Integration of the rice paddy water management into a coupled surface-subsurface water flow model in the Sakuragawa River watershed (Japan)
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ABSTRACT

Rice paddy water management was integrated into a distributed three-dimensional surface and subsurface coupling hydrological model of the Sakuragawa River watershed. This watershed is located in the Kanto Plain in Japan and includes the hillside of Mt. Tsukuba. Therefore, this watershed includes both steep mountainous areas and rice paddy-dominated flat land. Thus, water management of rice paddies is important and was calculated separately using a paddy model. The use of groundwater for rice paddy irrigation was considered as well as a water supply from outside of the watershed (Kasumigaura Lake). The model parameters were calibrated and validated with reference to the predictability of river water flow and the groundwater level. Using the calibrated model, three-dimensional streamlines, water travel time distributions, and water balance in some grids were clarified. The developed model will facilitate sustainable water resource management in the watershed.

Key words | groundwater, Kanto Plain, rice paddy, Sakuragawa River watershed, surface water, three-dimensional distributed hydrological model

INTRODUCTION

The importance of fresh water for the health of society cannot be overemphasized. The primary concern to preserve high-quality freshwater resources is to conserve a good water environment in the watershed. Various efforts related to watershed management, such as the Integrated River Basin Management and the Integrated Water Resources Management (Abell et al. 2002; Humphrey & David 2005; Cook & Spray 2012) have been implemented. The WHO’s Water Safety Plans, which require a risk assessment encompassing all steps in water supply from catchment to consumer, is another example (Davison et al. 2005; Breach 2012). In watershed management, it is important to study rivers that flow in highly populated plain areas because human activities, such as urbanization and agricultural activities, alter the water flow from its natural state in the post-development watershed (Yates & Miller 2011). These human activities alter not only surface water flows but also subsurface flows, and also affect water movement between surface and subsurface zones (e.g. changes in groundwater recharge due to land use changes, uptake of groundwater, etc.). Furthermore, increased environmental loads of chemical and biological pollutants as a result of human activities are also important concerns. These effects result in increased risks of shortages and deterioration of freshwater resources.

Rational watershed management based on an understanding of hydrology is important to minimize these risks.
One typical cause of such risk is excess nutrient loading in water bodies (Sagehashi et al. 2009a, b; Kawahara et al. 2011) from non-point sources. In particular, nitrogen plays an important role as fertilizer, including in rice cultivation (Ghosh & Bhat 1998). Penetration of nitrate into groundwater (O’Shea & Wade 2009; Buczko & Kuchenbuch 2010; Aquilina et al. 2012) is another risk.

On the other hand, as recognized in the renewed interest in the role of rice paddies as groundwater rechargers (Liu et al. 2001; Yu et al. 2006), the effects of rice paddies on the amount of groundwater are significant.

The investigation of surface water and groundwater was performed by monitoring and modeling approaches (Cho et al. 2009). However, as monitoring of the dynamics of groundwater is difficult and expensive, there is increasing interest in the modeling of groundwater dynamics. Progress in the modeling of soil-vegetation-atmosphere through pedotransfer functions improved the representation of soil-water dynamics (Vassena et al. 2012). Meanwhile, groundwater resources suffered from the impact of various human activities, such as the demands of various water (Green et al. 2011) and land use changes (Kimaro et al. 2003; Cho et al. 2009). Such impacts should be notable in the densely populated and urbanized flat land. Discharge of groundwater for irrigation, domestic, and industrial water supply is another impact. Paddy rice culture, which is an important agricultural practice in the Asian monsoon region (Jeon et al. 2007), has unique features of water management, such as keeping ponded water at a desirable depth (Li & Migita 1992) and temporary drainage (Yoshinaga et al. 2007).

