A semi-distributed groundwater recharge model for estimating water-table and water-balance variables

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Abstract A semi-distributed groundwater recharge model is presented, which estimates water-table fluctuation and water-balance variables. The model is expressed by the water-balance concept linking atmospheric and hydrogeological parameters to different water uses (industrial, agricultural, domestic, etc). It was calibrated and validated using 5 years of data collected in the Dogo Plain in Japan. A 3-year dataset, from 2000 to 2002, was used in the calibration, while a 2-year dataset, from 2003 to 2004, was used for the validation. Calibration of the model was achieved by the shuffled complex evolution automatic optimization of model parameters to match simulated results with measured water-table depth. Square roots of relative error (R^2) are 0.88 and 0.90 for calibration and validation processes, respectively. Monthly evolution of water storage change was then estimated and the water-table drawdown in different pumping scenarios was simulated. Finally, the groundwater-pumping amount planned by the government for future sustainable groundwater utilization was evaluated. The government-planned groundwater-pumping amount is feasible in most regions while the midstream region should be paid more attention. This study offers a scientific basis to control and prevent depletion of groundwater resources.

Received: 23 May 2007 / Accepted: 2 March 2008
Published online: 8 May 2008

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Résumé Un modèle semi-distributif de recharge d'eau souterraine est présenté, qui estime les fluctuations de la nappe et les variables du bilan d'eau. Le modèle est développé à partir du concept de bilan d'eau liant les aramètres atmosphériques et hydrogéologiques aux différents usages de l'eau (industriel, agricole, domestique, etc). Il a été calibré et validé en utilisant cinq années de données collectées dans la Dogo Plain au Japon. Une base de données de trois années, de 2000 à 2002, a été utilisée pour la calibration, alors qu'une base de données de deux années, de 2003 à 2004, a été utilisée pour la validation. La calibration du modèle a été réalisée par l'optimisation automatique Shuffled Complex Evolution des paramètres du modèle afin d'être en accord avec les résultats simulés à partir des profondeurs mesurées de la nappe. Les racines carrées de l'erreur relative (R^2) sont 0.88 et 0.90 pour les processus de calibration et de validation, respectivement. L'évolution mensuelle de la modification de l'emmagasinement de l'eau a alors été estimée et le rabattement de la nappe dans différents scénarios de pompage a été simulé. Finalement, le volume du pompage d'eau souterraine prévu par le gouvernement pour une utilisation future durable de l'eau souterraine a été évalué. Le volume du pompage de l'eau souterraine prévu par le gouvernement est atteignable dans la plupart des régions tandis qu'il faudrait prêter plus d'attention à la région médiane. Cette étude offre une base scientifique pour contrôler et prévenir l'épuisement des ressources en eau souterraine.

Resumen Se presenta un modelo semi-distribuido para la recarga de las aguas subterráneas que estima la fluctuación del nivel freático y las variables del balance de agua. El modelo se define mediante el concepto de balance de agua a partir del acople de los parámetros atmosféricos e hidrogeológicos a los diferentes usos del agua (industrial, agrícola, doméstico, etc.). El modelo se calibró y validó para una serie de datos correspondientes a un período de cinco años obtenidos en el Dogo Plain, Japón. Para la calibración, se utilizó un conjunto de datos de tres años pertenecientes al período 2000–2002, mientras que para la validación se utilizó el conjunto de dos años del período 2003 a 2004.La calibración del modelo se efectuó a partir de Shuffled Complex Evolution y mediante la estimación automática de parámetros basada en la comparación de valores simulados con valores estimados. El valor de la raíz cuadrada del error relativo (R^2) obtenido para la

 DOI 10.1007/s10040-008-0298-x

calibración y validación es de 0.8 y 0.9, respectivamente. Se estimó la evolución mensual de la variación de almacenamiento y se simuló el descenso del nivel freático para diferentes escenarios. Finalmente, se evaluó el volumen de bombeo previsto por el gobierno que permita el uso sostenible del agua subterránea en el futuro. El volumen de bombeo planificado es factible para la mayoría de las regiones, excepto para la región del tramo medio que debe ser objeto de una mayor atención. Este estudio presenta las bases científicas para controlar y prevenir el agotamiento de los recursos subterráneos.

Keywords Groundwater exploration · Groundwater recharge/water budget · Coastal aquifers · Japan

Introduction

Predicting seasonal or annual water-table fluctuation, groundwater recharge and water-balance by groundwater models is an issue of great practical relevance in coastal plains (Bierkens 1998; Tankersley et al. 1993; Yang et al. 2002; He et al. 2006). For groundwater simulation, traditionally, numerical modeling has been broadly applied in many research projects based on the physical modeling approach (Anderson et al. 1990; Yeh and Ward 1979; McDonald and Harbaugh 1988; McDonald et al. 1991). However, quantitative information on hydraulic properties and spatial characteristics, which are required for numerical groundwater modeling, are often poorly recorded for many measurement stations. Thus, sustainable groundwater management in most areas in the world is hampered by the fact that little hydrological, geological and meteorological information is available (Wagner et al. 2006), in which case, the conceptual model underlying a water-balance computation at a basin scale is preferred (Nels et al. 2004). Furthermore, more attention has been given to evaluating the use and productivity of water at a basin-scale by treating each basin as a whole unit of study (Molden 1997). Some general conceptual and analytical frameworks have been successfully applied in dynamic water-balance situations to estimate a basin's fluxes (Eagleson 1978).

Among these conceptual models, the popular applicable model is known as 'tank model' or 'multiple-box model'. The original tank model proposed by Sugawara and Funiyuki (1956) was intended for calculation of runoff, with the catchment area of a river substituted by a combination of a number of storage type model vessels. The tank model is a kind of deterministic, lumped, linear, continuous, and time-invariant model and can be applied to catchment rainfall-runoff modeling and flood analyses (Sugawara 1961, 1967, 1979, 1984, 1995). It has demonstrated its capability for modeling the hydrologic responses from a wide range of catchments (Dooge 1973; Franchini and Pacciani 1991). In the last decade, many researchers have developed water-balance models which are similar to the tank model. Tingsanchali and Gautam (2000) successfully applied two lumped conceptual hydrological models, one of which was the tank model, to flood forecasting in two river basins in Thailand. Khazaei et al. (2003) developed a catchment water-balance model for estimating groundwater recharge in arid and semiarid regions of south-east Iran. Alemaw and Chaoka (2003) developed a continental distributed geographic information system (GIS)-based water-balance model considering the surface and subsurface processes to estimate generated runoff from matrix of specific geo-referenced grids representing southern Africa. Chen et al. (2003) applied a diffusive tank model to analyze the rainfall-runoff relation in paddy fields in Taiwan. Sirajul et al. (2005) developed a deterministic water-balance model integrating natural hydrological balance, as well as several water uses and river regulation effects. Portoghese et al. (2005) designed a GIS-based water-balance model to evaluate hydrogeological water-balance and agricultural water demands under different climatic and management scenarios.

In this study, a semi-distributed groundwater recharge model based on the concept of the tank model or water-balance model was proposed to quantify the temporal changes of water table and water-balance variables. The monthly evolution of water storage change at a basin scale was estimated from the water-balance variables. The water-table drawdown in different pumping scenarios was simulated, and the groundwater-pumping regime planned by the government for future sustainable groundwater utilization was evaluated.

Methods

This section presents the main structure, hydrological processes, and parameters of the semi-distributed groundwater recharge model used in this study.

Model description

The proposed model (Fig. 1) is a conceptual groundwater recharge model consisting of three layers. The first is a surface layer with associated land uses such as paddy field, farm field, and urban area, etc. The second one is a subsurface layer. The last one is a groundwater layer. It functions as vertical tank storage with many outlets with outflow coefficients. The elements expressing the water input and output are discussed below.

