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

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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 paddy farming, 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 centered on each observation well, 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 of groundwater. 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 farming (Mitsuno et al. 1982; Matsuno et al. 2006). Furthermore, water flooding of paddy fields in winter is suggested to be an effective method of groundwater recharge (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 in order to provide background data for future sustainable paddy farming.

The groundwater level is an important parameter for evaluating spatial and temporal changes in groundwater environments. The groundwater level is governed by various factors such as topography, geological structure, land use, groundwater use, and climate conditions. At the site used in this study, there are some non-negligible 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 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 (hereafter called increments of groundwater levels) and paddy field area ratios to total area around the sampled wells, and used 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) as shown in Figure 1. 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 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).

Figure 2 illustrates geological conditions across the study site. 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 3 illustrates changes of land use conditions using 100 m mesh data, of which accessing method 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%, 3%, 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 area 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 city.

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% , respectively. In addition, about 32% of quantity of the drinking water is supplied by deep wells from the confined aquifer. Figure 4 shows the spatial distribution of annual groundwater use (using a 1km mesh) in 1987, 1993, and 2005 (Ishikawa Prefecture et al. 2007). The amount of pumping discharge is large in the downstream section of the Tedori River and in central parts of Kanazawa. Annual groundwater pumping increased until 1992 because of increasing drinking water requirements but showed little change from 1992 to 2005 by the regulation of groundwater overdraft (Ishikawa Prefecture, 2010).

Fig.3 Land use on the Tedori River Alluvial Fan

Fig.4 Groundwater use in the Tedori River Alluvial Fan

Analysis

Data sets

In the study area, there are 11 observation wells of groundwater level (A-K in Figure 1). 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 with automatic pressure type or float type water – gages from 1974 with some exception to 2006 for the wells A-C and to 2009 for the others. 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 observation wells in the middle part and 9 observation 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, 2011) for 1976, 1987, 1991, 1997, and 2006 (Figure 3).

Data Analysis

Figure 5 shows fluctuations in the decade-average groundwater levels at F well. The seasonal pattern of fluctuation observed in the wells (other than H and J (Deep) wells) 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. Third, during September to October (the beginning of the non-irrigation period), groundwater levels decrease dramatically. Finally, during November to April (the non-irrigation period), groundwater levels fluctuate influenced by rainfall, snowfall, and snowmelt. At H and J (Deep) wells, clear changes in groundwater level were not apparent because groundwater use by pumping was relatively large in the areas near these observation wells. 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 these 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 every year. At B and J wells, however, the low stable-level appeared later, so weekly mean groundwater levels before irrigation for these wells 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 centered on each observation well. As described later in this paper, there were indeed only a few changes in the correlation coefficients between the increments of groundwater level and the paddy field area ratio for the buffer radius lager than one plus decimal km. This supports and rationalizes the maximum buffer radius range (2.0 km) we set. 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 in using a circular buffer zone will not significantly affect consequent discussions. At near-coastal wells at B, D, E, and H wells, large circular buffer

Results and Discussion

Distribution of the groundwater level

Figure 6 shows contours of the groundwater level and depth from the soil surface 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 wells 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 (Hokuriku Regional Agricultural Administration Office, 1977) and depths of the strainer in the observation wells (Table 1), the shallow wells at E and J wells 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 7 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 around 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. At E (Shallow), E (Deep) and H wells in the lower part of the fan, the increments also decrease. J (Shallow). Groundwater levels at the J (Deep) well do not show seasonal pattern of fluctuation and the increment of groundwater levels at the J (Deep) well is very little typically less than 0.1 m. 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. It is considered to be due to the decrease of groundwater pumping in the area near the K well (Figure 4).

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 8. In particular, at A, C and D wells located near the urban area and at F, G and H wells are surrounded by many paddy fields, 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 temporal 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 9 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 4).