Including the role of rice paddies as groundwater recharge (Liu et al. 2001; Imaizumi et al. 2004; Yu et al. 2006), the water budget of rice paddies should be considered in the analysis of surface water and groundwater dynamics. Therefore, the development of a three-dimensional, surface/subsurface coupling hydrological model considering rice paddy cultivation offers a key to understanding watershed management, especially in the Asian monsoon region.

In this study, we selected a watershed in Kanto Plain to model the hydrology. The development of Kanto Plain began in ancient times, meaning that the surface water and groundwater systems have been influenced by human activities for a long time. Therefore, the groundwater travel time analysis (Schilling & Wolter 2007) or analysis of land use legacy based on the travel time model (Ray et al. 2012) can provide important information for appropriate watershed management.

For such practices, we should combine the surface water and groundwater dynamics in some manner. Cho et al. (2009) concluded that there are three types of modeling approach, i.e. integrated surface-groundwater model development, groundwater model and surface model linking, and utilization of packages of existing groundwater models (Cho et al. 2009). Some previous studies have applied a surface and groundwater model to Kanto Plain. The National Institute for Environmental Studies Integrated Catchment-based Ecohydrology model, which is a process-based model, reproduced water cycle changes and drying phenomena in a watershed, including ground surface, unsaturated, and saturated layers in underground (Nakayama & Watanabe 2004), was applied to describe the groundwater dynamics related to Kasumigaura Lake, the second largest lake in Japan, which is located in Kanto Plain (Nakayama & Watanabe 2005, 2008; Nakayama et al. 2007). Some studies dealt with a combined model with irrigation (Liu et al. 2003), or models incorporating paddy water use (Tani-guchi et al. 2009a, b, c). In addition, some studies applied a tank model to the groundwater model (Mekpruksawong et al. 2006; Takeuchi et al. 2009, 2010). To understand the spatial flow behavior of the water, a distributed model is required. However, there have been few reports of runoff simulation for rice paddies (Kang et al. 2006). In general, hydrological descriptions in mountainous areas and flat areas are different (Yu et al. 2006). Kubota et al. (2007) introduced a three-dimensional surface and subsurface coupling hydrological model with upland, rice paddy, and forest submodels to describe the water and nitrogen dynamics in the Koigawa River watershed located in the Kanto Plain, and pointed out that it will be necessary to validate groundwater level and groundwater quality in future studies (Kubota et al. 2007). Sufficient reproducibility of surface water flow and groundwater level taking water management in rice paddies into consideration are keys to clarifying the water circulation in Asian flat lands by a distributed model.

The objectives of this study were to integrate the rice paddy water management into a three-dimensional hydrological model coupling surface and subsurface water flows in the watershed of Sakuragawa River in the Kanto Plain,
and to clarify the water circulation characteristics that are essential for watershed management, i.e. streamlines, travel time to the mouth, and water balance, using the developed model. Especially, the groundwater level is strongly affected by the rice paddy, and we tried to reproduce this behavior with considering the separately developed paddy model.

MATERIALS AND METHODS

Site description

As described above, this study focused on the Kanto Plain, which is the largest depositional plain in Japan (Hayashi et al. 2009) and is a typical example of a plain with a long history of human activity. The Kanto Plain includes the Tokyo Metropolitan area, which is the most extensively urbanized region in Japan (Fujibe 2003). Similar to other parts of the Asian monsoon region, there are many rice paddy fields in Kanto Plain. To prepare sufficient water for this ponding, various irrigation water systems have been implemented in this area (Kitabatake 1986; Hayashi & Yasuhara 2008). The Sakuragawa River watershed is located at the center of the Kanto Plain and flows into the Kasumigaura Lake, which is the second largest lake in Japan. The river is 63.4 km in length, and the area of watershed is 345 km² (Ishihara et al. 2006) (Figure 1). This watershed has been urbanized around Tsukuba City from around the 1970s, but there are also large amounts of farmland and forest (Kusumoto et al. 2005). The area is flat and consists of alluvial low land with large-scale paddy development.
and diluvial plateau with paddies at the valley bottom (Kusumoto et al. 2005).