Precipitation, evapotranspiration, and canopy interception

Precipitation is the main input element for the surface layer. Potential evapotranspiration was calculated by the Penman method (Penman 1948, 1963). Evapotranspiration (ET) reduces water stored in the tank and is part of the output element for paddy field and other fields. If the water in the tank is exhausted, evapotranspiration can still occur by water uptake from the subsurface and groundwater layer through the unsaturated zone and the root zone

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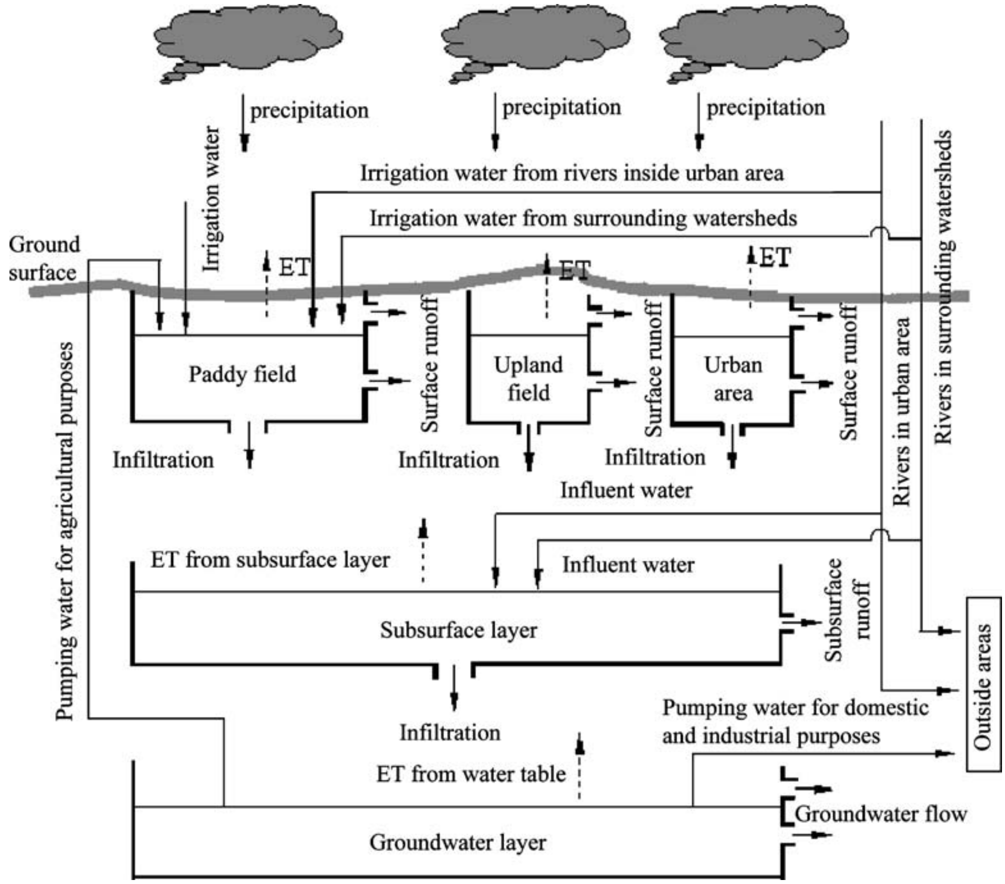

Fig. 1 Groundwater recharge model expressed by the water-balance concept

as explained by Bouwer (1978), Anderson and Woessner (1992). Interception is highly dependant on the canopy density and varies from one vegetation type to another and from one area to another, depending on the spatial distribution of vegetation. The storage in the interception zone is represented by a reservoir with a capacity. The water is extracted from the reservoir at potential evapotranspiration rate. The net precipitation, represented by the difference between precipitation and evapotranspiration, reaches the soil and forms the input for the subsequent model component (Giammarco et al. 1992).

Discharge from surrounding watersheds

The river discharge (Q) from surrounding watersheds flows into the groundwater basin and some of it was used as irrigation water (QIRR) for paddy fields and, thus, this part was an input element of the paddy field sub-model. Furthermore, it was assumed that the river discharge supplies water to the subsurface layer as influent water as shown in the following.

$$Q\mathrm{INT} = \mathrm{CINT}\cdot(Q - Q\mathrm{IRR}) \qquad (1)$$

where, QINT is the influent water from river discharge, and CINT is the coefficient of the influent water from rivers.

Irrigation water and pumped water for industrial and domestic use

The irrigation water for agricultural use, from dams, is an input element for the paddy field sub-model. The pumped water from the groundwater layer for industrial and domestic purposes directly flows into the outside regions (for example, sea, lake, neighboring city, etc.). The pumped water for agricultural purposes from the groundwater layer is an input element for the paddy field and contributes again to the inflow to rivers and infiltration.

River outflow

The paddy field sub-model and other field sub-models have two outputs. One is the infiltration to the subsurface layer and the other is flow as surface discharge, which finally converts to a part of river discharge. The inflow to the subsurface layer is also output as subsurface discharge to rivers and as percolation into the groundwater layer.

Groundwater outflow

The percolation from the subsurface layer to the groundwater layer is the input element as a recharge for the groundwater layer. The recharge induces a rise of the

 DOI 10.1007/s10040-008-0298-x

water table. Furthermore, the outflow from each tank was calculated by the following equation:

$$\mathrm{QOUT_i}=A_{1\mathrm{i}}\cdot(S_\mathrm{i}-H_{1\mathrm{i}})+A_{2\mathrm{i}}\cdot(S_\mathrm{i}-H_{2\mathrm{i}}) \tag{2}$$

where, $\mathrm{QOUT_i}$ is the outflow from each tank; $\mathrm{A2_i}$ and $\mathrm{A1_i}$ are the lateral flow coefficients for the lower and upper outlets in each tank, respectively; $\mathrm{H2_i}$ and $\mathrm{H1_i}$ are the heights of the lower and upper outlets for each tank, respectively; $\mathrm{S_i}$ is the depth of water storage in each tank. The infiltration and percolation were calculated by the following equation:

$$\mathrm{QIP_i}=C_\mathrm{i}\cdot S_\mathrm{i} \tag{3}$$

where, $\mathrm{QIP_i}$ is the infiltration or percolation; $\mathrm{C_i}$ is the infiltration or percolation coefficient in each layer.

Quantitative expression of water-balance in each layer

As shown in Fig. 1, the tank model consists of three layers: a surface layer, a subsurface layer, and a groundwater layer. The first layer corresponding to the first surface soil layer has two outlets for water outflow, and one outlet for deeper infiltration or percolation. The water-balance in the first layer is computed by an explicit form of the next equation:

$$\frac{dS_\mathrm{X}(t)}{dt}=R(t)+\mathrm{QI}RR(t)+\mathrm{DI}R\mathrm{I}(t)+\mathrm{PUMPP}(t) -\mathrm{QOUT_X}(t)-\mathrm{QIP_X}(t)-\mathrm{ET_X}(t) \tag{4}$$

where, X can be presented by different land use i.e. P (Paddy field), F (Farm field), and U (Urban field) in the first layer tank; $S_X(t)$ is the depth of the first layer tank on the t_th day (mm); $R(t)$ is the precipitation (mm/d); QIRR(t) is the irrigation water from rivers (mm/d); DIRI(t) is the irrigation water from dams (mm/d); PUMPP(t) is the pumping water from the groundwater layer for paddy field use (mm/d); $\mathrm{QOUT}_X(t)$is the lateral runoff from the first layer tank (mm/d); $\mathrm{QIP}_X(t)$ is the vertical infiltration or percolation from the first layer tank (mm/d); ET_X is the evapotranspiration of the first layer tank (mm/d).