Correlation coefficients between the increments of groundwater levels and the paddy field area ratios were calculated for the wells which have high positive relationships as shown in Figure 10. 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 the E well, correlation coefficients were low. It is considered that the buffer circle with the radius of 0.2 km cannot explain the decreasing of amount of water level rises at the E well. However, as the radius of the buffer circle is taken larger, the correlation between increment of groundwater level and the paddy field area ratio becomes more significant, showing that 1.0 km correlation is higher than 0.2 km. 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 10 (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 9. For those wells with high positive correlations, the slope of the fitted line was calculated for three different buffer distances as shown in Figure 11. 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 groundwater catchment 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 at the sampled wells and paddy field area within buffer circles whose radius ranged from 0.2 km to 2.0 km from each sampled well. 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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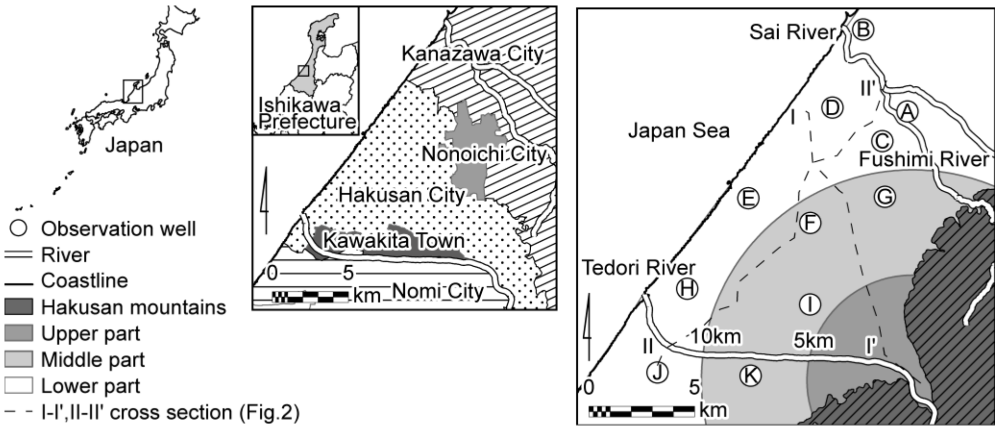


Fig.1 Study area and observation wells

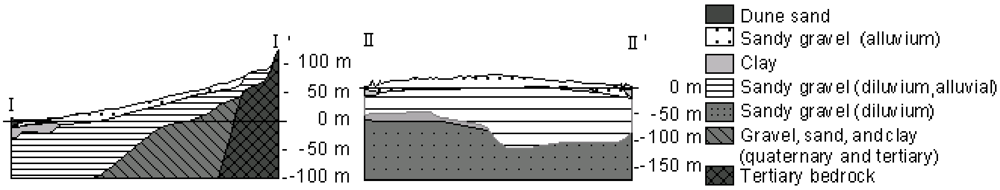


Fig.2 Geological conditions across the study site (Line I-I', II-II' in Fig.1) (Modified From Hokuriku Regional Agricultural Administration Office, 1977)

