Relationship between increment of groundwater level at the beginning of irrigation period and paddy filed area in the Tedori River Alluvial Fan Area

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Abstract

There are many paddy fields and large amounts of groundwater in the Tedori River Alluvial Fan in Ishikawa Prefecture, Japan. Water infiltration from paddy fields during irrigation may significantly contribute to groundwater recharge. Groundwater recharge is known to be one outcome of agriculture, and in general is usually related to land use. However, a decreased area of paddy fields because of socioeconomic factors such as urbanization and increasing area of fallow fields, has possibly affected the groundwater environment. Evaluation of the quantitative effect of paddy fields on groundwater is necessary for groundwater conservation. This study examined the relationship between differences in the depth of groundwater from just before the irrigation period to just after the first irrigation of paddy fields (increments of groundwater levels) in observation wells and the area of paddy fields around each well. The paddy areas within circular buffer zones, which were delineated at 0.2 km intervals between 0.2 km and 2.0 km, were calculated. A positive relationship was found between the rise in groundwater and the area of paddy field within different buffer zones at most wells. Additionally, in the middle or upper part of the fan, the effect of changes in the area of paddy fields surrounding the well on the groundwater level rise was greater than that on the lower part of the fan.

Keywords:

Groundwater recharge; Paddy field; Alluvial fan; Groundwater management

Introduction

Much groundwater is stored in the Tedori River Alluvial Fan in Ishikawa Prefecture, Japan. The groundwater is an important source of drinking and industrial water. To allow its sustainable use, it is necessary to evaluate the influence of natural and artificial impacts on changes in recharge, flow and runoff. Paddy field land covered about 50% of the Tedori River Fan in 2006. It is recognized that water infiltration from paddy fields during irrigation periods significantly contributes to groundwater recharge and that such recharge is an outcome of paddy agriculture (Mitsuno et al. 1982; Matsuno et al. 2006). Furthermore, water flooding of paddy fields in water is an effective method of groundwater recharging (Kiriyama and Ichikawa, 2004). However, over recent years the area of paddy fields has decreased because of socioeconomic factors such as urbanization, increasing areas of fallow fields and rice yield controls imposed by the government. This has possibly caused a decrease in the amount of groundwater recharge (e.g. Elhassan et al. 2001; Imaizumi et al. 2006; Anan et al. 2007). Accordingly, it is important to clarify the extent to which the decline in paddy field area affects the groundwater level to provide background data for future sustainable paddy agriculture.

The groundwater level is considered to be a major parameter for evaluating spatial and temporal changes in groundwater environments. The groundwater level is governed by some factors such as topography, geological structure, land use and climate conditions. At the site used in this study, there are some major factors influencing the groundwater level, including groundwater use for drinking and industrial water, and the interaction between the groundwater and river water including both river water infiltration to groundwater and groundwater flow to the river (Tsuchihara et al. 2010). However, in this first stage of a wider study we focused on evaluation of the direct relationship between groundwater levels and paddy field areas. We examine the relationship between differences in the depth of groundwater from just before the irrigation period to just after the first irrigation of paddy fields (hereafter called increments of groundwater levels) and paddy field ratios around the sampled wells, and use circular buffer zone analysis to investigate how the distance of paddy fields from the sampled wells influences changes in groundwater levels.

Materials and Methods

Study Area

Topography and Geology

The study site is the Tedori River Alluvial Fan in Ishikawa Prefecture, Japan. The center of the fan is at North 36°31′, East 136°34′ (WGS 84). The alluvial fan has been formed by the Tedori River and has a typical topographical shape. The right side of the fan is wider than the left side. The northeast area overlaps with the Sai River Alluvial Fan. The area studied is on the right side of the fan and is enclosed by the Tedori River, Sai River, Fushimi River, Japan Sea, and the Hakusan Mountains as shown in Figure 1. The study area covers about 140 km^2 and is about 16 km from north to south and 12 km from west to east. The top of the fan is about 90 m above sea level and the average slope is about 1/140 (the fan is relatively steep).