When $S_X(t)\leq H_{2X},\ \mathrm{QIP}_X(t)=C_X\times S_X(t),\ \mathrm{QOUT}_X(t)=0$

$$H_{2X}<S_X(t)\leq H_{1X},\ \mathrm{QIP}_X(t)=C_X\times S_X(t),\quad \mathrm{QOUT}_X(t)=A_{2X}\times(S_X(t)-H_{2X})$$

$$S_X(t)H_{1X},\quad \mathrm{QIP}_X(t)=C_X\times H_{1X},$$
$$\mathrm{QOUT}_X(t)=A_{1X}\times(S_X(t)-H_{1X})+A_{2X}\times(S_X(t)-H_{2X})$$

Where,

- $A_{1\mathrm{X}}$ is the coefficient of the upper outlet in the first layer tank
- $H_{1\mathrm{X}}$ is the height of the upper outlet in the first layer tank
- $A_{2\mathrm{X}}$ is the coefficient of the lower outlet in the first layer tank
- $H_{2\mathrm{X}}$ is the height of the lower outlet in the first layer tank
- C_X is the infiltration or percolation coefficient of the first layer tank

The water-balance in the second layer tank can be written as:

$$\frac{dS_2(t)}{dt}=\mathrm{QIP}_X(t)+\mathrm{QINT}(t)-\mathrm{QOUT}_2(t)-\mathrm{QIP}_2(t)-\mathrm{E}_2(t) \tag{5}$$

where, $S_2(t)$ is the storage depth of the second layer tank on the t_th day (mm); QINT(t) is the influent river water (mm/d); $\mathrm{QIP}_2(t)$ is the infiltration from the second layer tank (mm/d); $\mathrm{QOUT}_2(t)$ is the lateral runoff from the second layer tank (mm/d); $E_2(t)$ is the water uptake from the second layer tank (mm/d).

When, $S_2(t)\leq H_{22}, \mathrm{QIP}_2(t)=C_2\times S_2(t), \mathrm{QOUT}_2(t)=0$

$$H_{22}<S_2(t)\leq H_{12}, \mathrm{QIP}_2(t)=C_2\times S_2(t)$$
$$\mathrm{QOUT}_2(t)=A_{22}\times(S_2(t)-H_{22})$$

$$S_2(t)>H_{12},\quad \mathrm{QIP}_2(t)=C_2\times S_2(t)$$
$$\mathrm{QOUT}_2(t)=A_{12}\times(S_2(t)-H_{12})+A_{22}\times(S_2(t)-H_{22})$$

Where,

- A_{12} is the coefficient of the upper outlet in the second layer tank
- H_{12} is the height of the upper outlet in the second layer tank
- A_{22} is the coefficient of the lower outlet in the second layer tank
- H_{22} is the height of the lower outlet in the second layer tank
- $\mathrm{C_2}$ is the infiltration coefficient of the second layer tank

The water-balance in the third layer tank can be written as:

$$\frac{dS_3(t)}{dt}=\mathrm{QIP}_2(t)-\mathrm{QOUT}_3(t)-\mathrm{E}_3(t)-\mathrm{PUMPP}(t)-\mathrm{PUMP}(t) \tag{6}$$

where $S_3(t)$ is the storage depth of the third layer tank on the t_th day (mm); $QIP_2(t)$ is the percolation from the second layer tank (mm/d); $\mathrm{QOUT}_3(t)$ is the lateral runoff from the third layer tank (mm/d); PUMP(t) is the pumping

 DOI 10.1007/s10040-008-0298-x

water from the groundwater layer for industrial and domestic use (mm/d); $E_3(t)$ is the water uptake from the third layer tank (mm/d)
when $S_3(t) \le H_{23}$, $\mathrm{QOUT}_3(t) = 0$

$$H_{23} < S_3(t) \le H_{13}, \quad QOUT_3(t) = A_{23} \times (S_3(t) - H_{23})$$

$$S_3(t) > \mathrm{H}_{13}, \mathrm{QOUT}_3(t) = A_{13} \times (S_3(t) - H_{13}) + A_{23} \times (S_3(t) - H_{23})$$

Where,

A_{13} is the coefficient of the upper outlet of the third layer tank
H_{13} is the height of the upper outlet of the third layer tank
A_{23} is the coefficient of the lower outlet of the third layer tank
H_{23} is the height of the lower outlet of the third layer tank
$E_3(t)$ is the evapotranspiration of the third layer tank (mm/d)

The water-table height is calculated from the following equation

$$HGC(t) = S_3(t)/e/1000 \tag{7}$$

Where,

HGC(t) is the simulated water-table height (m)
$S_3(t)$ is the storage depth of the third layer tank on the t_{th} day (mm)
e is the effective porosity.

The depth to water table (DGW) can be further calculated by ground-surface elevation minus the water-table height.

Model calibration

Model calibration is the determination of the model parameters on the basis of the measurements and prior knowledge. In other words, calibration involves varying parameter values within reasonable ranges until the differences between observed and simulated values are minimized. In the groundwater recharge model of this study (see Fig. 1), there are a lot of model parameters. These parameters are partly calibrated and optimized by the shuffled complex evolution (SCE) method, which is attractive due to its objectivity as a genetic optimization method. The SCE method is a typical effective numerical method of nonlinear optimization algorithm to automatically calibrate hydrological models. The model itself is used to determine changes in the parameter values through non-linear regression by the procedure of automatic optimal parameter estimation (Duan et al. 1992, 1993, 1994; Back and Schwefel 1993; Ndiritu 2001).

In the present groundwater recharge model, the SCE method serves as a general-purpose global-optimization strategy designed to handle the various response problems encountered in the calibration of the groundwater model. The SCE method contains many probabilistic and deterministic components, which are controlled by some algorithmic parameters. For the method to perform optimally, these parameters must be chosen carefully. The initial selection of a ‘population’ of points distributed randomly throughout the feasible parameter space can be decided from the initial part of the regional groundwater model. Then the population is partitioned into several ‘complexes’, each consisting of 2n+1 points, where n is the number of optimized parameters. Each complex ‘evolution’ of the population will be independent in a manner that is based on the downhill simplex algorithm. The selected population is periodically ‘shuffled’ and new complexes will be formed so that the information gained by the previous complexes can be shared. The evolution and shuffling steps will be repeated until the prescribed convergence criteria of the groundwater recharge model are satisfied. A flowchart of the genetic optimization algorithm is shown in Fig. 2.

The calibration goal of this study is to adjust the model’s parameters to decrease the difference between

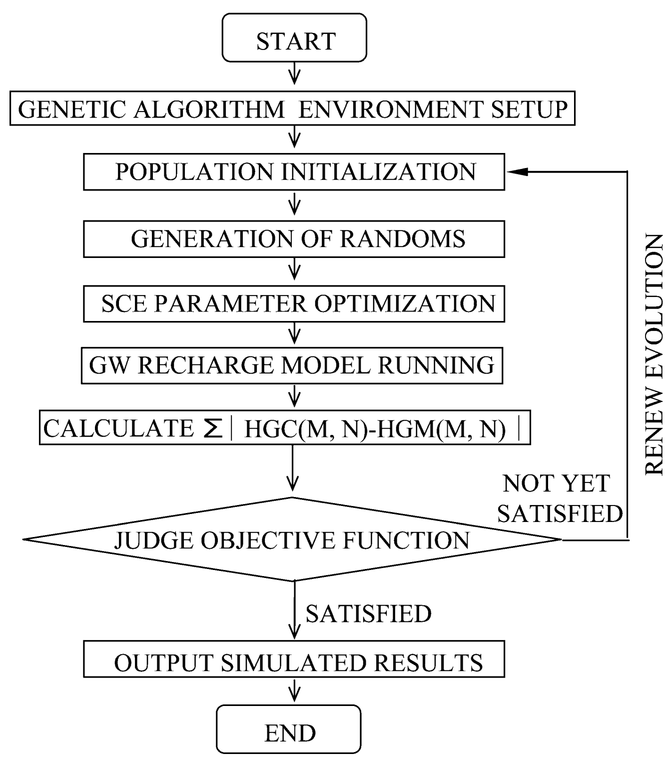

Fig. 2 Flow chart of the genetic optimization algorithm in this study

 DOI 10.1007/s10040-008-0298-x

observed and simulated water-table height. The optimized model was expected to achieve (1) small deviations (low square error) of computed from observed water-table height, (2) good reproduction of the historical trend of the water table, and (3) physically reasonable system behavior. The closeness of fit can be checked qualitatively by plotting the observed and simulated water-table graphs or quantitatively by using residual statistics such as the square error, bias, etc. Water-table height can be calculated using the groundwater storage height divided by the effective porosity. The equation of error function in the following is the sum of square errors between the measured and predicted water-table height:

