# Application of VS2DH numerical code in climate change studies

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## 1. Introduction

From an ecological point of view, the metabolic rates of organisms and the overall productivity of ecosystems are directly regulated by temperature. Changes in groundwater temperatures will alter fundamental ecological processes and the geographic distribution of aquatic species in groundwater-dominated coastal wetlands, estuaries and ponds. The ecological importance of aquifer temperature change is emerging under changing climate, especially in the countries like Japan, where many of the coastal estuaries, ponds and wetlands are dominantly sustained by the groundwater flows due to its unique topography and shallow groundwater tables. 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 2009). However, the major drawback of above analytical solutions when applying in climate change studies is that the change in ground surface temperature is treated as a linear constant, which in reality is a subsequent warming and cooling events on the scale of years and decades. Moreover, groundwater recharge is estimated or inputted as a time averaged constant over the simulation time, which under changing climate would significantly varies (Gunawardhana and Kazama 2010). Under these circumstances, numerical codes such as VS2DH facilitate us to simulate the heat transport in the subsurface layer under variable boundary conditions. Therefore, the objective of this study is to incorporate the different performances of global climate models in VS2DH numerical model that best provide a reliable range of potential climate change impact on aquifer thermal regime at local scale in the Sendai plain.

## 2. Theory

The VS2DH numerical code (Healy and Ronan, 1996), which has the capability of simulating heat transport under unsteady, non-uniform water flow and with variable boundary conditions, was used. The governing equation for subsurface temperature distribution can be written as

$$\partial/\partial t\left[\theta C_W + (1-\phi)C_S\right]T = \nabla.K_T(\theta)\nabla T + \nabla.\theta C_W D_H \nabla T - \nabla\theta C_W v T + qC_W T^* \quad (1)$$

where $t$ is time in sec; θ is volumetric moisture content; $C_W$ is heat capacity of water, in J/m$^3$°C; φ is porosity; $C_S$ is heat capacity of the dry soil, in J/m$^3$°C; $T$ is temperature, in °C; $K_T$ is thermal conductivity of the water and solid matrix, in W/m°C; $D_H$ is hydrodynamic dispersion tensor, in m$^2$/sec; $v$ is water velocity, in m/sec; $q$ is rate of fluid source, in sec$^{-1}$; and $T^*$ is temperature of fluid source, in °C.

## 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 20$^{th}$ century. Since 1947 until 2007, SAT shows significant increasing trend in the region (2.0 °C/century). In contrast, 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). Most of these well points have the monthly averaged water level records over 20 years and 1 hr water level records over three years. 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 ºC.

The domain was modeled using 180 columns, where grid spacing varied from 0.1 m at the surface to 1 m at depth. The total domain depth was 150 m. All parameter values used are based on the Geological survey of Japan and use of previous research. Considering the spatial heterogeneity of hydraulic conductivity, typical values were assigned from the available literature and later calibrated against to the observed water level records in SW2s. For the initial boundary conditions, the temperatures at the bottom and the top of the porous medium were assigned by extrapolating undisturbed linear portion of temperature-depth profile. Considering the fact that there is no significant SAT trend in the Sendai plain until mid of 20$^{th}$ 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. To account the convective effect of the groundwater flow on subsurface heat transport, predefined impulse response function in continuous time (PIRFICT) method was employed with Person type III function. This method has the capability of using irregular or high-frequency data. Moreover, it does not require several models testing to identify the order of the conventional ARMA type TFN model, because the transfer function is defined based on plausible physical behavior. To assess the performance of the different models, we used time series of temperature and precipitation of 2 GCMs for the 20C3M, A2, A1B and B1 scenarios, which produce 2 and 6 time series for each climatic parameter for the $20^{th}$ and $21^{st}$ centuries, respectively. For the use of these scenarios in climate predictions in the Sendai plain, bias correction is performed by quantile mapping.