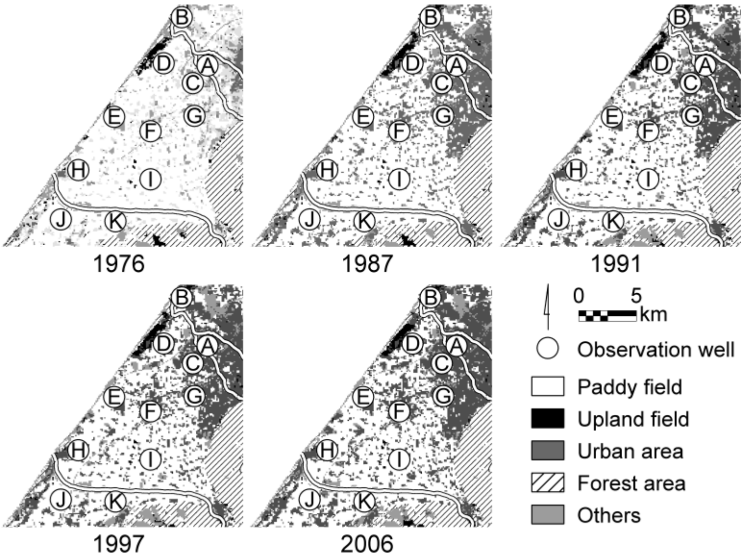


Fig.3 Land use on the Tedori River Alluvial Fan

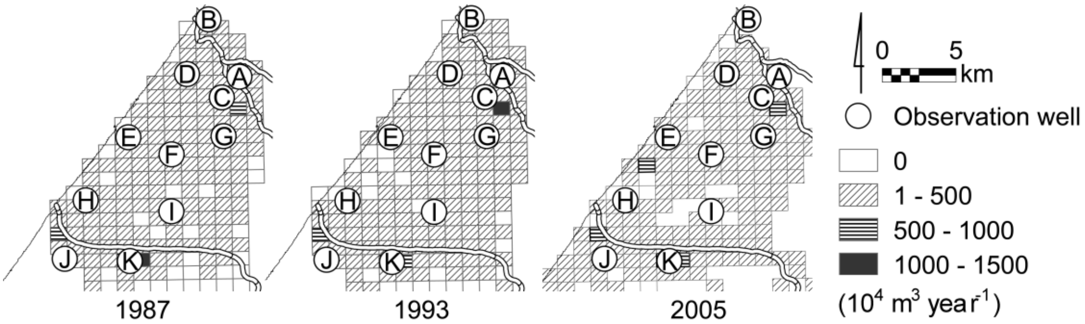


Fig.4 Groundwater use in the Tedori River Alluvial Fan

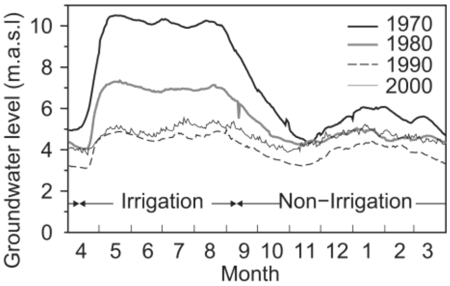


Fig.5 Fluctuation in the decade-average groundwater level at F well (m.a.s.l means meters above sea level)

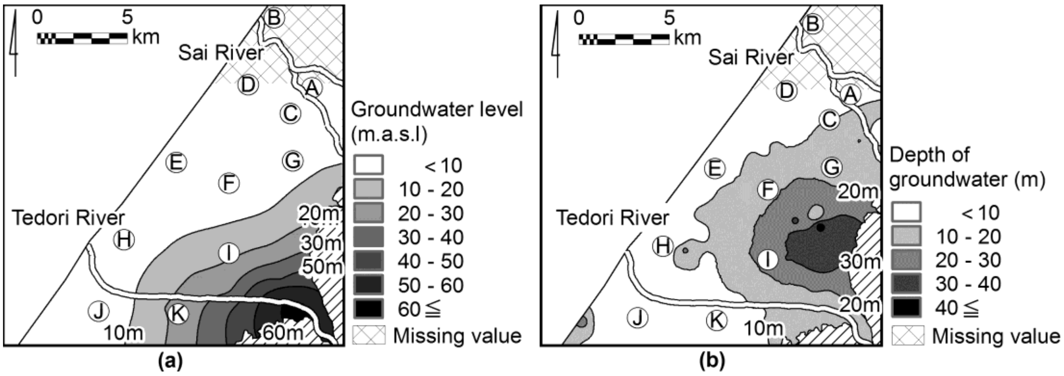


Fig.6 Spatial distribution of groundwater level in the irrigation period (**a** Groundwater level, **b** Depth of the groundwater level from the surface)

