SPATIAL DOWNSCALING OF GCM OUTPUT FOR ASSESSING THE IMPACTS ON GROUNDWATER TEMPERATURE IN THE SENDAI PLAIN

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Transfer function method was used to spatially downscale the raw GCM data to the Sendai plain for assessing the climate change impacts on groundwater temperature. Raw TAR HadCM3 A2c data and observed data from 1967-2006 were used to develop the transfer functions. Derived functions, that were tested for 1927-1966, were used to downscale GCM data of 2060-2099. These predictions were used in one dimensional heat transport model which was calibrated to the existing site conditions by the water budget technique. Compared with the baseline climate, annually averaged downscaled temperature of 2060-2099 would increase by 4.5 ^{0}C. Downscaled total monthly precipitation would decrease by 39% (max of 27 mm) in November but increase by 20% (max of 35 mm) in July. A2c scenario shows significant effect which will increase the groundwater temperature in average of 2.34 ^{0}C by 2080. Above findings with the developed methodology will be important to estimate the impact of climate change.

Key Words **:** *groundwater temperature, transfer function, climate change, Sendai plain*

1. INTRODUCTION

Ever rising global temperature in the atmosphere have had discernible impacts on many physical and biological systems in the world. The assessments of the Intergovernmental Panel on Climate Change[1)] has concluded that approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C. In terms of assessing the climate change effects on water resources, there has been increasing research of predicting the potential impact on fresh water quantity and quality[2),3)]. However, there is little attention on groundwater[4)] and even lesser attention on the groundwater temperature.

From an ecological point of view, the metabolic rates of organisms and the overall productivity of ecosystems are directly regulated to temperature[5)]. Changes in groundwater temperatures will alter ecological processes and the geographic distribution of aquatic species in groundwater dominated wetlands and estuaries. Groundwater temperature becomes more important for shallow aquifers[1)] and be influenced from both ground surface temperature change and groundwater recharge or discharge[6)].

The assessments of climate change impacts on groundwater temperature require reliable climate change scenarios at local scales that cannot be resolved by current Global Circulations Models (GCMs). This obstacle can be overcome by relating the coarse resolution GCM output to the heterogeneous local climate. Over the decades, both dynamic[7)] and statistical methods[8),9),10)] have been introduced; but the statistical methods are frequently used to downscale GCM projections to finer scales. All the statistical downscaling techniques translate the large-scale GCM data (predictors) into a high resolution distribution based on empirical relationships. Most commonly used predictors include airflow indices, wind strength and direction, mean sea-level pressure, and relative humidity[7),8)]. However, Widmann et al.[9)] found that statistical precipitation downscaling directly using GCM precipitation as a predictor performed considerably better than conventional methods using other predictors. Since then, Zhang[10] developed a method for spatially downscaling GCM estimates at the native GCM grid scale to station-scale using transfer functions derived by matching probability distributions of GCM output with those of local climatology for assessing the climate change effects on crop production and soil erosion.

However, in previous studies, there has been no attempt to simulate the site-specific impact of climate change on groundwater temperature. Therefore, the main objective of this study is to compose a methodology that can be used to evaluate the potential climate change impacts on groundwater temperature.

2. METHODOOGY

At first, reliable transfer functions were developed to downscale the GCMs temperature and precipitation to the local scale. Second, the groundwater temperature distribution in the Sendai plain was modeled and calibrated to cope with the specific site characteristics such as geology and land use types. Finally, the downscaled data were used in the Sendai plain to predict the scenarios of groundwater temperature change in future.