The main geological deposit is sandy gravel with a depth of over 130 m at the middle part of the fan. In the middle and upper parts of the fan, the aquifer is confined by alluvium composed of alternate layers of sandy gravel (diluvium and alluvium), and sandy gravel and clay (Quaternary and Tertiary) (Hokuriku Regional Agricultural Administration Office, 1977). Underlying the alluvium is tertiary bedrock. Along the coastline of the Japan Sea, a clay layer is wedged into the gravel layer.

Land use and Groundwater use

Figure 2 illustrates changes of land use conditions using 100 m mesh data, which will be described below. The land use of the area in 2006 consisted of paddy, upland, urban (building), river, and others covering 52%, 2%, 34%, 2%, and 9%, respectively. The city of Kanazawa, the prefectural capital, is located on the northeast of the fan, an area in which there is much expansion of the urban area. There are also many business entities (e.g. food factories, breweries, and precision machine factories), which need much groundwater, in this part of the fan. The paddy field area ratio (paddy field area/total area) was 70%, 62%, 61%, 58%, and 52% in 1976, 1987, 1991, 1997, and 2006, respectively. The upland field ratio is about 2% and this has changed very little over time. However, the area of urban land has increased considerably, particularly around the central part of Kanazawa.

Annual groundwater use in the Tedori River fan was 1.01×10^8 m^3 in 2009 (Ishikawa Prefecture, 2010), of which industrial water, city water, snowmelt water, irrigation water, and building maintenance water accounted for 59%, 30%, 4%, 4%, and 3%, by deep respectively. In addition, about 32% of quantity of the drinking water is supplied wells. Figure 3 shows the changes in distribution of annual groundwater use (using a 1km mesh) between 1987 and 2005 (Ishikawa Prefecture et al. 2007). The amount of pumping is large in the downstream section of the Tedori River and in central parts of Kanazawa. Groundwater pumping increased until 1992 because of increasing drinking water requirements but showed little change from 1992 to 2005.

Analysis

Data sets

In the study area, there are 11 observation stations (Figure 1. A-K). Two wells with different strainer depths exist at 2 points (E and J in Figure 1), so there are 13 wells in total, details of which are summarized in Table 1. Daily mean groundwater levels have been observed since basically 1974. In the study, we divided the fan into three parts. The area within 5 km of the crest of the fan is described as the upper part, from 5 km to 10 km of the crest is the middle part, and the farthest 10 km is the lower part (Figure 1). There are 4 wells in the middle part and 9 wells in the lower part.

Groundwater levels were measured simultaneously from June 2 to June 7, 2010 at 86 wells (including some observation wells) during the irrigation period. These measurements were used to depict the contour of the groundwater level.

The land use data are 100 m mesh data produced by the National Land Numerical Information download service (the Ministry of Land, Infrastructure, Transport and Tourism) for 1976, 1987, 1991, 1997, and 2006 (Figure 2).

Data Analysis

Figure 4 shows fluctuations in the decade-average groundwater levels at F station. The seasonal pattern of fluctuation observed in the wells (other than H and J (Deep) stations) showed first, a substantial increase of the groundwater level from the end of April to early May (the beginning of the irrigation period). This is due to the paddy fields being plowed and irrigated before the rice seedlings are transplanted. Second, during July to September (the irrigation period), groundwater levels remain high and stable. Finally, during October to April (the non-irrigation period), groundwater levels decrease and fluctuate slightly. At H and J (Deep) stations, clear changes in groundwater level were not apparent because groundwater use by pumping was relatively large.

The increments of groundwater levels at the beginning of the irrigation period are considered to be typical of the pattern of groundwater level changes in the paddy irrigation area (Horino et al. 1989). Our study examined the relationship between increments of groundwater levels of the observation wells and paddy field area ratios surrounding their wells. Increments were calculated by subtracting the weekly mean groundwater level before irrigation from that after the first irrigation. The low stable-level period is considered to be from April 13 to April 19 and the high stable-level period from May 1 to May 7. At B and J stations, however, the low stable-level appeared later, so weekly mean groundwater levels before irrigation for these stations were derived for the period from April 22 to April 28.

Paddy field area ratios were calculated within circular buffer zones, which were delineated in 0.2 km intervals from 0.2 km to 2.0 km. We recognize that the buffer zone may not necessarily be circular. However, we assume that a circular buffer zone with a radius of 2.0 km is sufficient for considering the effect of the infiltrated water from paddy fields on the groundwater level at a well located at the center of the circular zone and that the simplification inherent in using a circular buffer zone will not significantly affect consequent discussion. At near-coastal wells at B, D, E, and H stations, large circular buffer zones overlapped the ocean areas and the paddy field ratios were calculated for the land areas only.