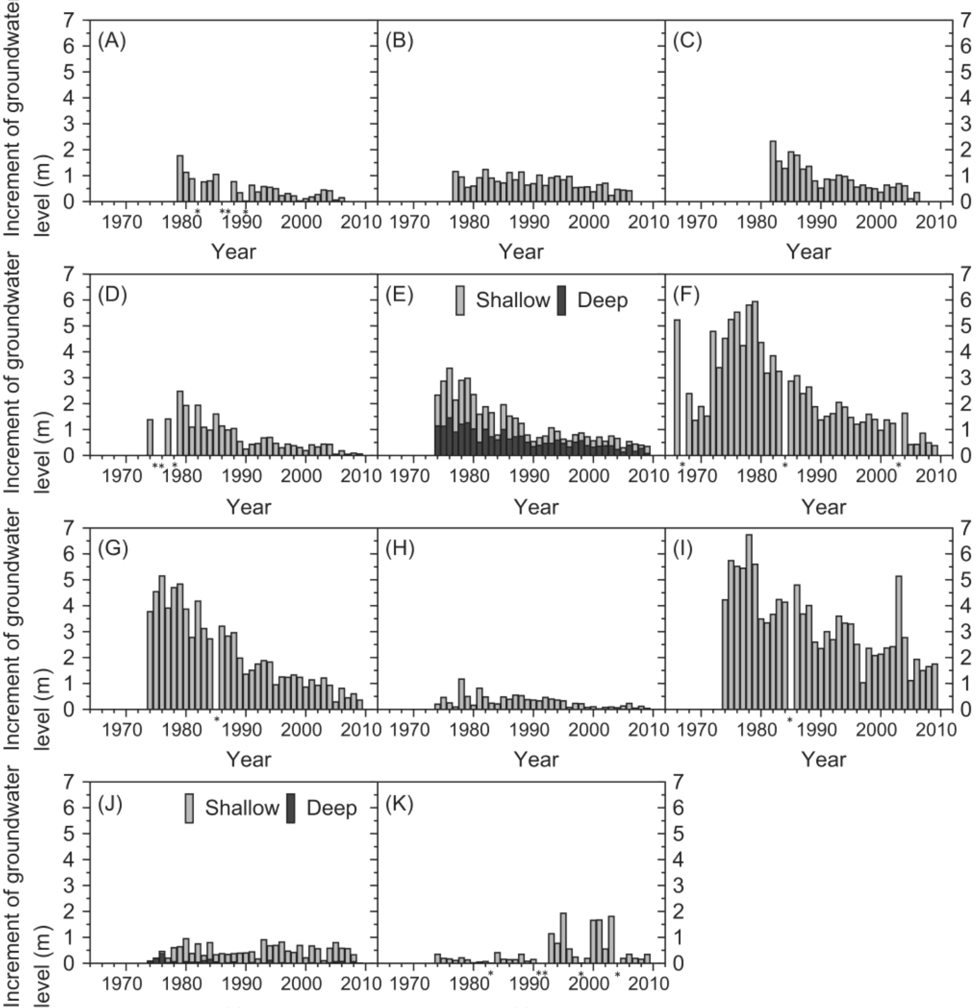


Fig.7 Changes in the increments of groundwater levels in the observation wells

*(asterisk) means missing value

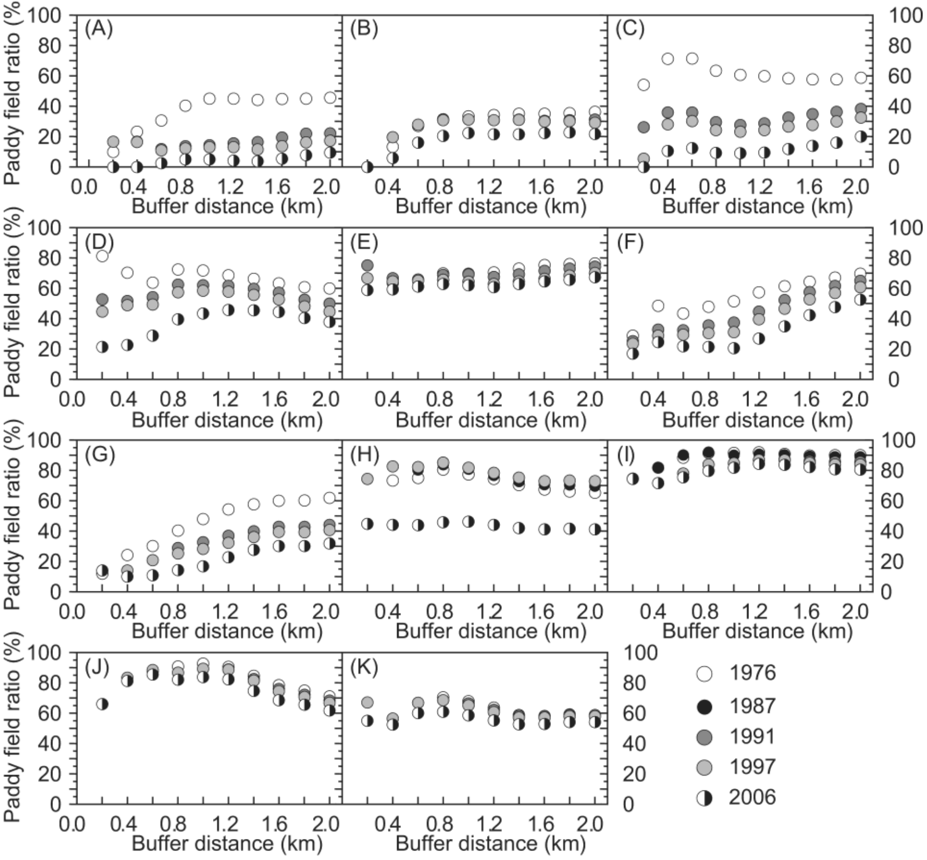
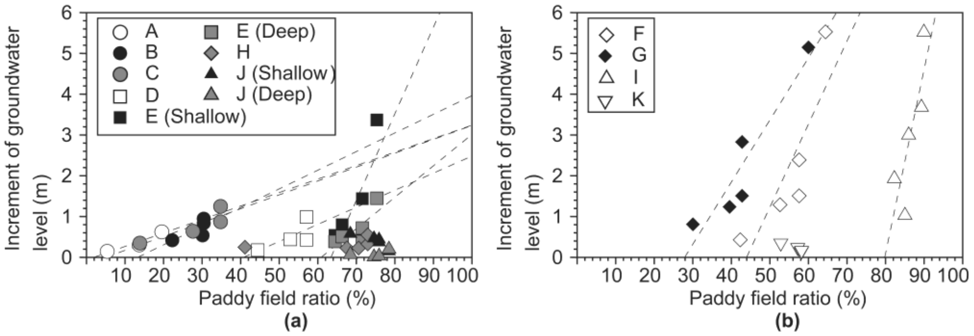


Fig.8 Changes in paddy field area ratios in the buffer zone for the observation wells



(a)

(b)

Fig.9 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)