$$ERR = \sum_{Block=1}^{M} \sum_{Day=1}^{N} (HGC - HGM)^2 \tag{8}$$

where, HGM is the measured water-table height, and N is the number of observation days. M is the number of blocks, which can be a different size of cells or grids chosen by users. HGC is the calculated water-table height, which can be obtained by Eq. (7).

Model application

Site description

The study site chosen for the model application is located along the western border of the Dogo Plain on the Shikoku Island in Japan (Fig. 3a). It is surrounded by mountains in the south, north and 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 of one large groundwater flow along the Shigenobu River and another groundwater flow along the Ishite River. The Shigenobu River watershed consists of forests. The joint groundwater flow, which finally flows into the Seto Inland Sea, comes from two sources. One source is groundwater from the Iyo city's watershed (Iyo City is the neighbor city of Matsuyama City) to the Seto Inland Sea on the south bank side of the downstream section of Shigenobu River; and the other one is groundwater from the Ishite River on the north bank side of the downstream section of the Shigenobu River. On the other hand, the groundwater along the Ishite River partly flows into the Seto Inland Sea on the north bank side and partly joins the groundwater following along the Shigenobu River on the south bank side (Yonden Consultants 2005).

In the coastal Dogo Plain of the Seto Inland Sea, groundwater is the primary source of water for domestic, industrial and agricultural uses. In recent decades, the increasing concerns over agricultural water use, municipal water supply, and groundwater storage changes have created a need for sustainable groundwater management. Previous studies in the coastal plain have shown that the water-table fluctuation and long-term trends depend on the groundwater recharge, which is a function of precipitation, evapotranspiration, and pumped water (Takase 2000; He et al. 2005). As a part of the regional development plan, current research in the Laboratory of Hydrology for Environmental Engineering (LHEE) at Ehime University, Japan has focused on estimating the impact of further urbanization on the hydrologic cycle in the Dogo Plain. The research includes long-term monitoring changes in the hydrologic cycle due to climate change and human activities. The seasonal changes of the hydrologic cycle and the water-balance in the Dogo Plain have been investigated as part of this study. Based on the measured hydrogeological and meteorological data in this basin, the proposed groundwater recharge model has been applied to analyze the water-balance and water-table fluctuation. Considering the groundwater flow properties and all components of the water-balance in this study, the whole plain was divided into four blocks as shown in Fig. 3b and the semi-distributed groundwater recharge model was constructed (for each block, one groundwater recharge model was included).

In terms of aquifer condition and hydrogeology survey, the Dogo Plain mainly consists of four layers. The deeper layer is an old terrace sediment layer, whose maximum thickness is 120 m. The new terrace sediment layer is above the old terrace sediment layer. The lower Dogo Plain consists of a sediment layer and alluvium. The upper Dogo Plain consists of a fan sedimentary layer. The river sedimentary layer is located along rivers in Dogo Plain. Judging from the results of field surveys conducted in Matusyama City, confined aquifer conditions do not seem to be located in the Dogo Plain. Based on the results of field surveys, the hydraulic conductivity and effective porosity in each layer were estimated and are shown in Table 1. Since these values change according to the location in the plain, they have wide ranges (Fujihara and Ohashi 2000).

Available databases

Precipitation and potential evaporation

In the Dogo Plain, precipitation is the main source of groundwater recharge. Average annual precipitation of the past 106 years, from 1900 to 2005, is 1,346 mm (Fig. 4), which is about two thirds of the average annual precipitation in Japan. Average annual precipitation of the past 30 years, from year 1974 to year 2003, is 1,305 mm (Takase 2005), which shows a decreasing tendency compared with the average annual precipitation from year 1900 to 2003. The amount of precipitation minus potential evaporation is a critical factor to evaluate the water resources in a basin. The average value of annual precipitation (1,350 mm) minus annual potential evaporation (1,150 mm), which was calculated by the Penman equation (Penman 1948, 1963), is about 200 mm, which is much less than the average value in Japan. The average values of monthly rainfall and evaporation for 1992–2002 and 1994 are shown in Fig. 5. The average monthly

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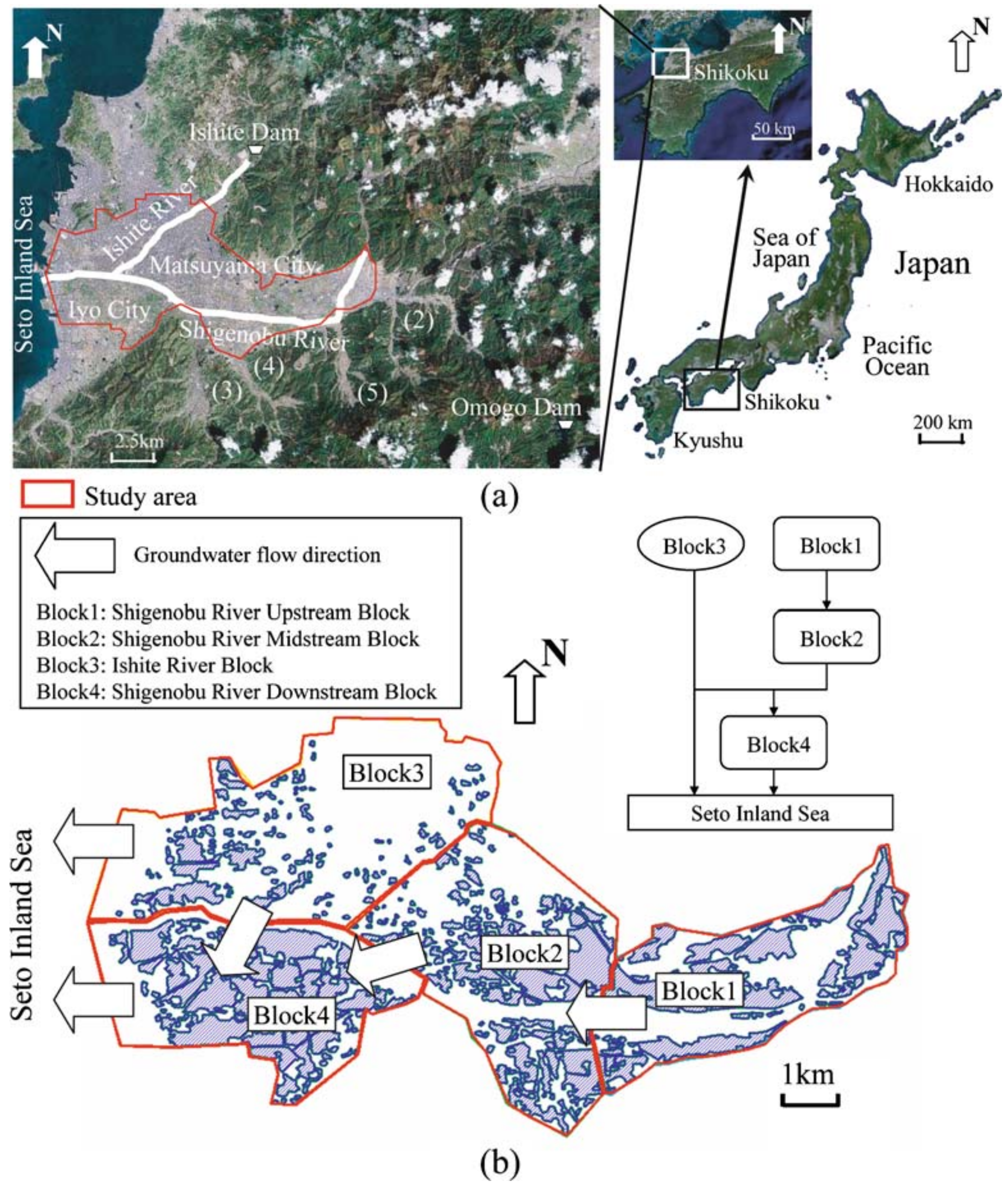