Results and Discussion

Distribution of the groundwater level

Figure 5 shows contours of the groundwater level and depth measured in the irrigation period (June, 2010). The groundwater level contours indicate that the groundwater flows from the upper zone of the fan to the northwest side. Depths of the groundwater level were 15-25 m at F, G and I stations which are located in the middle part of the fan, and 0-10 m at the other wells in the lower part. Underlying the area along the coastline is a clay layer 2 - 44 m below the surface. Considering results from bore explorations and depths of the strainer in the observation wells (Table 1), the shallow wells at E and J stations may be measuring the shallow groundwater level in the unconfined aquifer. The other wells are considered to be measuring the deep groundwater level of the aquifer.

Increments of groundwater levels

Figure 6 shows changes in the increments of groundwater levels at the beginning of the irrigation period. At F, G, and I wells in the middle part of the fan, the increments were about 3-5 m in about 1980 and declined to about 1-3 m until 2009. Similarly, some observation wells in the urban area (A, B, C and D) show decreases from 1-2m to 0.5 m of the increment of groundwater level. The K well, which is located near the Tedori River in the middle part of the fan, showed little increment during 1980s, but the increment increased around 2000.

Paddy field area ratio

Paddy field area ratios in each buffer zone have decreased over the past thirty years, from 1976 to 2006, as shown in Figure 7. In particular, A, C and D wells located near the urban area and F, G and H wells are surrounded by many paddy fields, and the temporal changes of paddy field area ratio were larger than for other wells. For the C and D wells especially, as the buffer distance is large the amount of change in the paddy field area becomes smaller because the land use change is averaged in the case of large buffer zones.

Relationship between the increments of groundwater level and the paddy field area ratio

Figure 8 shows relationships between the increments of the groundwater levels and the paddy field area ratios for a buffer distance of 1.6 km. At most wells, a good linear relationship was found for all buffer zones and correlation coefficients mostly exceeded 0.7. However, at the H and J (Deep) wells in which groundwater levels did not show the seasonal changes, correlation coefficients were low. In addition, J (Shallow) and K wells showed a negative relationship despite the paddy field area ratios being relatively high (J well around 70% and K well 60%) probably because the three H, J and K wells were influenced by infiltration of river water and the K well was also influenced by heavy groundwater use by pumping (Figure 3).

Correlation coefficients between the increments of groundwater levels and paddy field area ratios were calculated for the wells which have high positive relationships as shown in Figure 9. When the buffer distance increased from 0.2 km to 2.0 km, the coefficients mostly exceeded 0.7. However, when the buffer distance was less than 1.0 km, for instance in both the shallow and deep wells at E station, correlation coefficients were low. This is because the increments have declined since around 1990 (Figure 6), despite the paddy field area ratios exceeding 70% with little changes in paddy field area ratios over time (Figure 7). This result indicates that changes in paddy area within more than 1.0 km from the well have led to the groundwater level rising at the beginning of the irrigation period. Furthermore, Figure 9 (b) shows that the G well has a negative correlation coefficient at a 0.2 km buffer distance. The same reason as for the E well is suggested as the reason for this. At G well, the paddy fields influencing the groundwater increment are over 0.4 km from the well. The paddy field area ratios did not change significantly when the buffer distance increased, so the range which affects the groundwater level cannot be clarified. Overall then, paddy fields at least 1.0 km from observation wells affected the groundwater level rise at the start of the irrigation but this result can be significantly influenced by the location of the well on the fan.

Therefore, we explored the impact of land use conditions relative to position of the well. Linear relationships exist between the increment of groundwater level and the paddy field area ratio as shown in Figure 8. For those wells with high positive correlations, the slope of the fitted line was calculated for three different buffer distances as shown in Figure 10. The value of the slope implies the degree of the influence of a unit change in the paddy field area on the increment of the groundwater level. At F, G, and I wells which are located in the middle part of the fan, slopes are greater than for other wells in the cases of the three circular buffer zones. Additionally, the slope at E (Shallow) well was comparatively high. This is considered to be because the groundwater level at this well reflects the shallow groundwater in the unconfined aquifer which is more affected by infiltration water from paddy fields.

