

NUMERICAL SIMULATION OF SUBSURFACE TEMPERATURE DISTRIBUTION UNDER CLIMATE CHANGE

Tohoku University Graduate Student O Luminda GUNAWARDHANA
Tohoku University Fellow Member So KAZAMA

1. INTRODUCTION

Subsurface temperature is identified as one of the main parameter vulnerable to climate change. In recent studies, there have been several attempts to evaluate the future climate change impacts on aquifer thermal regime by incorporating analytical models for heat transport in the shallow subsurface layers (Gunawardhana and Kazama 2009a, b). However, some uncertainties of the estimations still remain due to inherent limitations of the analytical solutions due to their simplified assumptions of subsurface geology and ground surface climatic conditions. In such situations, numerical models can be applied to incorporate the effects of heterogeneous geological formations and the transient temperature change at the ground surface for the aquifer temperature distribution. Therefore, the objective of our study is to develop a numerical model to estimate the potential aquifer temperature change in the future under changing climate.

2. THEORY

The U.S. Geological Survey's computer program VS2DH, which simulates energy transport in porous media under variably saturated conditions, was used. The energy transport equation, which is in the form of advection-dispersion equation can be written as:

$$\frac{\partial[\theta C_w + (1-\phi)C_s]T}{\partial t} = \nabla K_T(\theta)\nabla T + \nabla \cdot \theta C_w D_H \nabla T - \nabla \theta C_w v T, \quad (1)$$

where t is time; θ is volumetric moisture content; C_w is heat capacity; ϕ is porosity; C_s is heat capacity of the dry solid; T is temperature; K_T is thermal conductivity of the water and solid matrix; D_H is hydrodynamic dispersion tensor; and v is water velocity.

3. METHODOLOGY

The area between the Nanakita and Natori rivers in the Sendai plain was selected. The Sendai plain is an alluvial formation and serves as the main aquifer of the catchment. The maximum depth of the aquifer ranges between 60–80 m and the permeability of the soil below that is significantly (approximately 10^4 times) less than the permeability of the main aquifer. The surface air temperature (SAT) records in Sendai meteorological station indicate no significant trend until the middle of 20th century. Since 1947 until 2007, SAT shows significant increasing trend in the region (2.0 °C/century). In contrast to temperature, annual total precipitation in the Sendai plain shows no strong trend over the last 80 years.

There are five water level observations stations located within the area. Among them, W1, W2, W4 and W5 have three sub-wells (SWs) each directed to different aquifer depths (e.g. 7, 26, 60 m at W1). Groundwater temperature was measured at W1, W2,

W3 and W4 at 1 m intervals. Groundwater temperatures presented in Water Environmental Map No. 1 were used for W5. Groundwater levels measured by the Sendai city office were also taken. All well locations are situated within seven kilometers of the city center. The magnitude of ground surface warming, which was calculated as the difference between the observed temperature depth (T-D) profile and the extrapolated steady state linear curve to the ground surface, ranges 0.9–1.3 °C.

The domain was modeled in one dimension using 3 columns and 519 rows. The vertical grid spacing varied from 0.1 m at the surface to 1m at depth. The total domain depth was 500 m. Water table position was determined from the annual average water level records in all observation wells. Thermal and hydrological properties of the aquifer were assigned based on the available literature, and the technical report from the geological survey of Japan. Initial T-D profile was estimated by extrapolating the undisturbed portion of the observed T-D profile to the ground surface. Considering the fact that there is no significant SAT trend in the Sendai plain until mid of 20th century, starting time of the model was selected to be 1947. Since 1947, SAT in the area has increased at a rate of 2.0 °C/century. While the actual ground surface temperature (GST) is unknown from 1947 to the present (observation time in 2007), variations of 5-year moving average of SAT was used to produce the damped nature of GST records relative to SAT records. This damping effect can generally be attributed to the difference in heat capacities of the air and ground. The deviations were calculated by subtracting the average SAT during 1927-1947 from the 5-year moving average of SAT. Later they were added to the GST, which was determined by extrapolating the undisturbed portion of the observed T-D profile to the ground surface. For the convective heat transport, groundwater recharge in the Sendai plain was estimated by the water budget technique for year 2007 (135 mm/year) and was verified with the estimations from two other methods; Darcy's method (100-210 mm/year), and water level fluctuation method (110-210 mm/year) (Gunawardhana & Kazama 2009b). Moreover, historical and future variations of groundwater recharge were estimated by the water budget technique with respect to the variations of SAT, and precipitation and later included as a specified vertical flux in to the domain.

