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Estimating Land Use Impacts on Regional Scale Urban Water Balance and Groundwater Recharge

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Abstract Anthropogenic activities have exerted increasingly large-scale influences on terrestrial ecological systems from the past century, primarily through agriculture; however, the impact of such changes on the hydrologic cycle is poorly understood. As one of the important land use (LU) in the coastal Dogo Plain of the Seto Inland Sea, Japan, paddy fields have been decreasing with the increase in urbanization in recent decades. As the main source of water in the Dogo Plain, groundwater plays an important role in providing people with fresh water and contributing to stream base flow. The purpose of this study is to analyze the water resource and evaluate the effect of LU change on groundwater table fluctuation in this coastal plain. Firstly, the observations of groundwater table and the investigation of water balance

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were carried out in this alluvial plain. Then, a distributed four-block three-layer water balance model was employed to analyze the groundwater table fluctuation with response to the change of paddy field area. Moreover, the role of paddy field in recharging groundwater in the basin has been clarified. Results show that groundwater table depends not only on rainfall and discharge from rivers, but also on irrigation water and topology of the study area. The net groundwater recharge was positive in irrigation periods whereas that in non-irrigation periods was nearly equal to zero or negative. The results of this study would be helpful to the urban development policy and land use planning decision.

Keywords Land use change · Paddy field · Coastal plain · Groundwater recharge

1 Introduction

There is an increasing recognition of the potential impact of land use (LU) change on the atmospheric components of the hydrologic cycle (regional and global climate; Pielke et al. 1998; Lambin et al. 2001; Pitman et al. 2004). Shallow groundwater plays an important role in river valleys and delta's around the world. However the impact of LU change on subsurface components of the hydrologic cycle, particularly groundwater recharge, is less well recognized. The potential scale of subsurface impacts is large because groundwater is the Earth's largest freshwater resource (Scanlon et al. 2005). In Japan, groundwater is commonly used for drinking, industry, and irrigation in alluvial plains and it is one of the most important water resources. Whereas, the lowering of groundwater table has occurred in a lot of alluvial plains and basins due to over-pumping of groundwater or decreasing of groundwater recharge. In the research site of this study, the coastal Dogo Plain of the Seto Inland Sea, Japan, the absence of reliable water resources leaves groundwater as the primary source of water, providing for municipal, industrial and agricultural uses. In order to fulfill the demands for agricultural, domestic and industrial needs, the dependency on groundwater in the Dogo Plain is rapidly increasing. In recent decades, the increasing concerns over agricultural water use, surface water reliability and groundwater storage changes have increased the demand for sustainable groundwater management. Previous studies in this coastal plain have shown that the groundwater table fluctuation and long term trends depend on groundwater recharge, which is a function of precipitation, evapotranspiration, and groundwater pumping (Takase 2000; He et al. 2005; He and Takase 2006).

As one of the important landuse in the Dogo Plain, paddy field performs important functions in the ecosystem, such as maintenance of groundwater supply, water purity, nitrogen cycle control, and mitigation of local climate. In the Dogo Plain (Fig. 1), which is a typical, irrigated agriculture site in a coastal region, the area of paddy fields has been decreasing with the urbanization in the recent decades and changing to other land uses such as residential area, roads, etc (Fig. 2). As a part of regional development planning, research has been initiated by the laboratory of hydrology for environmental engineering (LHEE), Ehime University, Japan, in order to estimate the impact of further urbanization on the hydrologic cycle and to propose effective alternatives. The research includes both long-term monitoring and assessment of changes in the hydrologic cycle.