The increments of groundwater levels caused by infiltration of the paddy water were more affected by changes in the paddy field area in the middle part of the fan. One reason for this is that the upper groundwater recharge area may be limited in the middle part of the fan relative to the lower part.

Conclusions

To evaluate the effects of paddy field on groundwater in the Tedori Alluvial Fan, we examined the relationship between the increments of groundwater levels and paddy field area within buffer circles whose radius ranged from 0.2 km to 2.0 km from the sampled wells. A positive relationship was found at almost all wells and the correlation coefficients did not change between different circular buffer zones. The effect of changes in paddy field area on groundwater level at a given well is greater in the middle part of the fan than in the lower part. It is confirmed that paddy fields have a profound effect on groundwater levels during the irrigation period. To raise the groundwater level during the irrigation period, conservation of paddy fields is very important, especially in the middle and upper parts of the alluvial fan.

Acknowledgments

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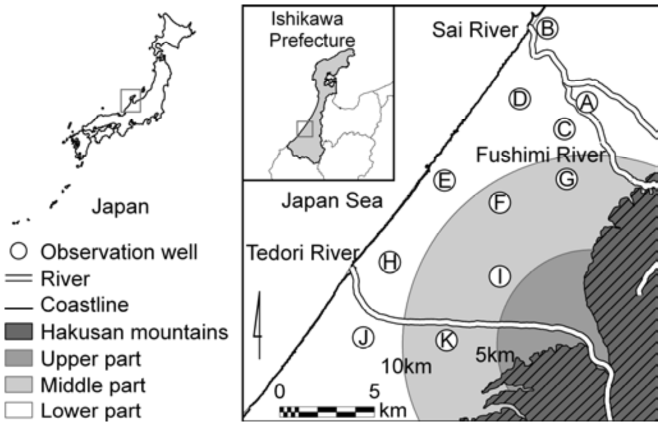