Fig. 3 Schematic figures showing (**a**) the study site, main rivers and (**b**) paddy field area (blue shaded area) and block distribution in the Dogo Plain. The whole Dogo Plain has been divided into four blocks (*block 1* Shigenobu River upstream block; *block 2* Shigenobu River midstream block; *block 3* Ishite River block; *block 4* Shigenobu River downstream block) according to the geographical and hydrological conditions. Two main rivers i.e. Ishite River and Shigenobu River, and other rivers, i.e. *(2)* Omote River, *(3)* Tobe River, *(4)* Kutani River, and *(5)* Hayashi River, are also shown in this figure

Table 1 Hydraulic conductivity and effective porosity in the Dogo Plain

Layers	Hydraulic conductivity (m/d)	Effective porosity
River sedimentary layer	200.0~100.0	0.11~0.14
Alluvium layer	80.0~40.0	0.16~0.20
Fan sedimentary layer	40.0~0.8	0.18~0.215
New terrace sediment layer	20.0~4.0	0.215~0.23
Old terrace sediment layer	10.0~1.0	0.21~0.235

rainfall is greater than or equal to evaporation in the whole year except for August for the averaged monthly value from 1992 to 2002. However, in the drought year 1994, the monthly rainfall is less than evaporation for the whole year except for January and February. Thus, it shows the serious water deficit condition in the Dogo Plain.

Inflow from the surrounding watersheds

The river discharge flowing from surrounding watersheds into the Dogo Plain is an important water resource. Some of the river discharge comes directly from the river's surface water, and some comes indirectly from river-bed water and groundwater. Such rivers are the Shigenobu

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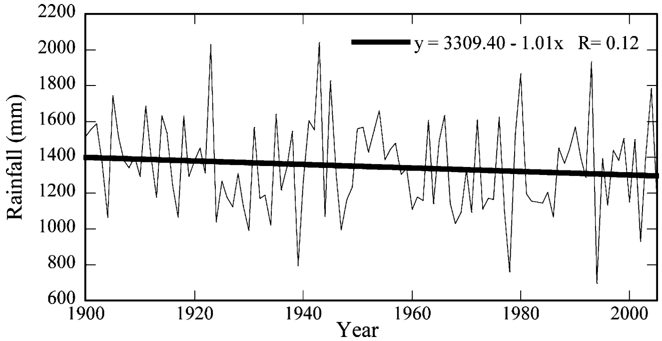


Fig. 4 Annual Rainfall from 1900 to 2005 in Matsuyama City

River, the Omote River and the Hayashi River in the upper Dogo Plain, and the Kutani River and the Tobe River in the midstream region. The annual outflow discharge of these rivers is indicated in Table 2. It shows that about 900–1,200 mm/year discharge flows from each surrounding watershed to each river except for the Hayashi River. As the area of the plain is about 100 km^2, the discharge from the surrounding watersheds, excluding the Ishite River, to the plain is estimated roughly as 3,000 mm/year. Furthermore, the controlled discharge from the Ishite River by the Ishite Dam also flows into the plain.

The amounts of annual discharge (ordinary, low and drought discharge) in each surrounding watershed are indicated in Table 3. From Table 3, the amount of drought discharge reaches a considerably small value excluding the Shigenobu River. Furthermore, it was reported that the average drought discharge of rivers in Japan is about 1.0 mm/day. From Table 3, the drought discharge in the Dogo Plain is less than that. It also demonstrates the water shortage issue in the Dogo Plain.

Representative water table for each block

The water tables were observed automatically at groundwater gauges, which are distributed in the whole plain. From the database analysis, the groundwater of Dogo Plain is composed of one large groundwater flow along the Shigenobu River and a groundwater flow along the Ishite River as shown in Fig. 3a. In this study, the representative depth to water table was a key issue and it constituted the observed values for calibration and optimization of the model parameters. To decide the representative DGW of each block, the average DGW for each block was obtained by averaging all the observed DGW. By comparing the averaged and observed DGW, the observed DGW that was closest to the average DGW was chosen as the representative DGW in that block.

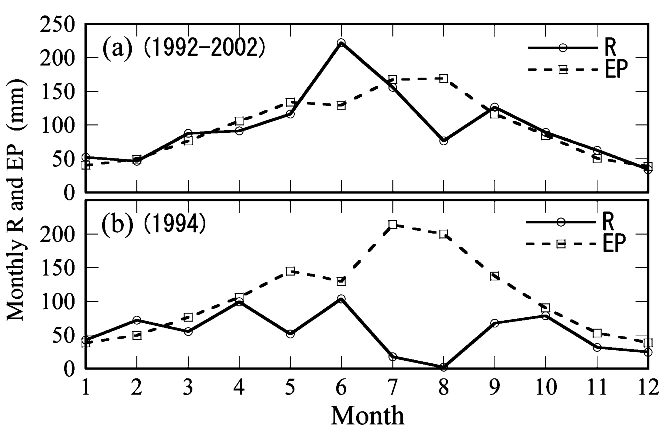


Fig. 5 Monthly rainfall (*R*) and potential evaporation (*EP*) averaged **a** from 1992 to 2002, and **b** 1994

Table 2 Comparison of annual outflow discharge in each watershed that flows into the Dogo Plain

Watershed	(1)	(2)	(3)	(4)	(5)
Area (km^2)	55.3	67.1	53.9	38.7	20.5
Average discharge (mm/year)	1,230	970	880	1,090	325

(1) Shigenobu River; *(2)* Omote River; *(3)* Tobe River; *(4)* Kutani River; *(5)* Hayashi River. These rivers are all shown in Fig. 3

Water use for domestic, industrial, and agricultural purposes

Monthly data of domestic and industrial groundwater use, including the pump area, the number of wells, volume of groundwater consumed by industry and domestic users, etc., in each block, is directly available from the record database of the Department of Water Conservancy of Ehime Prefecture, Japan. Daily data of domestic and industrial water uses is not available but it can be obtained through dividing the monthly values by the number of days in that month. Observed data of pumped groundwater for the purpose of irrigation was not available. Thus, the amount of pumped groundwater was directly measured in July, August, and September in 2004 in some farmland areas. The equivalent pumped groundwater height was calculated from subdividing the pumped groundwater amount by the pump area. The approximate monthly pumped groundwater amounts for domestic, industrial and agricultural water use were thus available to be used in the model. The daily amount of pumped groundwater was furthermore calculated through dividing the monthly values by the number of days in the month. Diverted water amount for the Dogo Plain's irrigation through the reservoir are measured and reported by the management office of the reservoir. Thus, the daily data of Dogo irrigation water are available and can be directly input into

Table 3 Properties of annual discharge (*Q*) in each surrounding watershed (mm/day)

Surrounding watershed	(1)	(2)	(3)	(4)	(5)
Ordinary *Q*	2.0	1.4	1.2	1.7	0.4
Low *Q*	1.3	0.7	0.7	0.9	0.2
Drought *Q*	0.7	0.1	0.3	0.3	0.1