**Hydrogeological model**

A hydrogeological simulator, GETFLOWS (GEneral pur-
pose Terrestrial fluid-FLOW Simulator) (Geosphere Environmental Technology Co., Tokyo, Japan), was used in this study. GETFLOWS is a general purpose fluid flow simulator that can compute the surface/subsurface coupled fluid flow system. This model was also employed in the study by Kubota et al. (2007). The code uses an integral finite differential method and has been used for multi-phase and multi-component fluid flow systems. The fundamental details including basic equations of GETFLOWS are described in the literature (Tosa et al. 2000, 2010). A grid dataset of 30 × 119 in horizontal resolution and 10 in vertical resolution (the total number of grids was 35,700) was assumed (Figure 2(a)) based on the information of elevation provided by the Geographical Survey Institute, Japan. Surface grids were classified into nine categories (Figure 2(b)) according to the information of land use provided by the Ministry of Land, Infrastructure, Transport, and Tourism, Japan. Many rice paddies are located near the river, and some paddies are also located in the mountainous area. Furthermore, fallow and abandoned paddy fields were also assumed. However, detailed information about their locations was limited. Therefore, they were allocated

![Figure 2](https://iwaponline.com/hr/article-pdf/47/1/137/369042/nh0470137.pdf)

**Figure 2** | Grid system (a), land use (b), geological group (c), and groundwater sucking part (d) of Sakuragawa River watershed assumed in the model.
randomly based on the census data provided by the Ministry of Agriculture, Forestry, and Fisheries (MAFF), Japan. Geographical data processing and drawings of maps and two-dimensional streamlines were also performed using ArcGIS Desktop (ESRI Japan, Japan). The three-dimensional grid picture shown in Figure 2(a) and three-dimensional streamlines were drawn using MicroAVS (Cybernet Systems, Japan).

In this study, the detailed boring data could not be obtained. Therefore, the watershed was divided roughly into four geologically different zones, namely the right bank far from the Sakuragawa (A), the right bank near Sakuragawa (B), the left bank (C) and the mountainous zone in the left bank (D), based on the land use, location, and literature information (Yoshitani et al. 2001; Geosphere Environmental Technology 2006) (Figure 2). A 2 m of top soil layer was assumed for each zone. Under the topsoil, 10 m of loam and clay layers were assumed to be located in zones A and B, whereas 10 m of alluvium layer was assumed to be located at the same position of the zone C. Under these layer(s), two layers (~100 m in depth and 100 m in depth under elevation level) were assumed to exist. This assumption is the presumption based on the reports by Sekimoto et al. (2009), and the bed lock is assumed to be located at 150 m in depth under sea level for zones A, B, and C, whereas, it was assumed to be located under the 2 m of top soil for zone D.

One of the most important goals of this modeling approach is to replicate the artificial water flows in the watershed. Actually, drinking water and industrial water are used in the watershed as well as agricultural water. At the Tonegawa River system in Ibaraki Prefecture, which includes the Sakuragawa River watershed, the amounts of supply (and demand) of drinking water, industrial water, and agricultural water were 7,423 (7.363) (m³/s), 16,693 (10.226) (m³/s), and 55.31 (63.86) (m³/s), respectively, in 2004 (Ibaraki Prefecture 2007). Considering this ratio and their circulation property, only the artificial water flow of agricultural water was considered in this model. Actually, irrigation is introduced for agricultural fields other than rice paddies. However, considering the dominance of the irrigation water used in paddy fields in Japan (MAFF Home Page), the irrigation was assumed to take place only in paddy fields.

