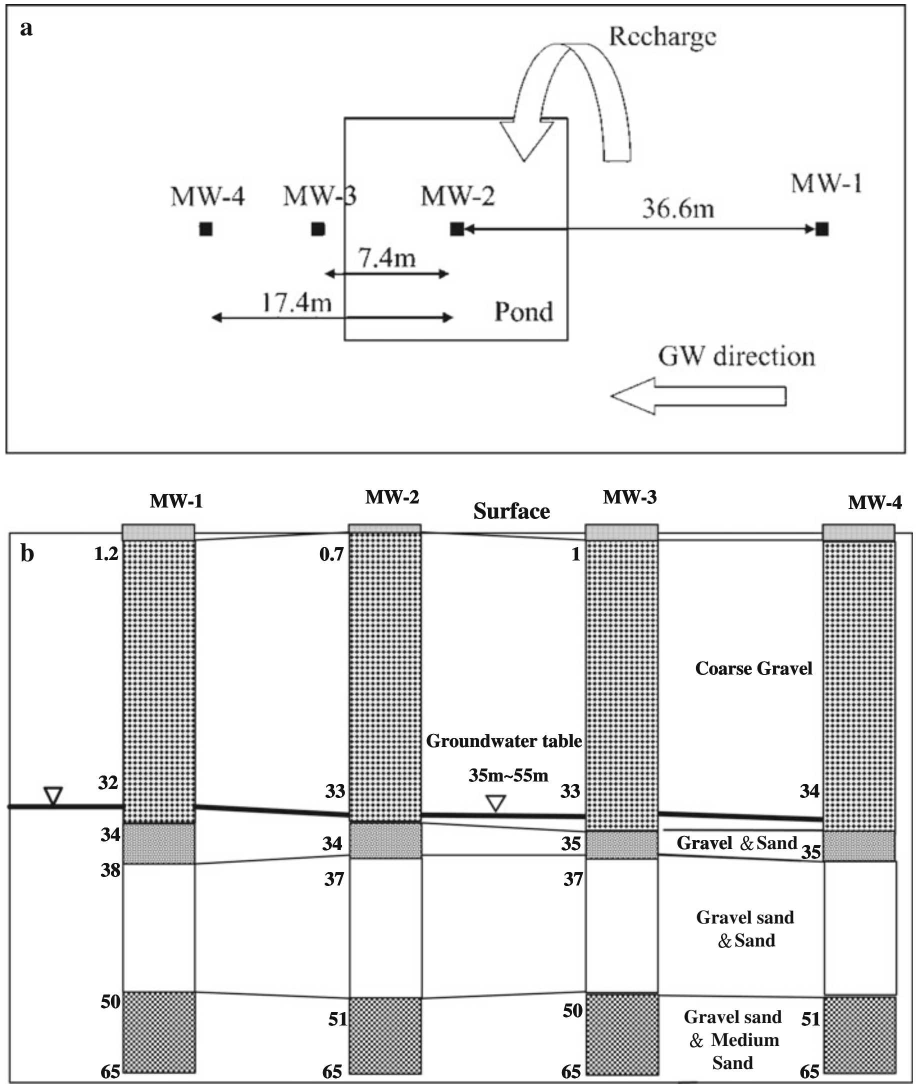

Fig. 3 Position of groundwater level and profiles of observation wells

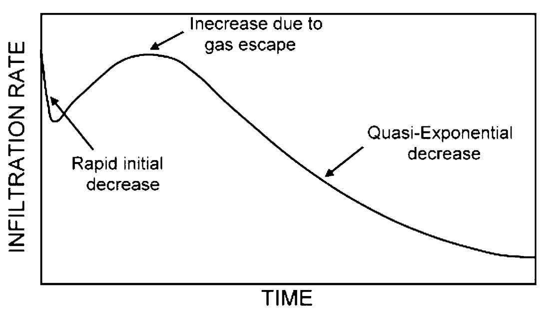

Fig. 4 Infiltration rate standard chart (Pérez-Parício and Carrera 1998)

coarse gravel and is occasionally intercalated with a thin layer of grain.

Hydrogeological conditions

Wanglong Farm is located at the top of the Linpien River alluvial fan, which consists mainly of coarse gravel (Fig. 1b). The natural recharge function of this region is quite reasonable. According to pumping test data, the transmissivity (T) is 18,818 m^2/day, the specific yield (S) 0.13 and hydraulic conductivity (K) 344 m/day.