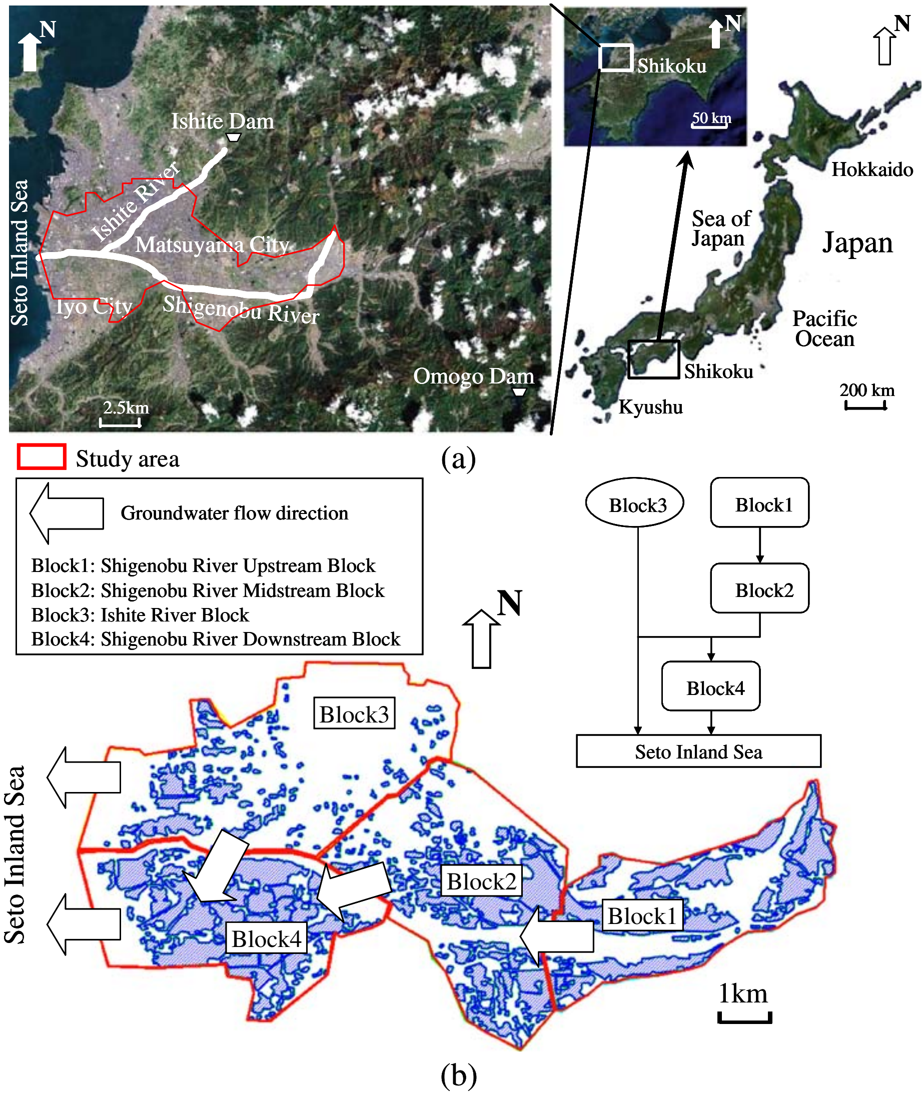


Fig. 1 Location of the study site in which four blocks have been divided (He et al. 2008)

Changes in land use occur continuously in response to population growth and changes in the primary production activities. Land cover and land use changes alter the hydrological cycle of a catchment by modifying rainfall, evaporation, and runoff. The Dogo Plain is typical of irrigated agriculture in coastal regions. To investigate the impact of these land use changes on groundwater recharge in this coastal plain, a distributed four-block three-layer water balance model was developed (He et al. 2006, 2008). For model verification, the simulation of groundwater level was carried out for 4 years using the optimized parameters, which are partly calibrated by the nonlinear optimization Shuffled Complex Evolution (SCE) method (Duan et al.