Irrigation water from agricultural canals, Sakuragawa River, and repetition irrigation were also assumed, as well as drawing of groundwater. Uptake of water from the river was assumed to take place from the river as a whole (the river was treated as one unit). The groundwater uptake is assumed to be held only at the southern part of the watershed, and, due to the limitation of groundwater well locations and its depth data, the simulation model postulates the groundwater sucking grids with the depth 100–150 m as indicated in Figure 2(d). In addition, the drawn water is assumed to be supplied equally to paddies in the watershed. Actually, groundwater is drawn up in many places for irrigation. It was reported that 13,559 facilities pumped 22,5071 × 10⁷ m³ water annually for the irrigation of 11,232 ha of paddy fields in Ibaraki Prefecture (MAFF 2003). However, detailed information of the pump locations is not open to the public (and that is why we employed such a rough setting for the suction of the groundwater as described above). Meanwhile, the local government makes it mandatory to report the amount of groundwater uptake by pumps with discharge ports more than a certain size. Considering the aggregate of the amount of groundwater uptake in each year from 1997 to 2001 (Department of Planning, Ibaraki Prefecture, personal communication 2014), and the area of paddy fields in each corresponding year (MAFF), the relative usage of the aggregated groundwater uptake to the paddy fields was considerably lower in the northern part of the watershed compared with the southern part. The Kasumigaura Canal supplied from Kasumigaura Lake is well developed in the northern part (i.e. Sakuragawa City and Chikusei City). In Tsukuba City located at the southern side of the watershed, large amounts of groundwater were used for the irrigation of rice paddy fields (Tobita et al. 2004). These conditions support the assumptions regarding groundwater uptake in the model to a certain extent. However, information about the groundwater uptake obtained in this study is limited, and the resultant uncertainty of the model cannot be denied. It would be possible to reduce the uncertainty in the model if we could obtain more detailed information regarding groundwater uptake.

Paddy model

There have been few studies of distributed, physically based, three-dimensional surface water and groundwater models of
a watershed ranging from steep mountainous areas to rice paddy-dominated flat land. One possible reason is that the distributed model employed simplified equations, such as Manning’s equation, while the water level in rice paddies is controlled artificially, meaning that it is difficult to describe the water budget in rice paddies by such simplified equations.

In this study, the daily water budget in rice paddies was calculated separately by a paddy model. A schematic diagram of the paddy model is shown in Figure 3. In the paddy model, the water budget was calculated taking into consideration the precipitation, evapotranspiration, irrigation, surface runoff, and penetration, as reported previously (Hitomi et al. 2016). The daily precipitation was determined based on the observations of the Automated Meteorological Data Acquisition System (AMeDAS) of Tsuchiura (Japan Meteorological Agency) (Figure 1). Evapotranspiration was calculated by Thornthwaite’s equation (Thornthwaite 1948; Yin & Brook 1992; Matsui 2005) using the temperature observed at the AMeDAS of Tsuchiura in 1997, and the hours of daylight at Tsuchiura City. Two periods, i.e. the paddy rice cultivation period and paddy rice non-cultivation period, were modeled separately because of their marked difference in water management as outlined below.

In the paddy rice non-cultivation period, no irrigation water was supplied and the surface runoff and penetration
were calculated using the Soil Conservation Service Curve Number (SCS-CN) method (Mockus et al. 1972; McCuen 1982). The parameter for the SCS-CN, i.e. CN, was set as 67 based on a previous study by Im et al. (2007).

In the paddy rice cultivation period, irrigation was supplied to maintain the desired water level (Figure 3). The desired water level was set according to the conventional pattern based on the Fertilization Standard for Ibaraki Prefecture (provided by MAFF). Irrigation water from Sakuragawa, Lake Kasumigaura, and groundwater were considered. The infiltration rate of water differs depending on the situation (Hitomi et al. 2010). In this study, a constant rate (1.1 cm/day) (Nakamura et al. 2004) was set for penetration. Surface runoff occurred when the water depth on a day passed the desired water level. Resultant calculations of water balance, the amounts of surface runoff, and penetration were input into GETFLOWS as daily discharge to the river (surface runoff) and penetration into the subsurface zone (penetration). The lateral flows into the paddy field grids were assumed to occur the same as other grids, and the calculations of paddy model were considered as additional flows.

