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Application of a modified conceptual rainfall–runoff model to simulation of groundwater level in an undefined watershed

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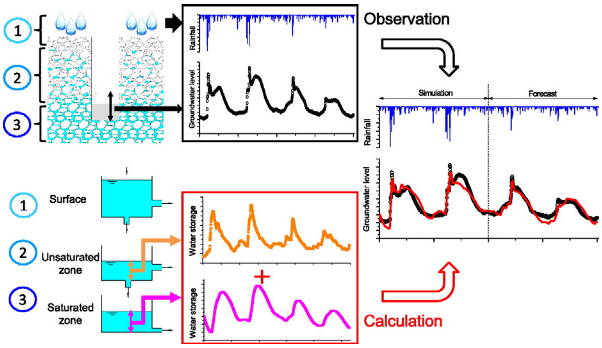
HIGHLIGHTS

- We establish a groundwater level tank model (GLTM) to simulate groundwater levels.
- The GLTM is based on a conceptual rainfall–runoff model.
- The GLTM simulates groundwater levels in an undefined watershed.
- The GLTM is developed using only rainfall and groundwater level.
- The applied GLTM provided accurate results in Kumamoto, Japan.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater level simulation models can help ensure the proper management and use of urban and rural water supply. In this paper, we propose a groundwater level tank model (GLTM) based on a conceptual rainfall–runoff model (tank model) to simulate fluctuations in groundwater level. The variables used in the simulations consist of daily rainfall and daily groundwater level, which were recorded between April 2011 and March 2015 at two representative observation wells in Kumamoto City, Japan. We determined the best-fit model parameters by root-mean-square error through use of the Shuffled Complex Evolution-University of Arizona algorithm on a simulated data set. Calibration and validation results were evaluated by their coefficients of determination, Nash–Sutcliffe efficiency coefficients, and root-mean-square error values. The GLTM provided accurate results in both the calibration and validation of fluctuations in groundwater level. The split sample test results indicate a good reliability. These results indicate that this model can provide a simple approach to the accurate simulation of groundwater levels.

1. Introduction

Groundwater is an important natural resource that is essential for agricultural, municipal, and industrial uses. During the last few decades, groundwater has become an important source of freshwater throughout the world. It is estimated that groundwater accounts for about 50%

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of the current global domestic water supply, 40% of industrial supply, and 20% of water use in irrigated agriculture (World Water Assessment Programme U.N., 2003). Groundwater levels are regarded as a dynamic response to external stresses, including rainfall, extraction, evaporation, and as an output of the groundwater system (Yang et al., 2014). The essential tasks of integrated planning, effective management, and exploitation of groundwater resources depend largely on the accurate prediction of groundwater levels (Mohanty et al., 2010).

Several types of models have been used to simulate groundwater resources. Physically-based numerical models (Al-Salamah et al., 2011; Beven et al., 1987; Kinzelbach, 1986; Refsgaard et al., 1999; Mohanty et al., 2013; Onta and Gupta, 1995; Reichard, 1995; Rodríguez et al., 2006; Xu et al., 2012) are used for characterizing the groundwater system; however, for reliable predictions, this approach requires large quantities of accurate data both to identify the physical properties of the domain and model parameters and to calibrate the model simulations (Yoon et al., 2011). Another approach for predicting groundwater level uses several black-box model, such as artificial neural network (Daliakopoulos et al., 2005; Emamgholizadeh et al., 2014; Nayak et al., 2006), to simulate the nonlinear relationship between input and output series. Otherwise, there were no physical means in model parameters. It is difficult to analyze the reason for the phenomenon and compare with other research areas.

