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Combined use of tracer approach and numerical simulation to estimate groundwater recharge in an alluvial aquifer system: A case study of Nasunogahara area, central Japan

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SUMMARY

In this study, we simulate the spatial and temporal distribution of groundwater recharge in an alluvial aquifer system in the Nasunogahara area of Japan. Natural stable isotopes (^{18}O, D) were considered as additional calibration targets in a numerical model. The reliability of the model outputs was further validated by comparing the results from the numerical simulation and an independent tracer approach. The results indicated that the calibrated model can effectively simulate the spatial and temporal characteristics of the contribution ratios of recharge sources to groundwater in the Nasunogahara area. However, the tracer approach (i.e., end member mixing analysis) provided more reliable results at point scale, particularly for the estimated contribution ratios of paddy field water. The precipitation in the Nasunogahara area is the major recharge source; its mean contribution ratio is 58% for a one-year period over the entire alluvial fan. River seepage is significant in the upstream area of the alluvial fan, and the contribution ratio of river waters along the river channels in the upstream area increases during the wet season. Paddy field water is a highly important recharge source in the midstream and downstream areas of the alluvial fan, and the contribution ratio of paddy field water obviously increases from dry season to wet season because of irrigation. This study demonstrates that combined use of the tracer approach and numerical simulation with stable isotopes as additional calibration targets can eliminate their respective limitations and can assist in better understanding the groundwater recharge mechanism in alluvial aquifer systems.

1. Introduction

Groundwater is a major source of drinking water for more than 1.5×10^9 people worldwide. Groundwater is nearly the sole water source for several cities, including Jakarta, Lima, and Mexico City (Sampat, 2000). Alluvial deposits, which have substantial thickness and high porosity, contain abundant groundwater resources. Many alluvial aquifers have an important role in supplying drinking water and irrigation water worldwide, such as those in the North China Plain in China (Foster et al., 2004; He et al., 2011) and Hueco Bolson in the United States and Mexico (Eastoe et al., 2010). However, excessive groundwater withdrawal to meet increasing demand for alluvial groundwater because of population increase and economic growth has resulted in declining water tables, land subsidence and groundwater salinization (Famiglietti et al., 2011; Galloway and Burbey, 2011; Liu et al., 2012). The renewal ability of the groundwater system, which is a key parameter determining the sustainable yield of such a system, highly depends on the quantity and quality of aquifer recharge (Mikita et al., 2011; Yamanaka et al., 2011). Thus, a thorough understanding of recharge and flow paths in alluvial aquifers is necessary in water resource management to ensure sustainability on a local or regional scale (Choi et al., 2010; Foster et al., 2004).

Numerical modeling provides an efficient method of clarifying the flow path and seasonal dynamics of groundwater, as well as quantifying the recharge amount of each recharge source. However, the reliability of recharge estimated by models depends on the accuracy of the measured and interpolated hydraulic parameters (Scanlon et al., 2002; Sibanda et al., 2009). Therefore, multiple methods or objective functions have been used to calibrate

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numerical models to achieve robust results. For example, Kim et al. (1999) determined the best calibration method among a set of possible options with the help of four sets of parameter values (i.e., steady-state heads, transient heads, head gradients, and flow path information). Sanford et al. (2004) used ^{14}C activities and the location of hydrochemical zones as additional calibration targets to determine the model parameters for the Middle Rio Grande Basin in the United States. Dahan et al. (2004) used a multi-variable mixing cell model that represents the hydrochemical approach to calibrate a groundwater flow model, and pointed out that using both hydraulic and hydrochemical tools can improve understanding of the hydrologic system. The simultaneous use of hydrochemical tools and groundwater flow models can also provide insight into strengths and limitations of each method (Carroll et al., 2008).

The stable oxygen and hydrogen isotopes (^{18}O and D) are kind of environmental isotopes, which widely exist in natural waters. The isotopic compositions (δ^{18}O and δD) in water are affected by meteorological process (temperature, humidity, and so on), but not as much by reactions with geologic materials, making ^{18}O and D suitable for investigating the provenance of groundwater (Clark and Fritz, 1997). The δ^{18}O and δD values are particularly useful for tracing water movement at river banks because two main water sources are typically present: (1) river water, which is depleted of heavy isotopes and originates upstream, and (2) groundwater, which comes mainly from local rainfall (Lambs, 2004). When the δ values are negligibly affected by evaporation processes and the effects of past climate regimes on δ signatures are ignored, ^{18}O and D can be considered as conservative tracers (Carroll et al., 2008). Although δ values are not technically concentrations, they can be considered as concentrations because δ values scale linearly with concentration. However, using δ values as simulation terms to calibrate numerical simulation results is highly limited. These studies are mainly restricted to steady-state conditions (Stichler et al., 2008), simple model (Yamanaka and Wakui, 2009), or coastal wetland system (Reynolds and Marimuthu, 2006).