Watershed initialization

Prior to the hydrological calculation, the initial conditions of water distribution in the watershed were estimated by steady-state calculation under a constant condition. First, all of the grid points except the atmosphere and surface were assumed to be filled with water. Then, calculations for 10,000 days under the assumption of uniform precipitation and evapotranspiration (3.26 mm/day in precipitation and 2.18 mm/day in evapotranspiration) were used considering the annual average precipitation, temperature, day length in the area, and Thornthwaite’s equation. Running the model for 10,000 days resulted in a steady state that reflected the proper starting conditions for the predictive simulation. In this initialization, the water budget in paddy fields was calculated by the SCS-CN method. The initial parameters shown in Tables 1 and 2 were used in this initialization.

Parameter calibration and validation

The values of the Manning’s roughness coefficient used in this model are shown in Table 1. All parameter values except for the golf course are from NILIM (2006). The value for the golf course was set the same as that of the forest. The calibrated values for permeability and porosity are shown in Table 2. The clay layer represents an aquiclude and the following layers are confining aquifers. Layer C, considered as Bedlock, can be classified as an aquitard. The ratio of irrigation from Kasumigaura Canal, Sakuragawa River, and the repeated use of irrigation water was based on personal communications with Ibaraki Prefecture (Department of Public Works) (2010) and Japan Water Agency (Kasumigaura Canal O&M Office) (2010), and actual inspection (2010), whereas the ratio of groundwater to total irrigation was calibrated.

With reference to the ranges, a parameter set that gives good reproducibility for the river flow rate at Fujisawa Shin-den and the groundwater level at Toride (Figure 1) in 1997 (provided by the Ministry of Land, Infrastructure, Transport, and Tourism) was estimated. Then, the predictive capability of the parameter set was confirmed by comparing the calculations and observations of the flow rate and groundwater level in 1998–2001.

Hydrological analyses

Using the finally calibrated model, the movements of water particles precipitated on the surface were calculated to
understand the water flow behavior in the watershed. Two days, i.e. January 2, 1997 (dry case) and September 16, 1998 (wet case) were chosen as typical examples of dry and wet conditions, respectively. The former was just after the watershed initialization, and the latter was a period of heavy rain and resultant high river flow. Especially, the total amount of rainfall during the period September 15–16 in 1998 was 148 mm, corresponding to 10.3% of the total precipitation in 1998, and the average river flow rate observed on September 16 and 17 was 149.4 m$^3$/s, which is 14.4 times larger than the average river flow in 1998. In this calculation, the water particles were assumed to be dropped at the center of each surface grid point, and the trajectory of each particle from its original position (surface) to the river mouth was calculated based on the water velocity distribution within the grid system (Figure 2) of the certain time. That is, the calculated trajectory and resultant travel time were predictions if the vector field at each time was kept constant.

### RESULTS AND DISCUSSION

#### Paddy model

Comparisons of calculation results of the paddy model and the ranges of values in the literature (Nakamura et al. 2004; Yoshinaga et al. 2004, 2007; Kitamura et al. 2010) during the paddy rice cultivation period are shown in Figure 4. Here, the calculated ratio of water allocation was compared. Note that the importance of considering irrigation water is also indicated in Figure 4. All of the calculated values except the surface runoff were within the range of values reported in the literature. However, the calculated value of the surface runoff (15%) was lower than that in the literature (22–43%). One possible reason is the assumption of ideal and effective (less waste) water management in the paddy model. Furthermore, because of the subsurface drainage system in the paddy fields (Ogino & Murashima 1991), some portion of the penetrated water

<table>
<thead>
<tr>
<th>Layer</th>
<th>Permeability (mDarcy)</th>
<th>Porosity ($m^3/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Calibrated</td>
</tr>
<tr>
<td>Topsoil (II)</td>
<td>10,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Alluvium (IV-1)</td>
<td>1,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Loam (IV-2)</td>
<td>1,000</td>
<td>100</td>
</tr>
<tr>
<td>Clay (IV-3)</td>
<td>100</td>
<td>0.287</td>
</tr>
<tr>
<td>Layer A (V-1)</td>
<td>10,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Layer B (V-1)</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Layer C (VII)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Literature values are described in the dimensions of [L·T$^{-1}$], and converted to [mDarcy] under the assumption of 1 Darcy = 0.01 cm/s.