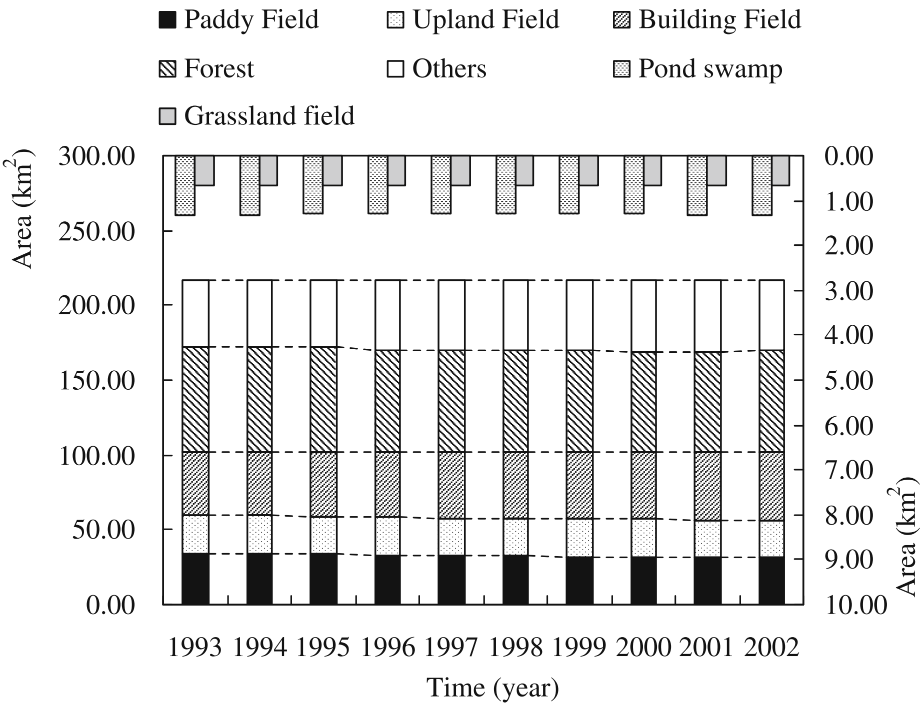


Fig. 2 Ratio and descendent trend of paddy field area in the coastal Dogo Plain

1992, 1993, 1994). By the comparison of the observed and simulated groundwater table, good agreement between them showed that the proposed model is capable of predicting the groundwater table and analyzing the water balance in this coastal region. In this study, the impact of LU change on the groundwater recharge was simulated by using this hydrological model and the measured hydrogeologic and meteorological data in this costal plain. The results of the simulated water-table fluctuations and trends in groundwater could provide important information on urban water balance and groundwater recharge response to LU changes at daily timescales.

2 Site Description

The study site chosen for this study is located on the western border of the Dogo Plain on Shikoku Island, Japan (Fig. 1). It is surrounded by mountains in the south, north, east, and by the Seto Inland Sea in the west. In the Dogo Plain, the Shigenobu River is the main river and the groundwater is composed by one large groundwater flow along the Shigenobu River and another groundwater flow along the Ishite River. The groundwater flow along the Shigenobu River comes from the background of forest watersheds. The joint groundwater flow, which finally flows into the Seto Inland Sea, comes from two sources. One is from the background watershed of Iyo city to the Seto Inland Sea on the left bank of the Shigenobu river's downstream and the other is from the Ishite River on the right-bank downstream of the Shigenobu River. Furthermore, the groundwater along the Ishite River partly flows into the Seto Inland Sea from the left bank side and partly joins the groundwater from the right bank (He et al. 2006, 2008).

A distributed four-block three-layer conceptual model was successfully developed to estimate the patterns of groundwater table change and water balance components numerically (He et al. 2006, 2008). Considering the groundwater flow property and all components of water balance in this study, the whole plain was divided into four blocks as discussed in He (He et al. 2006, 2008). The groundwater recharge model that expressed the hydrologic cycle in each block and the water input and output between each block was developed as shown in Fig. 3. The hydrologic system of the whole study area is conceptualized as consisting of three layers: (1) a surface water supply system with associated land uses such as paddy land, farm land, and urban area; (2) a subsurface aquifer layer; and (3) an underlying groundwater aquifer region system (He et al. 2006, 2008). The hydrologic cycle in each block is expressed by a water balance model and the elements expressing the water input and output in each block are described in detail in He et al. (2008). Summarily, the input elements include precipitation, discharge from surrounding watersheds, irrigation water. The output elements include evapotranspiration, pumped water for industrial and domestic use, pumped water for agricultural use from groundwater region, river outflow, and groundwater outflow. The article of He et al. (2006, 2008) has shown that the proposed groundwater recharge model is able to account for basin-scale groundwater table and water balance variable which responses to groundwater recharge. In this paper, the model will be employed to simulate the groundwater table fluctuation under the change of landuse.