The present study aims to: (1) reveal the spatial and temporal distribution of the contribution ratios of groundwater recharge sources in an alluvial aquifer system through combined use of a tracer approach and a numerical simulation; (2) improve the model calibration by adding stable isotopes as additional calibration targets of hydrometric data; and (3) clarify the capabilities and limitations of the tracer approach and numerical simulation applied to compute the contribution ratio of groundwater recharge sources.

The Nasunogahara area in Japan is used as a case study (Fig. 1). A hydrochemical and stable isotopic study was carried out in the middle of the alluvial fan. The results indicate that precipitation, river water, and paddy field water are the three main recharge sources of groundwater. The hydrochemical and stable isotopic study was also estimated the contribution ratios of each source to well waters through a three-end-member mixing analysis (Wakui and Yamanaka, 2006). According to the hydrochemistry and isotope characteristics of the sampled groundwater, the alluvial fan was generally divided into three sub-areas: Sabi River-influenced area (Fig. 2a), Naka River-influenced area (Fig. 2b) and Houki River-influenced area (Fig. 2c). The spatial changes of groundwater recharge/discharge fluxes along the Sabi River were characterized by a compartmental mixing cell model with stable isotopes as calibration terms (Yamanaka and Wakui, 2009). The compartmental mixing cell model revealed that precipitation was the most dominant recharge source to groundwater at the non-paddy area, while river water infiltration at the fan apex was important in driving groundwater flow system. However, paddy field infiltration is relatively small even during irrigation period. Elhassan et al. (2001, 2003, 2006) examined the groundwater budget of unconfined aquifer in the Nasunogahara area and analyzed the influence of paddy field irrigation on groundwater budget using a modified tank model with a two-dimensional groundwater flow model. However, the detailed spatial and temporal distribution of the groundwater recharge in this study area still needs to be elucidated with the help of a three-dimensional groundwater flow model.

2. Site description

The Nasunogahara area, one of the largest alluvial fans in Japan, is a compound alluvial fan formed by the Naka River, Houki River, Sabi River, and Kuma River (Fig. 1). The alluvial fan is bound by the Houki River on the west and south, the Naka River on the east, and the Shimotsuke Mountains on the northwest. The annual mean precipitation is 1533(±280) mm, and approximately 83% of the annual precipitation occurs during the wet season from April to October according to climatic normals (1981–2010) calculated from the observed data of Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html). The annual mean temperature in the area from 2004 to 2006 was 12.3(±0.4) °C, (which was close to the long-term annual mean temperature 11.7(±0.8) °C. The annual mean precipitation was 1553(±260) mm, which was also close to the long-term annual mean precipitation of 1533 mm. The largest monthly mean precipitation of 338(±46) mm occurred in July; the second highest monthly mean temperature of 23.0(±0.9) °C also occurred in the same month. The lowest monthly mean precipitation 20(±6) mm and the lowest monthly mean temperature 0.6(±0.3) °C occurred in January. Thus, the simulated results in July were used to represent the wet season conditions, while the outputs in January were used to represent the dry season conditions. Thornthwaite method was used to estimate the potential evapotranspiration, and the calculated annual mean potential evapotranspiration was 654(±11) mm in the study area (Thornthwaite, 1948). The precipitation and temperature data were obtained from the Kuroiso Station (36°58.9′N, 140°01.1′E, and 343 m above mean sea level (a.m.s.l.)).

The alluvial aquifers in the Nasunogahara area are mainly composed of gravel and sand, whereas aquitard consists of pumice and clay (Fig. 3). The northwestern part of the study area is bounded by an impermeable fault that behaves as an aquiclude. The impermeable fault separates the alluvial aquifers from mountain aquifers/mountain blocks. Given the high permeability of the river beds, the middle reaches of the Sabi River dries up and only has water on rainy days during the wet season. Downstream, the Sabi River receives groundwater discharge and becomes a permanent river reach again. The Houki River, a branch of the Sabi River, is also an intermittent river. The river bed and river banks of the Houki River are covered by concrete. The stable isotopic analysis showed that the influence of the Houki River on groundwater was limited (Wakui and Yamanaka, 2006). The seepage of the Houki River is expected to be limited for the entire study area; thus, it is not considered in this study. Moreover, many springs with large discharge occur downstream of the Nasunogahara area.

Forest, agricultural, and residential areas are the three major land use/land cover types in the Nasunogahara area. Rice is the major farm crop. Approximately 40% of the land (i.e., 164 km^2) is used as paddy field, but most of the paddies are distributed midstream and downstream of the Nasunogahara area, as well as along rivers (Fig. 4a). The irrigation period usually begins in April and ends in early August. The groundwater within the study area is abstracted for local consumption; however, none of these wells are metered. Moreover, no large water consumption wells are found for industrial and agricultural use in this area. Therefore, groundwater abstraction is expected to be extremely small and does not have a significant effect on the groundwater system in the area.