Tsutsumi et al. (2005).
Ochiai (1968).
Yiguchi et al. (2004).
RAEA (2008).
Values of sandy topsoil.
Values of the Kanto Loam Layer.
Values of the Jysoso Clay Layer.
Extrapolated range of value for clay by a regression formula based on various sizes of soils.
Values of the Shimousa Layer.
Extrapolated range of value for sand, fine sand, very fine sand and silt by a regression formula based on various sizes of soils.
Values of the Kazusa Layer.
Values of mud layer and clay layer.
Values of the Bedlock.
should be discharged to the river through the agricultural drainage system. Therefore, a slight underestimation of surface runoff is included in the paddy model. However, the precise quantification of these allocations is very difficult due to their uncertainty. Therefore, we concluded that the overall predictive capability was sufficient and the model was employed in this study.

Parameter calibration

Based on the preliminary sensitivity analysis, three geological parameters (Manning’s roughness coefficient, permeability, and porosity) of the watershed, excluding the surface of the paddy fields as well as the ratio of groundwater usage for the total irrigation of paddy fields, were calibrated to give good prediction of the river water flow and ground water level in 1997. The finally calibrated ratio of groundwater for the total irrigation of paddy fields was 23.6%. The groundwater dependence ratios of agricultural irrigation water in Ibaraki and Kanto were 70% and 15%, respectively (Isozaki 1974). In addition, the specific groundwater supply to rice paddies (=total of groundwater drawn for rice paddy irrigation/total area of paddy fields that used the groundwater) for Ibaraki Prefecture was 2,003 mm, whereas a value of 1,476 mm was estimated for the Hitachi Terrace, in which the southern part of the Sakuragawa River watershed is included (Ooi et al. 2015). As mentioned in the previous section, the Kasumigaura canal supplies irrigation water mainly at the northern part of the watershed. It was concluded that such conditions reduce the watershed dependence on groundwater. Meanwhile, the irrigation water from rivers, lakes, and repeated use are 48.7%, 6.6%, and 21.0%, respectively.

Predictability of hydrological behavior

The hydrographic comparison of calculated and observed daily average river water flow at Fujisawa Shinden is shown in Figure 5. In the paddy rice non-cultivation period (September 21–April 19) (gray zones in Figure 5), the river water flow was relatively stable due to less agricultural activity and low levels of precipitation. Therefore, the river flow in this period characterized the base flow of the Sakuragawa River.

For estimation of the predictive capability, the Nash–Sutcliffe equation (Nash & Sutcliffe 1970) was employed (Equations (1) and (2)):

\[
\text{NSE} = 1 - \frac{\sum_{i=1}^{N} (q_0(i) - q_c(i))^2}{\sum_{i=1}^{N} (q_0(i) - q_{av})^2} \tag{1}
\]

\[
q_{av} = \frac{1}{N} \sum_{i=1}^{N} q_0(i) \tag{2}
\]