(1) Spatial downscaling

The climate change scenario of A2c from Hadley Center's third generation climate model (TAR HADCM3 with resolution of 2.5^0 by 3.75^0 in latitude by longitude) was used. The grid box (between 37.5^0N and 40.0^0N and from 138.75^0E to 142.5^0E), containing the target station of the Sendai metrological station (38.25^0N and 140.9^0E), was selected. Projected data of 1967–2006 were used as the control to develop transfer functions in conjunction with measured data of the same period. As an example, for each calendar month, the ranked observational monthly precipitation was plotted with the ranked GCM projected precipitation (qq-plot) and simple linear and non-linear functions were fitted to each plot to obtain appropriate transfer functions for each month[10]. Those transfer functions were then used to downscale the 1927-1966 GCM data to the Sendai plain and later verified with the observed precipitation. For climate prediction, those transfer functions were further used to downscale 2060-2099 GCM monthly precipitation. Likewise, the GCM projected monthly temperatures were downscaled in the same manner as precipitation.

(2) Sub-surface temperature distribution

Temperature distribution in one dimensional homogeneous porous media with constant incompressible fluid flow can be described as

$$\alpha\left(\partial^2 T/\partial z^2\right) - \beta\left(\partial T/\partial z\right) = \partial T/\partial t \tag{1}$$

where T is groundwater temperature; z is the depth from the ground surface; t is time, α (= $k/c\rho$,) is the thermal diffusivity of the aquifer in which k is thermal conductivity; and $\beta = vc_0\rho_0/c\rho$ where v is the vertical groundwater flux (positive downward), $c_0\rho_0$ is the heat capacity of the water, and $c\rho$ is the heat capacity of the porous medium. Among the various analytical solutions, Carslaw and Jaeger[11] obtained an expression for the temperature distribution considering a linear increase in ground surface temperature as,

$$T = T_0 + a(z - \beta t) + \{(b + \beta a)/2\beta\} \times [(z + \beta t)\exp(\beta z/\alpha) \\ \mathrm{erfc}\{(z + \beta t)/2(\alpha t)^{1/2}\} + (\beta t - z)\mathrm{erfc}\{(z - \beta t)/2(\alpha t)^{1/2}\}] \tag{2}$$

where T is the present groundwater temperature due to the changes during past t years, T_0 is the ground surface temperature at t = 0, a is the thermal gradient, and b is the rate of surface warming. The β value is positive or negative depending on whether v is downward or upward.

(3) Groundwater recharges estimation

As the heat in the subsurface layer is transported not only by conduction, but also by convection through the groundwater, the change of the β value with groundwater recharge must be identified. In local scale, the actual evapotranspiration and the runoff greatly depend on the type of soil and land cover. Under these circumstances, the concept of water balance (Eq. (3)) provides a framework for estimating groundwater recharge at different sites and under different climatic conditions.

$$P - ET = R + RO \tag{3}$$

where P is the precipitation, ET is the evapotranspiration, R is the groundwater recharge and RO is the surface runoff.

a) Surface runoff estimation

The Soil Conservation Service Curve Number (CN) method from United State Department of Agriculture (USDA) was used. The CN is a particular value assigned to a specific watershed based on soil group, land cover, and antecedent moisture condition (AMC). Then, the surface runoff is directly estimated from the CN value, and the precipitation depth by reading the set of type-curves developed based on the empirical relations. This method is not dependent on the time duration or intensity but only the rainfall volume is used. National Engineering Handbook[12] present the relevant CN values for different land use types.

This study used the available GIS data and land use maps to classify the different land use groups. Soil hydraulic groups were identified based on a geological survey and past borehole results. AMCII was taken as the representative moisture condition.

b) Evapotranspiration estimation

The SCS Blaney Criddle method[13)] was used. This method estimates the potential evapotranspiration in terms of the temperature and daily percent of annual daytime hours. The Bagrov relationship estimates the actual evapotranspiration from the precipitation and potential evaporation and is also modified by the storage properties. Storage properties in a location are particularly influenced by the type of land use as well as soil type[14)].