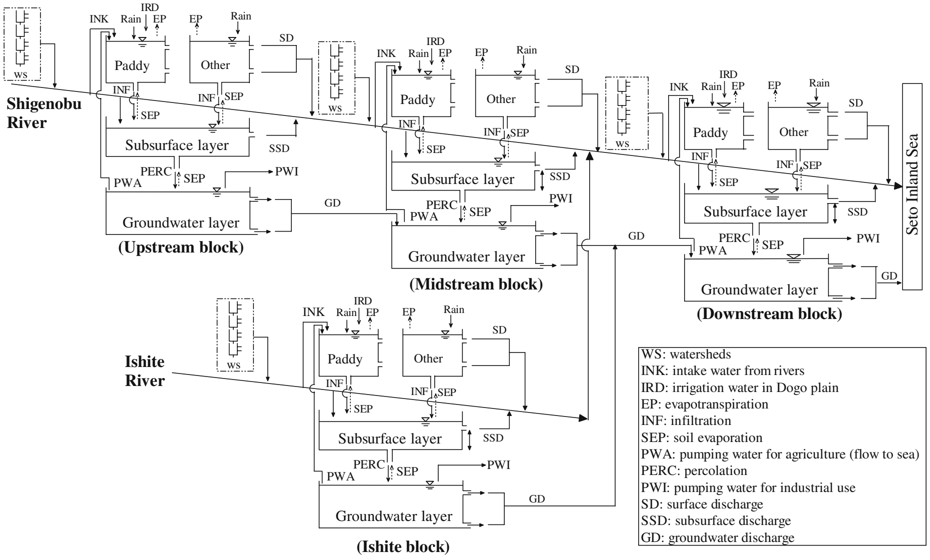


Fig. 3 Schematic figure of the distributed groundwater recharge model (*Upstream Block*: Block1; *Midstream block*: Block2; *Ishite block*: Block 3; *Downstream block*: Block 4)

3 Results and Discussion

3.1 Water Balance Analysis

As results, the water balance of the whole basin are illustrated in Figs. 4 and 5. The total volume of water which flowed in the Dogo Plain as rainfall, diverted water for irrigation, pumped water for irrigation and inflow from surrounding mountainous area was about 4 times as much as that of rainfall. The outflow from the surface and subsurface region as runoff and evapotranspiration was two third of the total inflow. As a result, one third of the total inflow to the area of interest was distributed to the groundwater. Furthermore, groundwater storage comparison from the measured data has been conducted for both irrigation period and non-irrigation period in Table 1. From the table it can be seen that the evapotranspiration, groundwater recharge, and agricultural water use in the irrigation period (from May to September) is larger then that in the non-irrigation (from October to April) periods.

Judging from the above analysis and the results of water balance investigation in irrigation periods and non-irrigation period, it could be concluded that the percolation from paddy field in irrigation periods might occupy an important part in recharging groundwater in the area of interest. A part of the recharge was used for the irrigation and municipal purpose and the other parts flowed out to the sea as groundwater flow.

3.2 Groundwater Table Simulation Following the LU Change

A variety of approaches can be used to assess the impact of LU changes on subsurface hydrology (Knowles et al. 1984; Salama et al. 1999). The most direct approach is relating LU changes to water table fluctuations. The comparison between the measured and simulated groundwater table using the optimized parameters by the SCE method is discussed in preliminary studies (He et al. 2005, 2006, 2008). The model parameters were optimized by comparing the calculated and observed groundwater table for the Dogo Plain. Results indicated that calculated groundwater tables were able to adequately describe the behavior of the shallow aquifer. For further analyzation of the groundwater recharge change with different ratios of paddy field in the Dogo Plain, the ratio of paddy field area has been assumed as one of the following two scenarios. Cases 1 and 2 represent 60% and 30% of the present paddy field area, respectively. The simulated groundwater table fluctuation in the typical hydrologic years of 2003 (normal flow year), 2001 (high flow year), and 2002 (drought year) in cases 1 and 2 are shown in Fig. 6.

Fig. 4 Average ratio of water balance components in the Dogo plain for the non-irrigation period (unit: %)

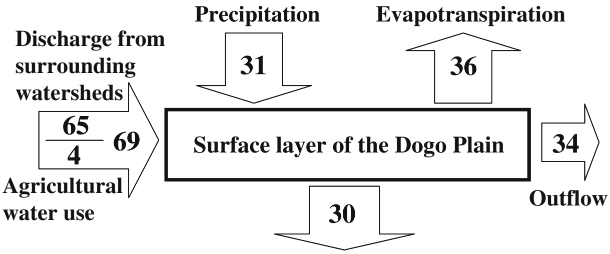
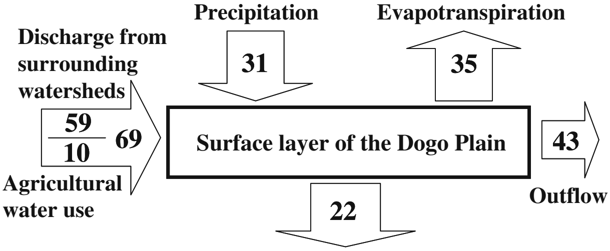