Pilot study site

Based on a pilot study of groundwater recharge, basic hydrogeological data and results of in situ investigations, one part of Wanlong Farm was chosen as a pilot test site (Fig. 2c). The main channel of the Linpien River originates in the Lai-I and Ku-Lo villages, areas considered as the main sources of groundwater recharge. The following statements summarize the site descriptions:

- The pilot site is hydrogeologically representative of Wanlong Farm.
- There are two pumping wells close to the site, an advantage for understanding groundwater table fluctuations and flow direction.

- There is an irrigation channel nearby (the Er-Fon irrigation channel), and the subsurface weir intake gives a high-quality water source with reduced suspended material.

Water intake considerations

To achieve groundwater recharge in the current experiment, an abundant and stable water supply is needed. The study area is close to the Er-Fong irrigation channel and the Linpien River. The original water from the Er-Fong irrigation channel, which is pure, supplied water to Site 1, while Linpien River supplied water to Site 2. The difference between the original water in Sites 1 and 2 can be compared in this study.

Results of recharge

In-site experiments have been implemented six times since 2000. The results are shown below.

Geometric scale analysis

Small basin

The duration of experiment is 7 days and 20 h. Variations in time of the groundwater table were recorded under the condition of a 1.7 m surface water head on the pond base. Results showed that the average discharge was 2,129 m^3/day, and that the water table in the infiltration basin was ca. 1.7 m. Discharge and water table instabilities were caused by variations in the quantity of water supplied; the total amount of discharge supplied was 16,677 m^3 (Fig. 5a).

Large basin

The total water supply duration was 30 days; discharge and surface water level changes with time are shown in Fig. 5b. Water level was kept at 1.7 m, and the amount of discharge was determined using a V-notch weir. Results showed that long-term average discharge was 12,136 m^3/day, and that average surface water level was 1.63 m above the bottom of the basin. There were some fluctuations in the discharge, but the variation in water level was slight. Total quantity of water supplied was 436,080 m^3.

Groundwater dynamics analysis

Focusing on the start and stop time of the water supply, Fig. 6 shows that the groundwater table rose rapidly and after 50 min achieved stability. The groundwater table for MW-1 started to rise 48 min later, reaching an elevation of 75.38 m after 66 min. The table for MW-2 rose rapidly 12 min after the water supply began, reaching an elevation of 77.68 m after 30 min and becoming stable after 3 h. The level in MW-3 showed a gradual rise for 105 min, reaching an elevation of 76.73 m; 4 h and 20 min later, the