Fig.1.tif Study area and observation wells

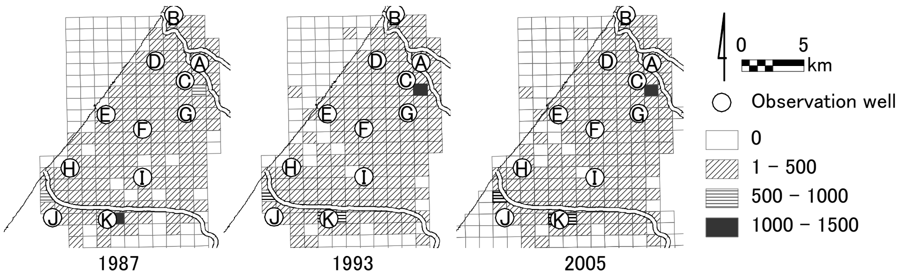

Fig.3.eps Groundwater use in the Tedori River Fan

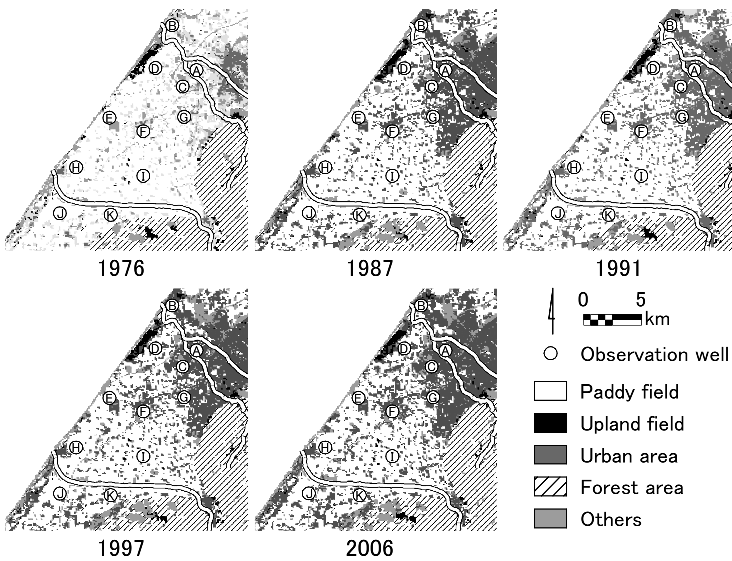

Fig.2.eps Land use on the Tedori River Fan

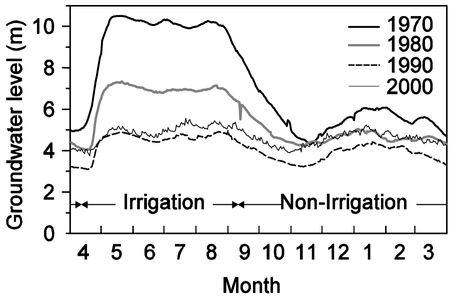

Fig.4.eps Fluctuation in the decade-average groundwater level at F station

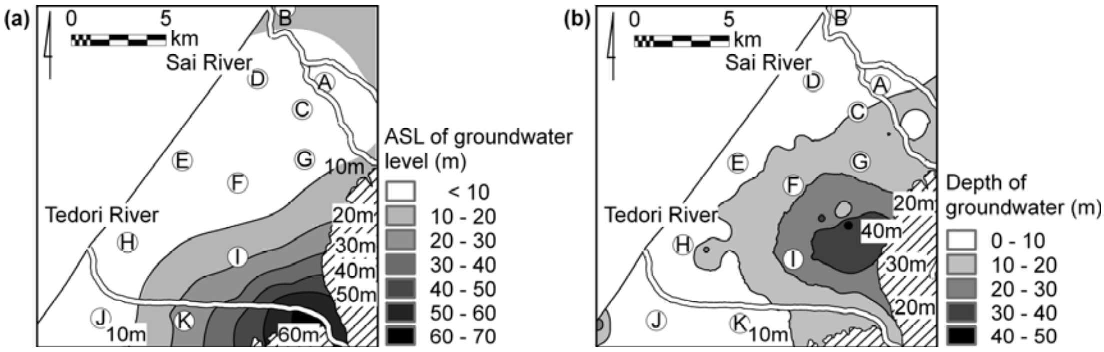

Fig.5.tif Distribution of groundwater level in the irrigation period. (**a** ASL of groundwater level. ASL means above sea level, **b** Depth of the groundwater level)