In order to estimate the global climate change impacts at the Sendai plain, we examined time series of temperature and precipitation for the 20C3M, A2, A1B, and B2 scenarios of MRI model. Model results containing the target station in the Sendai

meteorological station (38.26 °N and 140.9 °E) were spatially downscaled by matching the statistical distributions of observed temperature and precipitation with respective GCM climatic parameters. Observed data and MRI simulations from 20C3M scenario for the period of 1927-1999 are used as the control to develop the cumulative probability distributions (CDF) in future.

4. RESULTS AND DISCUSSION

To assess the changes of climatic parameter in future, we compared the downscaled results of temperature and precipitation during 2060-2099 time periods with the climatic observations during 1968-2007. Among the scenarios of concerned, A2 shows the highest warming in the future (3.4 °C) followed by A1B (3.3 °C) and B1 (2.3 °C) scenarios. For the precipitation, B1 and A1B scenarios depict increasing precipitation trend (129 mm/year and 98 mm/year, respectively), but A2 scenario predicts almost no change during 2060-2099 time periods relative to precipitation average during 1968-2007. The possible variations of groundwater recharge were estimated with respect to the change in surface runoff and evapotranspiration due to changing climate in future. MRI-A2 scenario predicts the strongest hydrological impact, which reduces the groundwater recharge to 50 mm/year by year 2080 (average over 2060-2099) in the Sendai plain. According to MRI-A1B, anticipated groundwater recharge would decrease to 87 mm/year, despite the projected 98 mm/year increase in precipitation, due to higher degree of evapotranspiration resulting from a 3.3 °C increase in surface air temperature. However, due to its slow rate of warming (2.3 °C) and higher precipitation rise (129 mm/year), MRI-B1 predicts 18% of recharge increment in 2080 relative to 2007 estimation (135 mm/year). Moreover, combined effects of groundwater recharge variations and ground surface temperature change were applied in VS2DH numerical code to estimate the resulting aquifer warming (**Fig. 1**). The deepest depth to the water table occurs approximately at 8m depth near W4. Therefore, it was

selected as the representative depth for the comparison of impact by different scenarios. The strongest effect in shallow aquifer depths is produced by MRI-A2, which causes approximately 3.0 °C warming by the end of 21st century (2099) relative to observations in 2007. MRI-A1B also exhibits a strong effect as A2 scenario, which causes 2.7 °C change. MRI-B1 predicts the lowest impact among the three scenarios (1.7 °C). All model scenarios produce concave shape T-D profiles such a way that the magnitude of warming is smaller in deeper aquifer depths than the shallow areas. This is because; background temperature in the aquifer is higher than the annual average surface air temperature, giving an upward heat flow from the interior of the earth. Therefore, in the presence of significant groundwater recharge, cool water infiltration from the top of the aquifer eventually slowdown the rate of aquifer temperature rise due to surface air temperature change owing to climate change.

5. CONCLUSIONS

In this study, we incorporated three GCM scenarios from MRI model to evaluate the potential impacts of climate change on aquifer thermal regime in the Sendai plain, Japan. With respect to 2.3-3.4 °C warming and 3-129 mm/year precipitation rise, groundwater recharge would vary in a range of 50-160 mm/year during 2060-2099 time periods compared to the estimated 135 mm/year recharge in 2007. When, different degrees of groundwater recharge and ground surface warming rates were incorporated, aquifer in the Sendai plain may warm in 1.7-3.0 °C range by 2099 with respect to the observations in 2007.

According to IPCC AR4, approximately 20-30% of animal species are likely to be at risk of extinction if increases in global average temperature exceed 1.5-2.5 °C. Therefore, estimated range of aquifer warming will have a critical impact for the ecological balance in the groundwater dominated ecosystems in the Sendai plain. Our estimations will inform the decision makers to take immediate mitigation measures.

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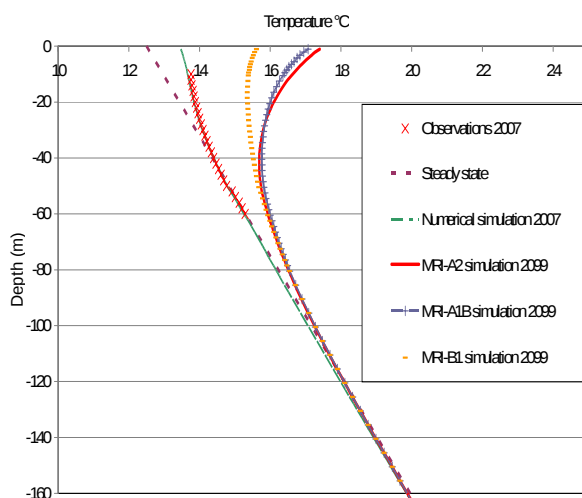


Fig. 1 Potential impact on aquifer thermal regime by different scenarios.