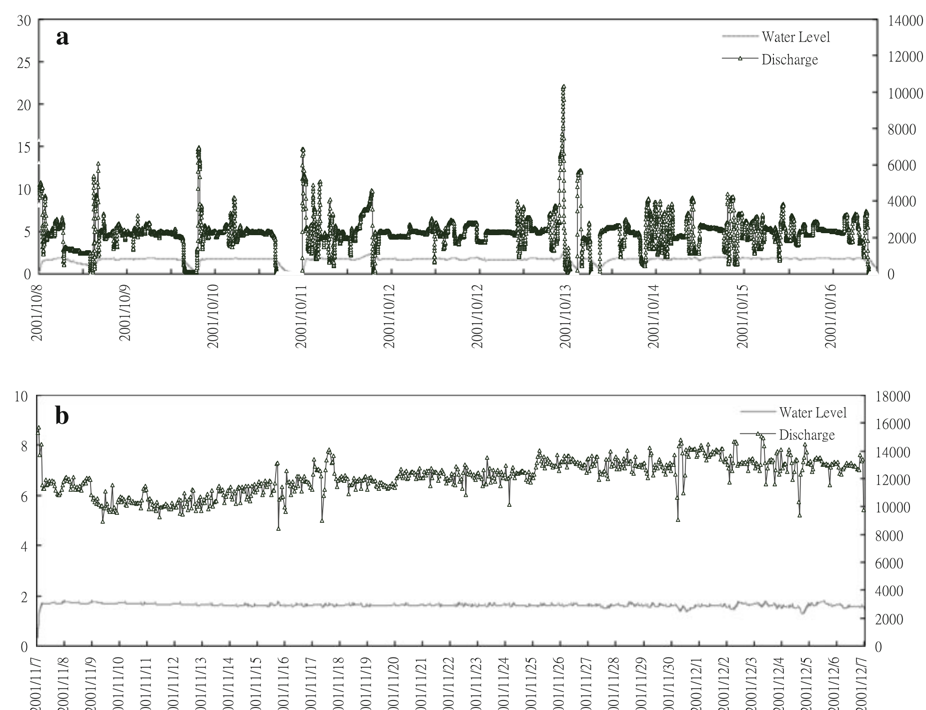

Fig. 5 The variation of discharge and water level for geometric scale analysis

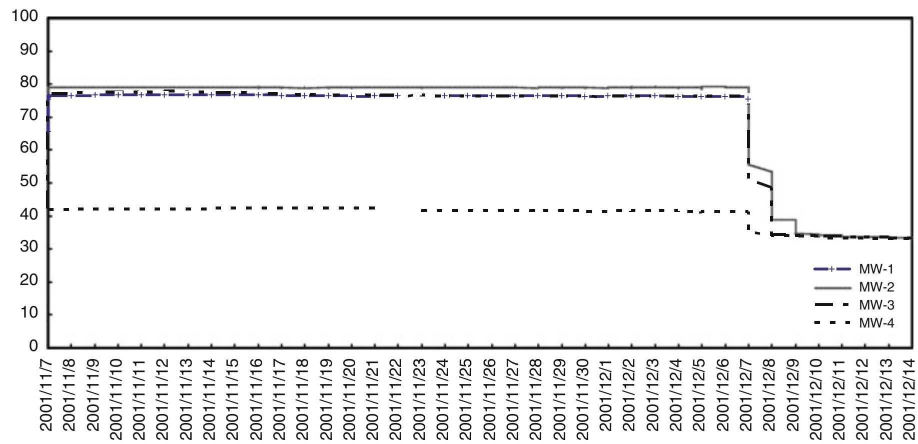

Fig. 6 Temporal variation of groundwater level

groundwater table varied with the water table of the infiltration basin. The groundwater table for MW-4 remained close to 41.7-m elevation.

Infiltration rate analysis

The first stage of the experiment was completed in 2002. When the recharge was first executed in the said experiment site, the duration was 7 days and the total amount of discharge was 16,677 m^3. Infiltration velocity is given by the volume of discharge divided by the projection area of the infiltration basin. Average infiltration velocity (Fig. 7a) in 2002 was 22.76 m/day.

The second stage of the experiment was also completed in 2002. Results of the infiltration velocity calculations are shown in Fig. 7b. The larger fluctuations in infiltration velocity had the same tendency as the discharge variations; average infiltration velocity was 17.26 m/day. Algae were found growing at the bottom and sides of the infiltration basin after 10 days of recharge; growth height after 15 days was about 20 cm. Algal growth was not observed during the first stage of the experiment.

The third stage of the experiment was completed in 2003. The recharge experiment was executed for 17 days to allow for the investigation of the effects of different sand contents on infiltration rate. The sand addition test was prepared during the last 3 days of the experiments (Fig. 7c). The initial infiltration rate was 13.11 m/day, which stabilized at 15.61 m/day. The infiltration rate fell gradually at ca. 5.25 m/day on the sand addition test, showing a reduction of ca. 67%. Hence, the classification of sand is a key factor influencing groundwater recharge.

The fourth stage of the experiment was completed in 2006. The recharge experiment was executed for 17 days. The object of the experiment was to analyze the infiltration rate and the effect factor. During the recharge experiments, the basin water level was maintained at a depth of 1.8 m to provide constant head (Fig. 7d). Average infiltration rate was 10.33 m/day, and infiltration volume was 8,088 m^3/day. Hence, the fine sand that clogged the basin during in situ experiments had to be cleared so that the initial infiltration rate in this site could be restored.

The fifth stage of the experiment was completed in 2006, with the recharge experiment executed within 30 days. The object of the experiment was to identify the effects of infiltration rate and water volume by extending the recharge time.

Results of the experiment show that the basin water level was maintained at a depth of 1.84 m. The initial infiltration rate was ca. 8.55 m/day, and the infiltration volume was 6,466 m^3/day. Results showed that the infiltration rate fell gradually along with the extended time of the recharge experiment (Fig. 7e).

The sixth stage of the experiment was completed in 2007, during which the recharge experiment was performed within 40 days. The final infiltration rate in the experiment was expected to be obtained in this part of the study, hence its design for the extension of the recharge experiment.

Results showed that the initial average infiltration rate was 8.71 m/day, while the initial average infiltration volume was 6,097 m^3/day. After more than 40 days, the final average infiltration rate was 7.15 m/day, while the infiltration volume was 5,555 m^3/day (Fig. 7f).