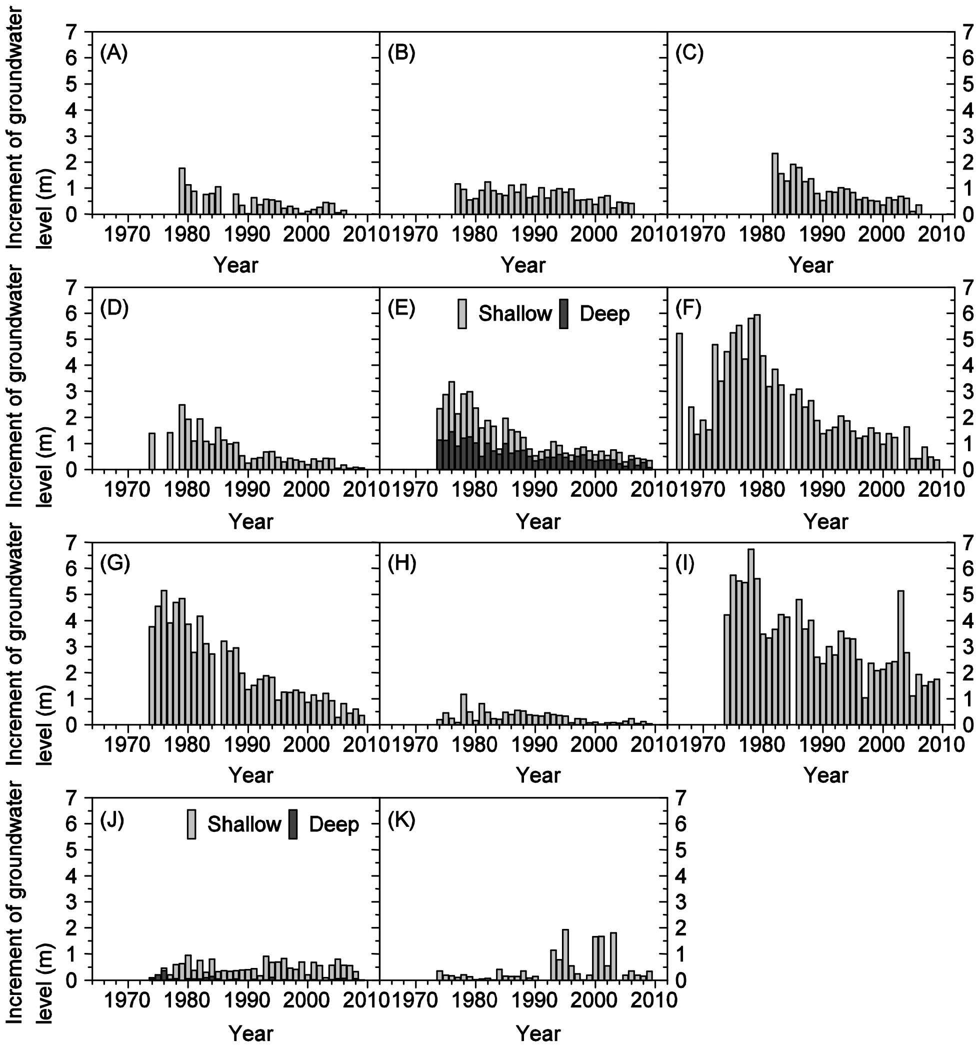

Fig.6.eps Changes in the increments of groundwater levels in the observation wells

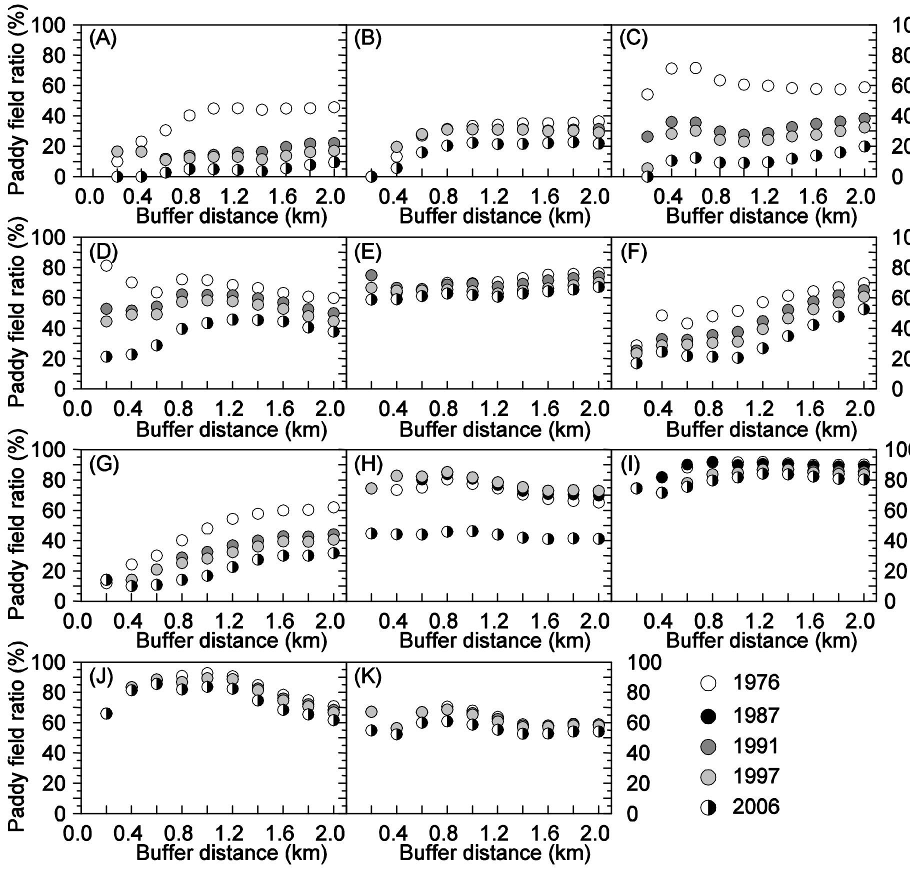

Fig.7.eps Changes in paddy field area ratios in the buffer zone for the observation wells