Fig. 5 Average ratio of water balance components in the Dogo plain for the irrigation period (unit: %)



From the figure, the following results were obtained:

1. With the decrease of the paddy field area and increase of the urban area, the regional urban groundwater table decreased, especially in the irrigation seasons from June to October for each hydrologic year. The largest drop in groundwater table was in the drought year of 2002. Then the normal flow year was the second, and the low flow year was the smallest.
2. For the normal flow year 2002, the drop in groundwater table after the irrigation seasons increased and this increase continued to the next year if the paddy area decreased. However, following the drought year 2000, the groundwater table drop of the high flow year 2001 did not appear in December because of a sufficient water supply in this year.
3. Comparing cases 1 and 2, the paddy field area decreased by half but the groundwater level dropped more than half in most periods of all simulation years. From the above analysis, the impact of the LU change on the groundwater recharge was large, especially in drought seasons.
4. In block 1, the impact of LU change on groundwater is small because Block 1 is located in the upstream area and the groundwater storage is sufficiently large. Whereas, in Block 2, 3 and 4, groundwater table falls remarkably, especially in the irrigation periods of the normal flow year.

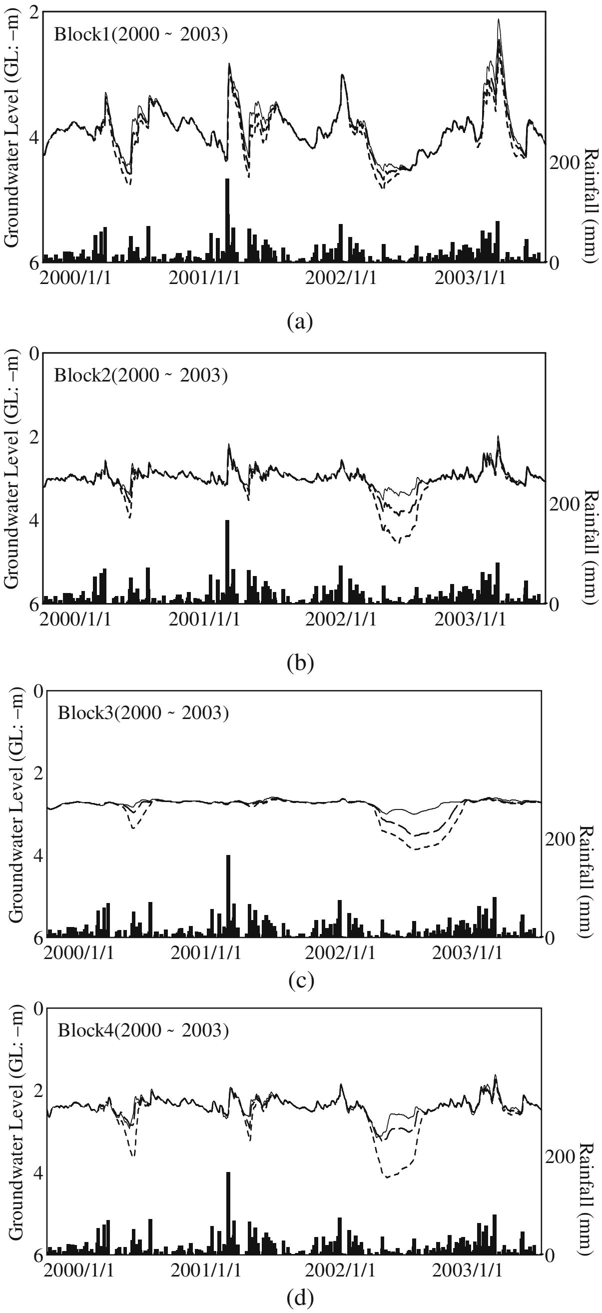
3.3 Indication for Urban Water Resources Management