Results and data analysis

Table 1 shows the results of the geometric scale. The area of the small basin was 132.25 m^2, while the other was 900 m^2. The large basin is ca. 6.8 times the size of the small basin. However, infiltration volume was very close to 1 m^3/day/m^2 because the duration of the experiment on the large basin was 30 days longer than that on the small basin. The infiltration rate decreased gradually according to the times set during the extension of the recharge experiment.

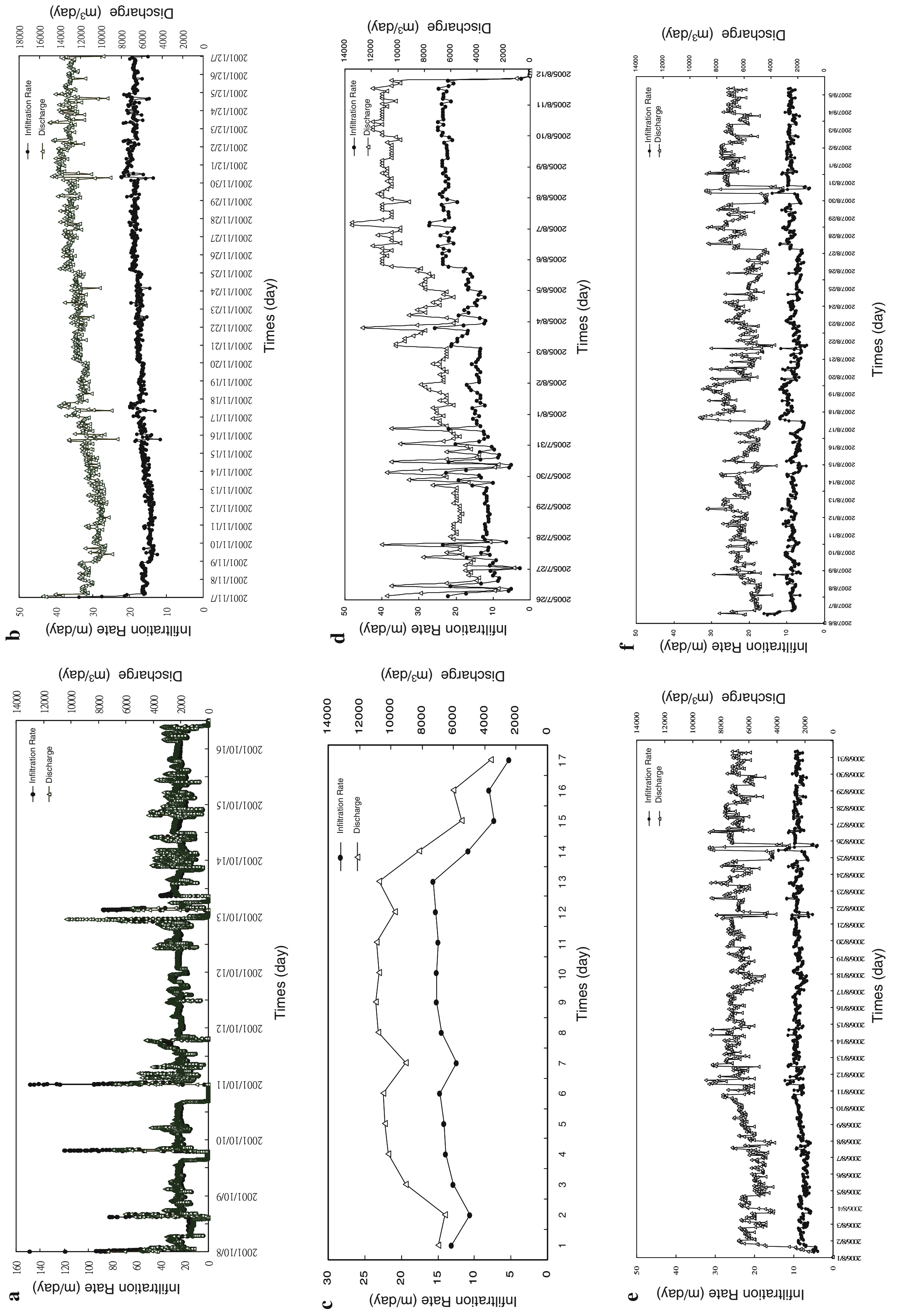

Fig. 7 Variation of infiltration rate for recharge experiment

Table 1 Results of geometric scale analysis

Item	Basin size (m)	Depth (m)	Infiltration rate (m/day)	Infiltration volume (m^3/day)
Small basin	11.5 × 11.5	2.7	22.76	2,129
Large basin	30 × 30	2.5	17.26	12,136

According to temporal groundwater variation during the in-site experiment, results for the observation wells MW-1 and MW-4 had no relationship with the beginning and ending of the water recharge, but showed a continuous decline. Meanwhile, the groundwater table of observation well MW-2 rose rapidly 7 min after starting the supply, achieving stability after 50 min. The observation well MW-3 gradually rose after supplying water for 46 min and achieved stability about 4 h later. The groundwater table again varied with the infiltration basin water table.