where NSE is the Nash–Sutcliffe efficiency, N is the total number of time steps, \(q_0(i)\) is the measured flow rate at \(i\), \(q_c(i)\) is the calculated flow rate at \(i\), and \(q_{av}\) is the average measured flow rate. For this calculation, NSEs are estimated separately for January 1–April 19 (rice non-cultivation), April 20–September 20 (rice cultivation), and September 21–December 31 (rice non-cultivation) as
well as the whole year. The results are shown in Figure 6. Note that the calculation was terminated on December 4, 2001, and thus NSEs of the whole year and September 21–December 31 were not calculated. According to Moriasi et al. (2007), NSE > 0.5 gives a satisfactory prediction, and that between 0.0 and 1.0 is generally viewed as acceptable. From this figure, NSEs of the whole year and paddy rice non-cultivation periods were >0.3 except for January 1–April 19 in 1999 (NSE = 0.16). In addition, NSEs for the paddy rice cultivation period were lower than those of the non-cultivation periods (0.16–0.57). Furthermore, a comparison of calculated and observed river water flow in the rice non-cultivation period is shown in Figure 7. These results
indicated that the developed model can predict the river flow of the Sakuragawa River in the paddy rice non-cultivation period well. On the other hand, in the paddy rice cultivation period (white zones in Figure 5), the predictive capability for river water flow was decreased, indicating the difficulty of river flow rate prediction when human-induced water use is active. Furthermore, although the calculation of GETFLOWS was performed using a time step of less than 1 day, the input data related to water management in paddy fields and precipitation were given with the resolution of 1 day. That is why the calculation results look oscillated in the paddy rice cultivation period. However, the times of floods related to heavy rain were well reproduced.

The monthly average river water flow is another important index, and the results are shown in Figure 8. A slight underestimation was observed, especially in spring to early summer. The vegetation phenology is also important in the distributed hydrological model (Nakayama & Watanabe 2004). In this study, the phenology was not replicated except for the rice paddies, and it seemed to be one reason for this underestimation. Another possible reason is that the model parameters were calibrated not only for the river flow but also for the groundwater level. The groundwater level in the irrigation period is changed dynamically, and the underestimation possibly occurred in compensation for reproducing such change in the groundwater level at calibration. However, the overall tendency of the monthly average river water flow was predicted. From these results, we concluded that the model has sufficient predictive capability for the river water flow.

Comparisons of calculated and observed groundwater levels at Toride are shown in Figures 9 and 10 (monthly average). As shown in Figure 4, the irrigation of paddy fields greatly affects the water budget. On the other hand,
the groundwater level was obviously decreased in the paddy rice cultivation periods (Figure 9). The paddy model considers the irrigation from various water sources including groundwater of which its ratio was calibrated; therefore, one of the most remarkable effects of the paddy model incorporation is the improvement of reproducibility for the groundwater level (Figure 9). The predictive capability is higher during January to June (i.e. late phase of
paddy rice non-cultivation period to early phase of paddy rice cultivation period), whereas it is decreased during July to December (i.e. late phase of paddy rice cultivation period to early phase of paddy rice non-cultivation period). Especially, overestimation of the late phase of paddy rice cultivation period seemed to be a trigger of the decrease in predictive capability. The groundwater level is strongly affected by pumping discharge. In this study, the dependence ratio of irrigation water for various water sources, including groundwater, was assumed to be constant throughout the calculation period because of the limited availability of information about irrigation. Naturally, there is a possibility that the dependence ratio changes within the significant level to affect the groundwater level, and, there is still room for improvement of the accuracy of groundwater uptake. As described, the location of the suction of groundwater was roughly postulated in this model because of the lack of information about the locations of groundwater pumping. There is a possibility that the groundwater level at Toride is strongly affected by the assumed suction, which is located near Toride. However, the overall tendencies of the groundwater level and also the river flow rate were reproduced, and therefore we concluded that the developed model was sufficient to predict the hydrology in the Sakuragawa River watershed.

**Hydrology analyses**

The travel time distributions in the dry case and wet case are shown in Figures 11 and 12, respectively, with the streamlines viewed from the upper side. Furthermore, Figure 13 shows the comparison of altitude and travel time around Mt. Tsukuba. The estimated travel times from grids of forest are long, whereas relative short travel times are estimated from rice paddies, other crop fields, and wasteland. Relatively long travel times from areas covered by artificial materials (buildings, transport) were also observed. Commonly, the water retentivity of such areas is low. On the other hand, in this watershed,
these areas are scattered and adjoin non-artificially covered areas. Therefore, the travel time from such artificially covered areas was not remarkably low in the present study.