## 4. Results and discussions

Figure 1 depicts one example of the observed and simulated water level records in SW1. All simulations from PIRFICT method (in SW1 and SW3) well agree with the observed water level records with $R^2_{adj}$=62~67% and RMSE=0.162~0.188m. Moreover, simulated water level records at SW2 by the VS2DH model show good fit with the observed water level records with $R^2_{adj}$=86~91% and RMSE=0.031~0.037m, which confirm the adequate accuracy of the calibrated aquifer parameter values. A summary of the different GCM scenarios predicting local impact in the Sendai plain is shown in Table 1.

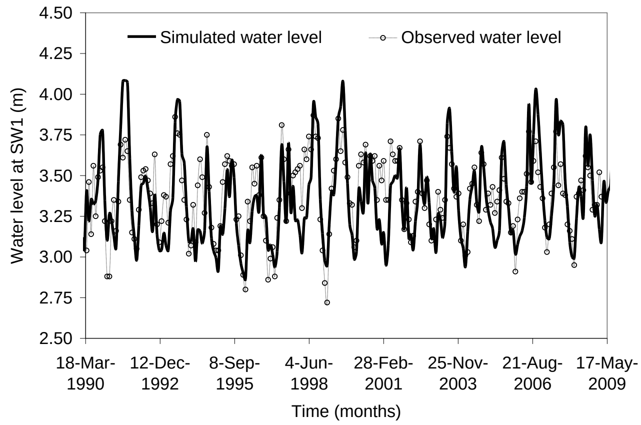


**Fig. 1** Simulated water level records at W1

Table 1: Impact of different GCMs on aquifer temperature

| Scenario | Precipitation $[P_{2060-2099} - P_{1967-2006}]$ (mm/year) | Air temperature $[T_{2060-2099} - T_{1967-2006}]$ (°C) | Aquifer temperature change at 8 m depth from ground surface $[T_{2080}-T_{2006}]$ (°C) |
|---|---|---|---|
| MIROC-A2 | 246 | 4.73 | 4.28 |
| MIROC-A1B | 247 | 4.38 | 3.8 |
| MIROC-B1 | 164 | 2.87 | 2.32 |
| CSIRO-A2 | 38 | 2.65 | 2.2 |
| CSIRO-A1B | 68 | 2.12 | 1.75 |
| CSIRO-B1 | -9 | 1.33 | 1.02 |

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. Table 1 shows the potential range of aquifer temperature change in the Sendai plain. Above scenarios also show that the depth of departure from a steady state profile increases by different amounts, demonstrating the possibility of future climate change impacts at deeper aquifer depths. Six scenarios in this study predict that aquifer in the Sendai plain may warm in a range of 1.02–4.28 ºC, which according to IPCC AR4 may have critical impact on ecological balance of the groundwater dominated ecosystems in the Sendai plain.

## 5. Conclusions

In this study, climate change impacts on aquifer thermal regime in the Sendai plain, Japan were evaluated. The VS2DH numerical code was employed to simulate the heat transport in the subsurface layers. To simulate the water level records in the future (2009-2099) and during the past time periods where we had no observations (1947-1989) PIRFICT method was followed with a predefined Person type III function. All simulations from PIRFICT method in SW1s and SW2s and from VS2DH numerical model well agree with the observed water level records with $R^2_{adj}$ = 62~91% and RMSE = 0.031~0.188m. To incorporate the future climate change impacts, 6 GCM scenarios were used. All model scenarios predict increasing trend of surface air temperature in the future, which may warm the Sendai area in a range of 1.3-4.7 °C during 2060-2099 time period compare to observed average during 1967-2006. Bias corrected precipitations also show increasing trend in same time periods (38-247 mm/year), except CSIRO-B1, which predicts 9 mm/year reduction. When the effect of all model scenarios were concerned, aquifer in the Sendai plain may warm in a range of 1.0–4.28 ºC at an 8m depth from ground surface compared to 2007 observations. The analysis presented in our study focused on the direct impact of climate change only. In addition, land-use change also can significantly impact aquifer temperature and therefore need to be considered in more for complete impact assessments. On the other hand, land use practices such as reforestation programs are proved to be effective of decelerating aquifer warming. These findings are therefore will guide the decision makers to come up with suitable mitigation measure to cope with future climate change impacts.

## References

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