(1) Shigenobu; *(2)* Omote; *(3)* Tobe; *(4)* Kutani; *(5)* Hayashi

 DOI 10.1007/s10040-008-0298-x

Table 4 List of typical range and final values of parameters which are used in the calibration process

Layer	Parameter		Unit	Maximum value				Final value			
				Block 1	Block 2	Block 3	Block 4	Block 1	Block 2	Block 3	Block 4
Surface region	Paddy field	H_{1P}	mm	150	150	150	150	29.1	29.1	29.1	29.1
		$A_{2P,}$	day^{-1}	0.50	0.50	0.50	0.50	0.16	0.16	0.16	0.16
		A_{1P}	day^{-1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		H_{2P}	mm	100	100	100	100	21.80	21.80	21.80	21.80
		C_P	day^{-1}	0.75	0.75	0.75	0.75	0.16	0.16	0.16	0.16
	Other field	H_{1O}	mm	150	150	150	150	68.2	68.2	68.2	68.2
		$A_{2O,}$	day^{-1}	0.75	0.75	0.75	0.75	0.02	0.02	0.02	0.02
		A_{1O}	day^{-1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		H_{2O}	mm	2.5	2.5	2.5	2.5	0.60	0.60	0.60	0.60
		C_O	day^{-1}	0.25	0.25	0.25	0.25	0.10	0.10	0.10	0.10
Subsurface region	A_{22}		day^{-1}	0.75	0.75	0.75	1.00	0.14	0.49	0.22	0.07
	$H_{22,}$		mm	200	75	75	200	23.30	18.70	25.30	54.50
	H_{12}		mm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C_2		day^{-1}	0.50	0.50	0.25	0.25	0.07	0.30	0.03	0.01
Groundwater region	A_{13}		day^{-1}	0.50	0.75	0.50	0.50	0.20	0.48	0.06	0.08
	$H_{23,}$		mm	5000	5000	5000	5000	167	700	21	975
	H_{13}		mm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	A_{23}		day^{-1}	0.10	0.10	0.10	0.15	0.07	0.04	0.01	0.00
Coefficients		CIRR	None	1.00	1.00	1.00	1.00	0.03	0.29	0.08	0.78
		CINT	None	1.00	1.00	1.00	1.00	0.32	0.86	0.41	0.46
		CG3	None	/	/	0.50	/	/	/	0.48	/

Legend:

A_{2P}, A_{1P}: flow coefficients for the lower and upper outlets in the paddy field sub-model; A_{2O}, A_{1O}: flow coefficients for the lower and upper outlets in the other land-use sub-model; A_{22}: flow coefficient in the surface region sub-model; A_{23}, A_{13}: flow coefficients for the lower and upper outlets in the groundwater region sub-model; H_{2P}, H_{1P}: heights of lower and upper outlets in the paddy field sub-model; H_{2O}, H_{1O}: heights of lower and upper outlets in the other land-use field sub-model; H_{22}, H_{12}: heights of the lower and upper outlets in the subsurface region sub-model; H_{23}, H_{13}: heights of the lower and upper outlets in the groundwater region sub-model;C_P, C_O, C_2: infiltration coefficients in each sub-model; *CIRR* coefficient of water-supply from rivers for agricultural use; *CINT* coefficient of water infiltrating to the subsurface or groundwater region; CG3: coefficient of groundwater flowing from block 3 to block 4

the groundwater recharge model. The intake water from rivers for irrigation (QIRR) was measured by Yonden Consultants.

Missing data estimation

The hydrologic conceptualization of virtual conditions relies on monitored data at various monitoring gauges and there are frequently missing values in the monitoring database. Reasonably estimating these missing values is important for the complete analysis and modeling of the hydrologic cycle. In the case of missing data, the multi-variable regression method and artificial neural network (ANN) technique were used, which are described in He and Takase (2006a). The ANN technique mimics the cognitive response of the human brain. It is a flexible mathematical structure patterned after the biological functioning of the nervous system and considered to be a versatile tool for approximating complex functions that are difficult to model mathematically or evaluate numer-

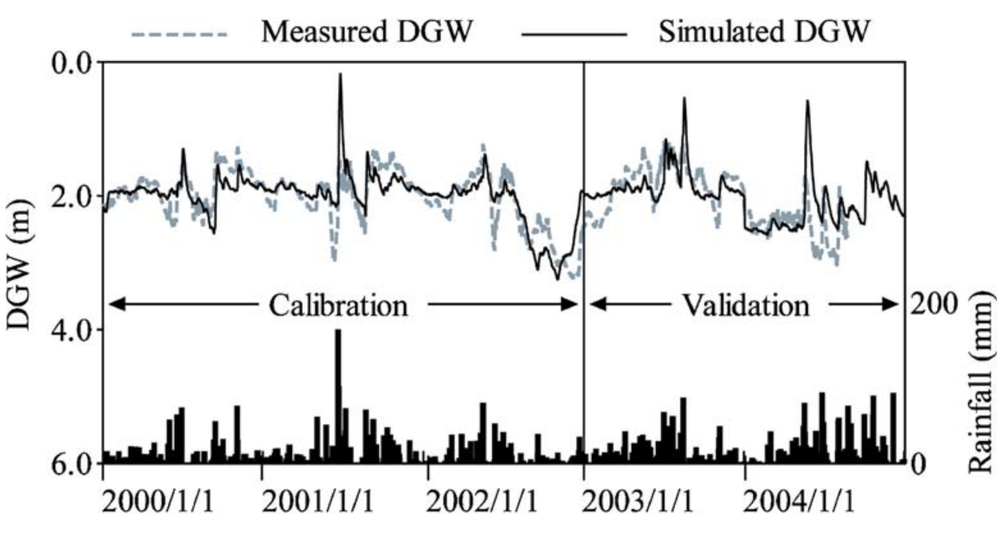


Fig. 6 The comparison between the measured and predicted depth to the groundwater level (*DGW*) in the example block (block 4: Shigenobu River downstream block)

 DOI 10.1007/s10040-008-0298-x

ically. ANN has been used in many hydrologic problems such as forecasting reservoir inflow and river flow prediction (Coulibaly et al. 2000; Karunanithi et al. 1994), and determining aquifer parameters (Aziz and Wong 1992), water quality parameters (Maier and Dandy 1996), etc. ANN modeling can be seen as a sophisticated data oriented modeling technique to find the relationship between input and output patterns without using detailed process knowledge. The ANN technique has the ability to represent non-linearity by means of a smaller number of parameters and least requirement of information regarding the process to be modeled.

In this study, three types of datasets including precipitation data, discharge data and groundwater data were prepared for the input layer. They are most important datasets for hydrologists. A dataset of precipitation is a discontinuous one, which includes rainy and no-rainy days. A discharge dataset is a continuous one, which ranges widely, for example, from a few (10^{-1}) to several 10 or 10^2 mm/day. A water-table level dataset is also continuous but it ranges in several meters or centimeters. For each dataset, the missing data occur in varying periods (several months or several weeks). However, only parts of the data are missing in the same period for all gauges, so it is possible for one to use the available data to predict the unknown data by the ANN method. Detailed description about missing data estimation can be found in He and Takase (2006a).

Results analysis

Model calibration and validation

In the stage of model calibration, the simulation was performed for the period from January 2000 to December 2002. For this hydrologic model, some parameters were chosen from long-term experience (He et al. 2005, 2006; He and Takase 2006b; Takase 2000, 2002, 2005; Yonden Report 2005), and other parameters were optimized using the SCE method (He et al. 2005, 2006). Table 4 is the list of maximum values and finally calibrated values of parameters that are used in the calibration process. In the stage of model validation, the simulation was performed for the period January 2003 to December 2004. The simulated results of the comparison between the measured and predicted DGW using the optimized parameters by SCE method is shown in Figs. 6 and 7 for both calibration and validation processes.