Results in literature are shown in Table 2 and Fig. 8. For the infiltration volume, the experiment used the same basin since 2002, showing that the volume gradually fell from 12,136 to 5,555 m^3/day. This is particularly evident in the data from 2005, which showed that the decrease in volume was achieved at a maximum ca. of 2,000 m^3/day while the volume tended to be stable in 2007.

The infiltration rate decreased from 22.76 to 7.15 m/day. The difference in infiltration rate between 2003 and 2005 has a maximum variation ranging from 15.2 to 10.33 m/day. This is due to the sand addition experiment, which caused the infiltration rate to fall to the lowest level of 5.3 m/day in 2003. Although the use of machines for cleaning can restore infiltration capability, it also confirms that cloggy soil could be overcome by manual cleaning. By extending the recharge time, results showed that infiltration rate fell gradually similar to what could be observed from 2005 to 2007.

Conclusions and recommendations

Results of the geometric factor showed that the large basin was ca. 6.8 times the size of the small basin. The infiltration volume was almost very close to 1 m^3/day/m^2. In the experiment, MW-2 was located immediately below the infiltration basin; therefore, its water level rose much more rapidly than MW-3 at the edge of the infiltration basin. Water levels in MW-1 and MW-4 remained virtually unchanged over the course of the infiltration experiment because the wells were positioned outside of the impact radius of the infiltration basin.

For the infiltration volume, the experiment used the same basin since 2002; thus the volumes gradually fell from 12,136 to 5,555 m^3/day This was particularly evident in the data from 2005, which showed that the decrease in volume was at a maximum of ca. 2,000 m^3/day, while the volume tended to be stable in 2007.

Table 2 Results of recharge experiment

Item	Year				
	2002	2003	2005	2006	2007
Duration days for experiment	30	17	17	30	40
Infiltration volume (m^3/day)	12,136	10,000	8,088	6,466	5,555
Infiltration rate (m/day)	17.26	15.20	10.33	8.55	7.15

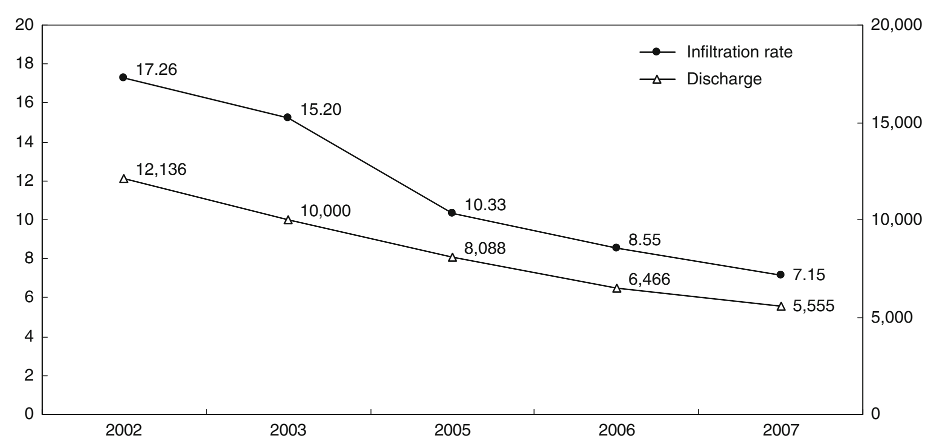

Fig. 8 Results of literature on variation of infiltration rate and infiltration discharge

Meanwhile, infiltration rate decreased from 22.76 to 7.15 m/day. The difference in infiltration rate between 2003 and 2005 had a maximum variation from 15.2 to 10.33 m/day due to the sand addition experiment, which caused the infiltration rate to fall to the lowest level of 5.3 m/day in 2003. Although the use of machines for cleaning can restore infiltration capability, it also confirms that cloggy soil could be overcome by manual cleaning. By extending the recharge time, results showed that the infiltration rate fell gradually similar to those observed from 2005 to 2007.

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