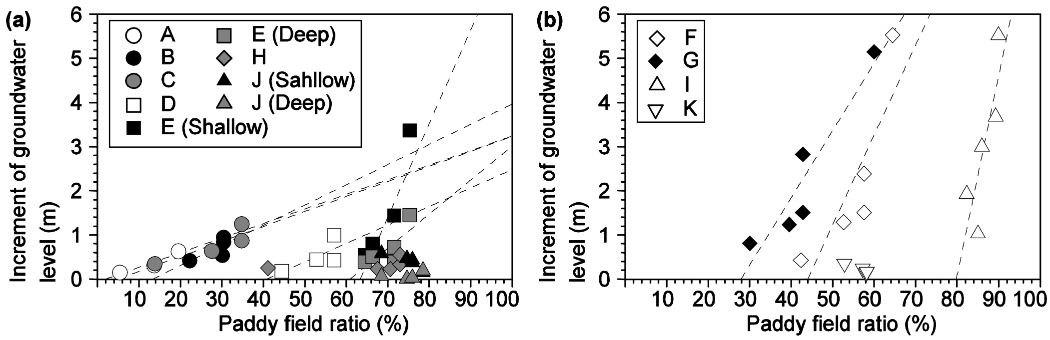

Fig.8.eps Increments of groundwater levels and paddy field ratios. (Buffer distance is 1.6 km) Fitted lines are shown only for wells in which the correlation coefficient exceeds 0.7 (**a** Relationships in lower part and **b** in middle part)

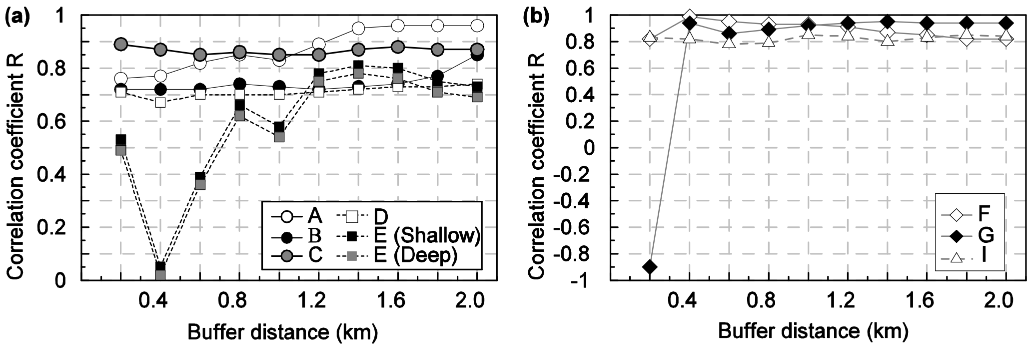

Fig. 9.eps Changes in correlation coefficients for different buffer distances. Only wells with high positive correlations are shown (**a** Changes in lower part and **b** in middle part)

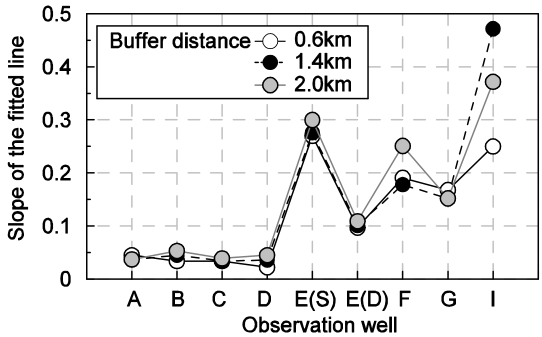

Fig.10.eps Changes in the slope of fitted linear correlations for three buffer distances (0.6, 1.4, and .2.0 km)

Table 1 Characteristics of the observation wells

Well	Elevation (m)	Depth of well (m)	Depth of strainer (m)
A	7.40	150	137-145
B	1.91	150	58-80, 113-131, 137-145
C	9.67	150	123-128, 134-150
D	3.85	200	134-151
E	8.93	82/200*	23-32, 43-55/160-172, 183-189*
F	24.08	30	21-27
G	23.20	150	123-139
H	5.78	200	120-139
I	42.73	100	72-88
J	7.99	70/150*	24-42/78-93*
K	23.84	60	11-22, 38-49

Note: Depth of the strainer at E and J refers to shallow well/deep well.