In Fig. 6, the seasonal variations of DGW can be clearly seen. It indicates the importance of temporal distribution of precipitation in generating recharge to groundwater. The smallest measured DGW of the four blocks during this 5-year period was 1.61 m below the soil surface. Most groundwater recharge occurred during the late winter and early spring because of precipitation, and melting snow and ice. Water tables generally reached their maximum annual height during this period.

From Fig. 7, it can also be clearly seen that the predicted DGW agrees well with the measured DGW, and thus it is judged that a reasonable hydrologic cycle of the plain has been achieved using this model. On the other hand, there are also some periods in which the predicted DGW can not reproduce a temporary rise or fall of the measured DGW. This is because the input data of pumped water for industrial, agricultural, domestic, and irrigation uses was the monthly value and the detailed daily data were not available at that stage.

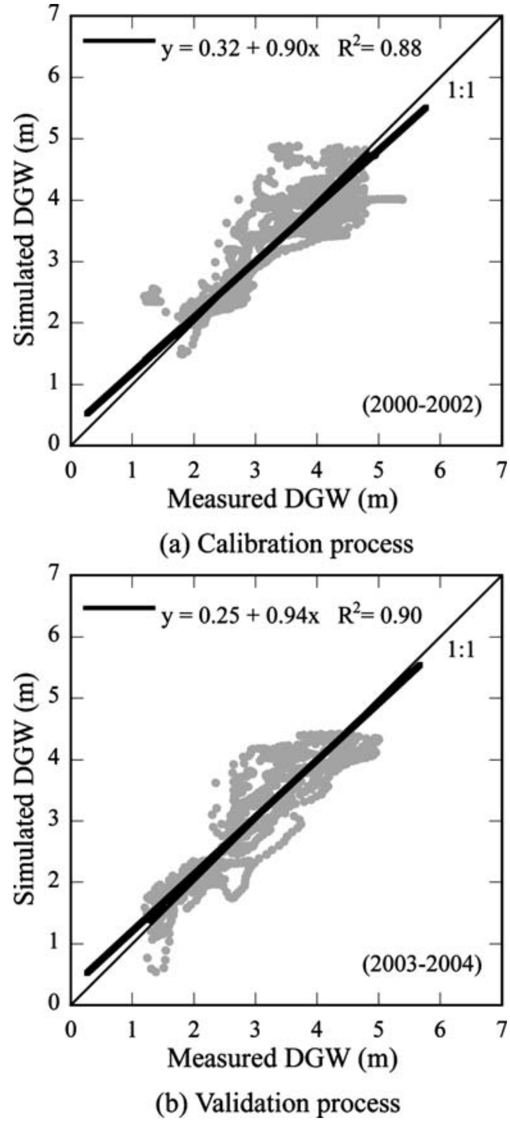


Fig. 7 Comparison between measured and simulated depth to the groundwater levels (DGW) for **a** 2000–2002, and **b** 2003–2004

Water resource evaluation

Figure 8 shows the annual and average value of total water input (TIN) and total water output (TOUT) in the Dogo Plain from year 2000 to 2003. From this figure, water inputs were almost equal to water outputs in all years except for the drought year 2002 in which the water output was a bit higher than water input. To analyze the water cycle and water-balance in the Dogo Plain in more detail, the water-balance in each block from year 2000 to 2003 was calculated. Figure 9 shows the monthly water-

 DOI 10.1007/s10040-008-0298-x

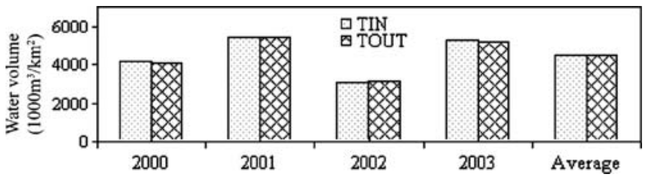


Fig. 8 Annual and average value of total water input (*TIN*) and total water output (*TOUT*) in the Dogo Plain from year 2000 to 2003

Table 5 Pumping scenarios for each block

Scenario number	Block 1	Block 2	Block 3	Block 4
1	Pumping amount in summer of drought year 2002 (V_{2002})			
2	Government-planned groundwater-pumping amount (V_{plan})			
3	$1.5\times V_{plan}$	$1.5\times V_{plan}$	$0.5\times V_{plan}$	$1.5\times V_{plan}$
4	$1.5\times V_{plan}$	$2.0\times V_{plan}$	$0.5\times V_{plan}$	$1.5\times V_{plan}$

V_{plan}: using the pumping amount that is 2.2 times the pumping amount in drought year 2002

balance in the Shigenobu River upstream block (block 1) as an example. The monthly evolution of storage change was estimated from the water-balance components. From the figures, it can be found that the storage column was filled and emptied during different periods in different hydrologic years. In the drought year 2002, the storage was emptied during the irrigation period from June to September. In the normal flow year 2003, the storage was emptied from the end of August to the middle of October. It is easy to understand the difference of the inflow elements of the surface region in each block and the difference of the water-supply form in each block from the figures. It is also helpful to obtain a clear understanding of the peculiar water-balance structure in each block.

Evaluation of groundwater utilization capability under different scenarios

One of the objectives of this study was to analyze the groundwater capability for future groundwater utilization. With the pumping scenarios changing, the water table will also change. For this purpose, groundwater use was classified into four pumping scenarios (see Table 5) and then the water table in these scenarios was predicted by employing the proposed hydrologic model. The simulated water table in each case was compared with the observed water table.

Figure 10 shows the change of water table in the four blocks for scenarios 1, 2, 3 and 4 and the results are compared with the current water table in the Dogo Plain. It is clear that the water table in the Shigenobu River upstream block (block 1) was not influenced by any scenarios because the groundwater storage in the upstream block was sufficiently large.

For the Shigenobu River midstream block (block 2), there is no great influence or change in scenario 1 compared with the actual water table in 2002. In other cases, the water table falls remarkably. It can be seen from the results for scenario 2 that the influence of different scenarios on the water table is comparatively small if the dry season of the anomalous drought year (2002) is excluded.

In the Ishite River block (block 3), there is also no large influence or change in scenario 1 compared with the actual water table in 2002 but the downward trend in the water table continues for a long time in scenario 2 (see Fig. 10).

In the Shigenobu River downstream block (block 4), there is no large influence or change in scenario 1 compared with the actual water table in 2002. In other cases, the water table will recover in the irrigation period of normal flow year and the dropped water table of 0.6–1.2 m is found in the dry season. The water table in scenario 4 is almost the same as in scenario 3. In both cases, the water table dropped substantially because the pumped groundwater amount increased and the lateral groundwater outflow amount decreased. On the other hand, salt water intrusion in the coastal areas may be expected because the Shigenobu River downstream block