There are also accounting models that track water flows into and out of a particular hydrologic system. Conceptual rainfall–runoff models, which are utilized to simulate the response of runoff to the rainfall process in a basin, have the advantage of being able to represent nonlinear stream flow behavior and to reach a solution quickly. Such models have been developed based on conceptual representations of the physical processes of water flow aggregated over the entire catchment area: examples of this type of model are the Stanford Watershed Model (Crawford and Linsley, 1966), the Sacramento model (Burnash et al., 1973), the HBV model (Bergström, 1976), the MIKE 11/NAM model (Havnø et al., 1995; Nielsen and Hansen, 1973), the Xinganjiang model (Zhao et al., 1980; Zhao, 1992) and the tank model (Sugawara, 1979, 1995). There are also some models, such as the CATPRO hydrosalinity model (Kuczera and Mroczkowski, 1998), which is utilized to simulate water and chloride dynamics in hillslope catchment. Among these models, tank model can use simple relationship between water storage and runoff process to simulate complex rainfall–runoff processes without detailed watershed properties, such as land use and geostructure. Tank model has been applied to simulation in arid region and snow component (Sugawara, 1995). Tank model has also modeled hydrologic responses in a wide range of watersheds (Franchini and Pacciani, 1991; Kuok et al., 2010; Lee and Singh, 1999; Tingsanchali and Gautam, 2000). Tank model uses several tandem tanks to describe each element (such as water storage, runoff, and infiltration) in rainfall–runoff process directly. Therefore, it is easy to combine these elements with geographic processes to extend the hydrogeographic process simulation. Nowadays, the tank model's high expandability enables it to be used in modeling the interaction between watershed hydrology and geology (Chen and Adams, 2006; Lee and Singh, 2005). Takahashi et al. (2008) introduced a multi-tank model to predict groundwater table in slope. However, this model only focuses on disaster prediction rather than hydrological process simulation. In a specific well basin, the groundwater level can be reflected by water storage which is calculated by model. Tank model defined a series of tandem tanks to simulate each geological layer and measured-water storage by height rather than volume, which propose a simple link between groundwater level and water storage without basin area related with a specific well.

In this study, we establish a groundwater level tank model (GLTM) based on a conceptual rainfall–runoff model (tank model) to simulate the fluctuation of groundwater level at observation wells in Kumamoto City, Japan. The purpose of our study is to provide a simple model to simulate the relationship between rainfall and groundwater level fluctuation using simple observed data. In this report, using rainfall and groundwater level data only, we present a simple approach for simulating the groundwater level in the monitoring wells of an undefined watershed through use of a modified conceptual rainfall–runoff model.

2. Methodology

2.1. GLTM structure

In this study, we introduce a GLTM to study the relationship between rainfall and the fluctuation of the groundwater level in the basin that drains into each monitoring well. In each well basin, the rainfall–runoff process is simulated by modeling the water storage as a function of the runoff and infiltration of the rainfall in tandem sequences of three tanks with lateral holes through which water partly discharges and bottom outlet holes through which water partly infiltrates. The amount of runoff (or lateral discharge) or the amount of infiltration through an outlet is linearly proportional to the water storage height at the outlet. The first tank is used to simulate the rainfall, surface runoff, and infiltration; the second tank is used to simulate the intermediate runoff and infiltration; and the third tank is used to simulate the base flow and discharge. The model then converts water storage height in the second and third tank to the height of their respective real water tables. The water storage in the monitoring well can then be estimated as a combination of the real water table heights of the second and third tank. The model then predicts that the water storage height in the groundwater level monitoring well is equal to the monitored groundwater level.

The volume balance equations for a tank model consisting of three tanks are calculated as follows:

$$\frac{dh_1}{dt} = r - i_1 - q_1, \tag{1}$$

$$\frac{dh_2}{dt} = i_1 - q_2 - i_2, \tag{2}$$

$$\frac{dh_3}{dt} = i_2 - q_3, \tag{3}$$

where h_1, h_2, and h_3 represent the water storage height (mm) of the first, second, and third tanks; t represents calculation time interval (d); r represents rainfall intensity (mm); i_1 and i_2 represent the infiltration rates (mm/d) of the first and second tanks; and q_1, q_2, and q_3 represent the surface, intermediate, and base runoff (mm/d), respectively, from the first, second, and third tanks.

The rate of runoff or infiltration through an outlet is linearly proportional to the height of water at the outlet, which is same as a linear reservoir problem (Rimmer and Hartmann, 2012), can be expressed as follows:

$$q_1 = \begin{cases} a_1 \times (h_1 - H_1) & h_1 > H_1 \\ 0 & h_1 \le H_1 \end{cases}, \tag{4}$$

$$q_2 = \begin{cases} a_2 \times (h_2 - H_2) & h_2 > H_2 \\ 0 & h_2 \le H_2 \end{cases}, \tag{5}$$

$$q_3 = a_3 \times h_3, \tag{6}$$

$$i_1 = b_1 \times h_1, \tag{7}$$

$$i_2 = b_2 \times h_2, \tag{8}$$

where a_1, a_2, and a_3 are the lateral output coefficients (dimensionless) for each tank; b_1 and b_2 are the infiltration coefficients (dimensionless) for the first and second tanks; and H_1 and H_2 are the height (mm) of the runoff outlets of the first and second tanks.