The results of this study shows that land use change have significant effects on hydrological processes such as soil moisture and groundwater recharge. Other researcher's studies has shown that vegetated soils with soil moisture losses from ET retain more infiltrating precipitation than bare soils with soil moisture loss from evaporation alone. In another word, vegetated soils would produce less groundwater recharge than bare soils (Laio et al. 2001; Guswa et al. 2002). The study in this paper also shows that groundwater makes a significant contribution to the water budget of the Dogo plain. During periods of low rainfall, when direct runoff to streams is reduced, groundwater may provide the water to keep streams flowing. Furthermore, the demand of groundwater in the Dogo plain would be increased. Generally, there are obviously two ways to cater to the increased demand of groundwater. One way is to find additional sources of groundwater and/or surface water. However, it is increasingly difficult to find and utilize new sources of water to satisfy the rapidly growing population, particularly in urban areas (Dragnet and Cronin 2004; Niemczynowicz 1999). The other way is to manage the demand by changing technol-

Table 1 Water balance components from the measured data for irrigation period and non-irrigation period

Year	Inflow				Outflow			Groundwater storage (mm)
	Rainfall (mm)	Discharge from surrounding watersheds	Water for agriculture use	Total	Discharge to rivers	Evapotrans-piration	Total	
Irrigation period (May–Sep)								
1991	753	1,743	159	2,655	1,312	659	1,971	684
1992	580	993	142	1,715	783	684	1,467	248
1994	405	293	564	1,262	62	827	889	373
1995	828	1,604	146	2,578	1,129	752	1,881	697
1996	576	1,254	115	1,945	777	722	1,499	446
1997	668	1,478	92	2,238	1,224	713	1,937	301
Average	635	1,228	203	2,066	881	726	1,607	458
Non-irrigation period (Oct–Apr)								
1991	159	1,012	9	1,180	591	420	1,011	169
1992	517	1,060	12	1,589	744	434	1,178	411
1994	243	666	258	1,167	277	452	729	438
1995	399	537	8	944	183	448	631	313
1996	407	540	11	958	223	432	655	303
1997	527	897	4	1,428	450	462	912	516
Average	375	785	50	1,211	411	441	853	358

Fig. 6 Simulated groundwater table fluctuation in four blocks in the Dogo Plain under the impact of paddy area. (*Dark line* observed value; *Dashed line* simulated value in Case 1; *Dashed short line* simulated value in Case 2)



(a)

(b)

(c)

(d)

ogy and policies as well as increasing water use efficiency. Obviously, it is better to meet the needs with currently available water resources while preserving the ecosystems rather than trying to satisfy projected future increases in demand (Gleick 2001).

In addition, as commonly known, water as an industrial input enhances the productivity of capital, labor, and other factors of production. To proactively cope with increasing urban water demand accompanying rapid regional economic growth, government should endeavor to uncover the causal relationship between urban water consumption and regional economic growth and to make appropriate water policy. Therefore, the governments can collaborate with municipalities to have water efficiency plans and monitor their implementation. Furthermore, the integrated water resources management (IWRM) has been in focus of research in the last decade. It aims to consider quality and quantity problems of both surface and groundwater resources simultaneously with the water demand affairs. It is possible for us to use IWRM as a platform to the better cooperation of experts and decision makers with different backgrounds. Summarily, the study of groundwater recharge and urban water balance in this paper can be a preliminary step for the further integrated water management in urban areas.

4 Conclusion

The objective of this research is to analyze the hydrologic cycle and water resources for a coastal plain in the Seto Inland Sea by considering the change of land use. Using the measured meteorological and hydrogeologic data of the Dogo Plain, the hydrologic cycle of this plain was studied. A distributed four-block three-layer conceptual water balance model was applied to estimate the patterns of groundwater table evolution under the LU change. As results, it is concluded that:

1. The groundwater in the area of interest for our research depends on rainfall, irrigation water, the inflow or base flow from the rivers and evapotranspiration. The groundwater table descends in winter, rises up in spring and maintains high water level in summer. It also showed that the paddy field played a significant role in the hydrological cycle in the coastal plain.
2. The results of water balance investigation indicate that the groundwater recharge in irrigation periods may be much more than that in non-irrigation periods. In irrigation periods, the net recharge is positive and ranges from 8 to 30 mm/day, whereas, it may be negative in non-irrigation periods.
3. The results from the distributed groundwater recharge model demonstrated that one third of the volume of inflows into the area, which consists of rainfall, diverted water for irrigation and to the rivers, pumped water for irrigation and inflow from the surrounding mountainous area, contributes to the groundwater recharge. The recharge from the paddy field during irrigation periods is very important.

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