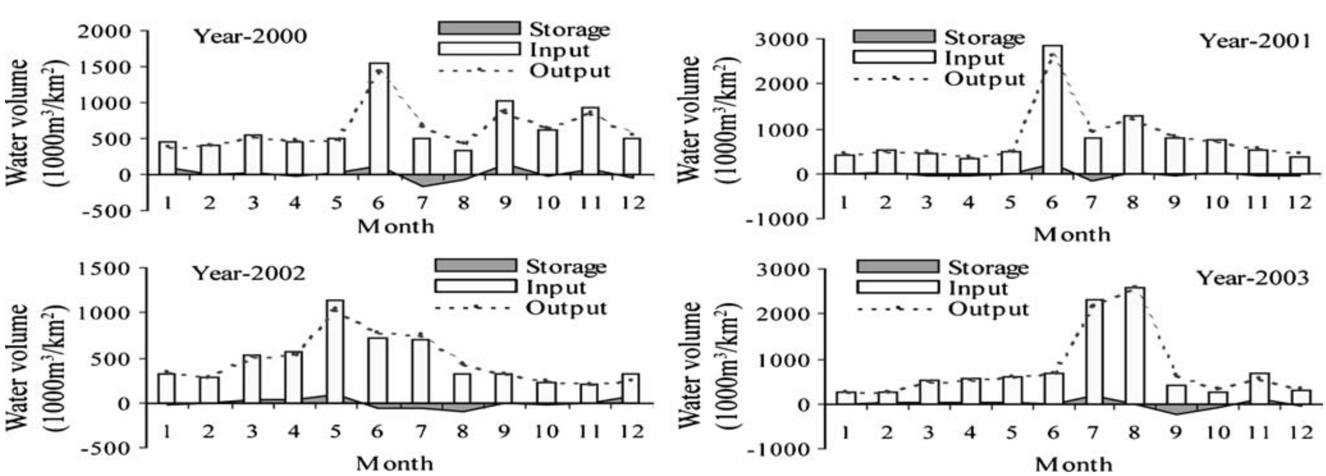
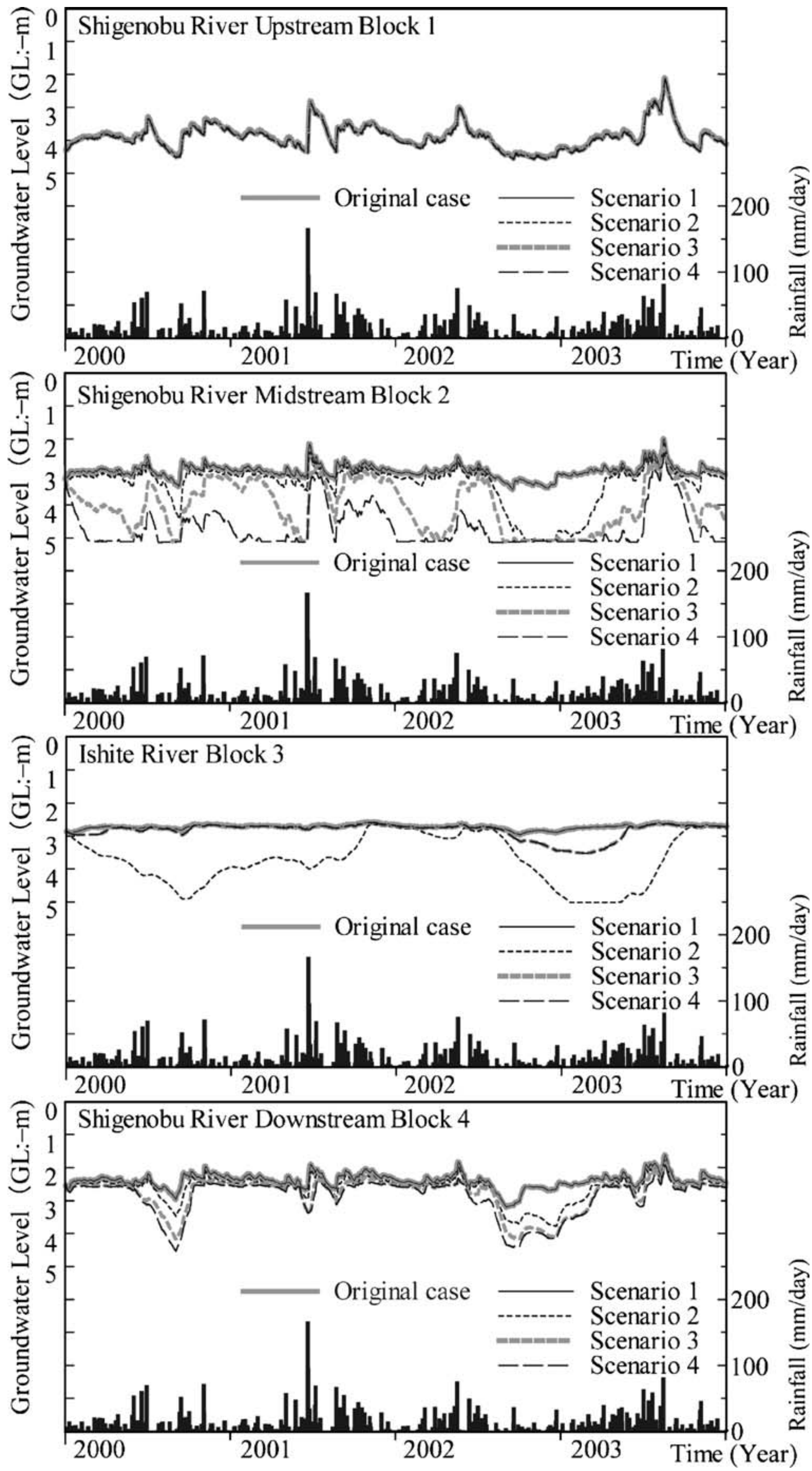


Fig. 9 Monthly water-balance for upstream block 1 (*input*: includes precipitation, discharge from mountainous surrounding watershed, Dogo irrigation water; *output*: includes evapotranspiration, river outflow, groundwater lateral outflow, pumped groundwater)

DOI 10.1007/s10040-008-0298-x

Fig. 10 The comparison between measured and predicted groundwater levels in the four blocks. (Here, the groundwater level means the depth to groundwater)



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directly faces the Seto Inland Sea and the water table dropped a lot in these scenarios.

Judging from the above analysis, a great amount of groundwater in the Shigenobu River upstream block can be further utilized for pumping purposes, as there is not much difference between measured and simulated DGW for all pumping scenarios. In the Shigenobu River midstream block, the amount of groundwater that can be further pumped can not be greater than the government planned value of groundwater pumping; otherwise the water table would fall year by year and a groundwater depletion problem would occur. For the Ishite River block, the water-table drawdown is not so much if the groundwater is pumped by the amount that the government plans to pump. The water table dropped by about 0.5 m in the dry season if half of the government planned groundwater-pumping value was used. In this case, the water-table drawdown on both normal flow year and high flow year is the same. For the Shigenobu River downstream block, the water table dropped by 0.6 m using the government planned groundwater-pumping amount and 1.0 m using the pumping groundwater amount, which is 1.5 times the government planned groundwater-pumping amount. Thus, it would be feasible to use the planned groundwater-pumping amount in the Shigenobu River downstream block.

Conclusions

The objective of this research was to develop a semi-distributed groundwater recharge model to simulate water-table fluctuation, groundwater recharge, and water-balance variables. The proposed hydrological model was applied in a coastal plain by the Seto Inland Sea, Japan. Based on the measured meteorological and hydrogeological data of the coastal plain, DGW and water-balance of the plain were studied. For the model verification, the simulation of DGW was carried out for a 5–year period, using parameters that were partly calibrated and optimized by the Shuffled Complex Evolution nonlinear optimization method. Then, the water-balance components in the coastal basin were evaluated by the proposed hydrologic model. Results showed that, by comparing the observed and simulated DGW, reliable agreement between them was found and the proposed model was capable of predicting the fluctuation of DGW and also the components of water-balance. The model has shown that with a more detailed input database, it is capable of predicting better numerical results. Further studies will be carried out to assess the impacts of climatic changes and anthropogenic activities on groundwater utilization.

Acknowledgements The research was financially supported by the Sasakawa Scientific Research Grant from The Japan Science Society. The authors are grateful for their support. The authors also thank the Yonden Consultants for their suggestions and data collection during the research. Thanks to the Managing Editor (Prof Philippe Renard) and the Technical Editorial Advisor (Sue Duncan) of Hydrogeology Journal and two anonymous reviewers for their helpful comments on an earlier version of this manuscript.

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