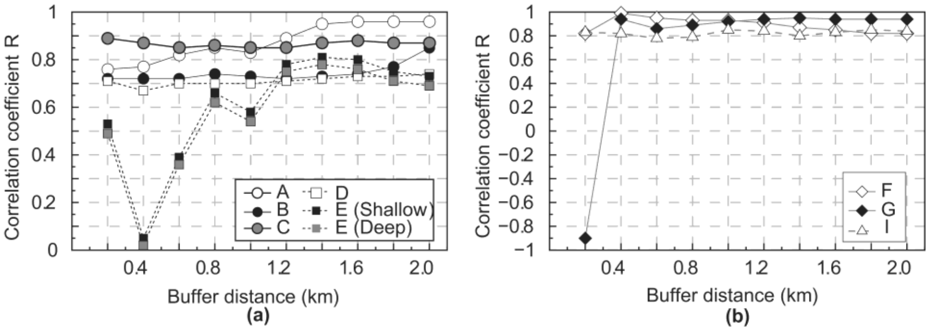


Fig.10 Changes in correlation coefficients for different buffer distances. Only wells with high positive correlations are shown (**a** Changes in lower part and **b** in middle part)

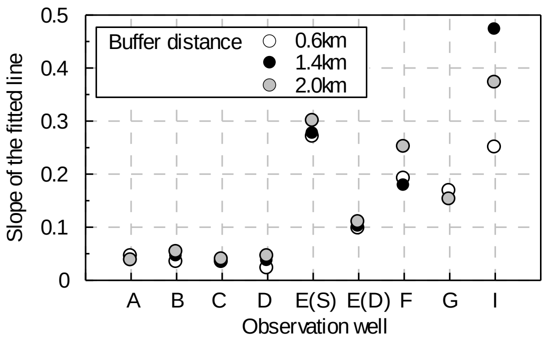


Fig.11 Changes in the slope of fitted linear correlations for three buffer distances (0.6, 1.4, and .2.0 km). Note: E(S) means shallow well and E(D) means deep well