The three-dimensional streamlines near Mt. Tsukuba in the wet case are shown in Figure 14. From this figure, we can see that most of the streamlines from the mountainous area (covered by forest) went underground, and then appeared above ground again. As a result of this movement characteristic, the travel time from the mountainous area was long. This result indicated that when toxic materials easily accompanied with water (high solubility, low adsorptive potential for soils, e.g. nitrate, etc.) are applied in the mountainous area, its residence time in the ground water is long.

In the analyses described in Figures 11 and 12, individual streamlines from a representative point at each surface grid were drawn based on the velocity distribution at a given instant, and the travel time was calculated using the streamline. On the other hand, considering the water balance in a grid, there is a certain distribution of the water due to precipitation/evapotranspiration, runoff, and penetration/spring water, as shown in Figure 15. To consider these distributions, it is necessary to understand how much water results in surface runoff, how much water results in penetration, etc. As a typical example, the water balance in some grids in the wet case was estimated. As shown in Figure 16, three grids near the summit of Mt. Tsukuba (Grids A, B, C) and at the lowest latitude grid of the forest zone connected tandemly to Grids A, B, and C (Grid D) were chosen for this calculation.

Table 3 shows the results. The ratios of runoff and penetration were about 70–80% and 20–30%, respectively, in the grids analyzed here, indicating that the surface runoff is two to three times larger than the penetration within the grids of 70,000–80,000 in the area located at Mt. Tsukuba under the wet conditions assumed in this study. On the other hand, there are about 10 grids from the top of...
Mt. Tsukuba to the river (Figure 16). It is a very simple calculation under the assumption that only a straight line flow from the top of the mountain to the river occurred, but 3% (i.e. 0.710) of water precipitated at the top of Mt. Tsukuba is estimated to reach the river directly by surface runoff. Conversely, 97% of water precipitated at the top of Mt. Tsukuba penetrates into the subsurface zone at least once.

**FUTURE PERSPECTIVES**

There are some perspectives to utilize the model developed here for future watershed management in the Sakuragawa River. Simulation of the effects of land use changes on water resources is one example. Actually, fallow and abandoned rice paddies have increased in Japan (Kusumoto et al. 2005). From the viewpoint of regional vitalization, the effective utilization of these unused paddy fields (Sagehashi et al. 2008; Yang et al. 2012) is essential. Meanwhile, there has been renewed interest in the role of paddy fields as groundwater rechargers (Liu et al. 2001; Yu et al. 2006), and they are considered an effective means of securing freshwater resources. Furthermore, rice paddies also have the potential to serve a role in flood mitigation (Yu et al. 2006). Therefore, it is expected that a freshwater resource management system will be realized based on the appropriate utilization of unused rice paddies in Japan as well as other Asian countries facing a lack of freshwater resources. The model developed in this study will become a powerful tool to simulate such
management practices. The increase in extremely hot days in summer observed in this plain (Fujibe 1998; Watarai et al. 2009) may also lead to increased water usage and evaporation, and may result in serious water shortages. The model developed in this study will play an important role in estimating such changes in climate and in discussing rational countermeasures.

CONCLUSIONS

The rice paddy water management was integrated into a distributed three-dimensional surface and subsurface coupling hydrological model of the Sakuragawa River watershed. The predictive capability of this model for river water flow and groundwater level was judged to be sufficient. Especially, the changes in groundwater level in the irrigation periods were predicted successfully by considering the paddy model. Three-dimensional streamlines of the water, the distribution of water travel time, and the water balance in some grids, which represent important information for watershed management, were clarified using the developed model.
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