When the surface runoff and actual evapotranspiration are estimated by the above methods, the resulting recharge rate automatically accounts for the effects of land cover type and the soil characteristics. Thus, this study applied the water budget method to obtain a representative value for the groundwater recharge rate in the Sendai plain. Further, the observed temperature depth profiles were used to estimate the average recharge rate for the Sendai plain, and it was compared with the results from the water budget method. Moreover, two climate change scenarios;

(1) Continuing present trend of surface warming calculated from the past temperature records (1927-2006) until year 2080 and

(2) Surface warning trend based on A2c scenario,

were considered to find the response of aquifer thermal regime to future climate change.

3. STUDY AREA AND FIELD RECORDS

In the Sendai plain, the Nanakita, Natori, and Abukma rivers (**Fig. 1**) emerge from the peripheral mountain regions and flow toward the sea. It has an alluvial formation (60-80 m depth) and serves as the main aquifer of the catchment. Permeability of the soil below the main aquifer is significantly less than (approximately 10^4 times) the main aquifer[15)].

Land area around the Nanakita and Natori rivers was selected. There are five water level observations stations located within the area (**Fig. 1**). Among them, W1, W2, W4 and W5 have three sub-wells (SWs) each directed to different aquifer depths (ex. 7, 26, 60 m at W1). Groundwater temperature was measured at W1, W2, W3 and W4 at 1 m intervals by means of Tidbit temperature loggers. Ground-water temperatures presented in geological survey[16)] were used for W5. The 1 hour water level records observed by the Sendai city office also obtained.

4. RESULTS AND DISCUSSION

(1) Spatial Downscaling

The determination coefficient (r^2) of the linear and non-linear regressions was considered for the appropriate transfer functions selection. Non linear

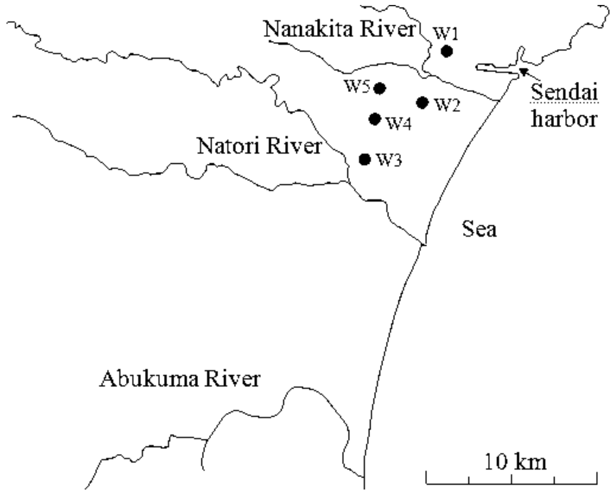

Fig.1 Study area and locations of the observation wells.

regression always gives the better agreement (minimum r^2 of 0.96 for precipitation in July and maximum r^2 of 0.99 for temperature in January) than the linear regression. However, r^2 of linear regression also gives good closer values as non-linear regression (above 0.85). Therefore, both linear and non-linear functions were used such a way that the r^2 of the corresponding transfer function is always above 0.9.

a) Temperature downscaling

The qq-plots of the measured vs. raw GCM for temperature indicated that raw GCM projections are consistently greater than the corresponding measured values for January and consistently less for August, showing an overall under prediction from May to August and over prediction in the rest of the months. The downscaled temperature values were plotted in **Fig. 2 a)** for all months of the year, illustrating how well the selected transfer functions reproduce the temperature values to the Sendai station. According to the **Fig. 2 b)** which depicts the verification of the derived transfer functions from 1927-1966, downscaled temperatures indicate slightly over prediction and under prediction for January and August, respectively. However, in general, the derived transfer functions show good applicability for all the months.

b) Precipitation downscaling

The GCM projections are consistently greater than the corresponding measured total monthly precipitation for January and consistently less for September, showing an overall under prediction from May to October and over prediction for the rest of the months. In contrast to temperature, sea level patterns govern the local variability in precipitation. Therefore, fitting a linear or a simple non-linear transfer function for precipitation is rather difficult for the precipitation than the temperature. Thus, compare with the temperature, downscaling results for precipitation **(Fig. 2 c-d)**

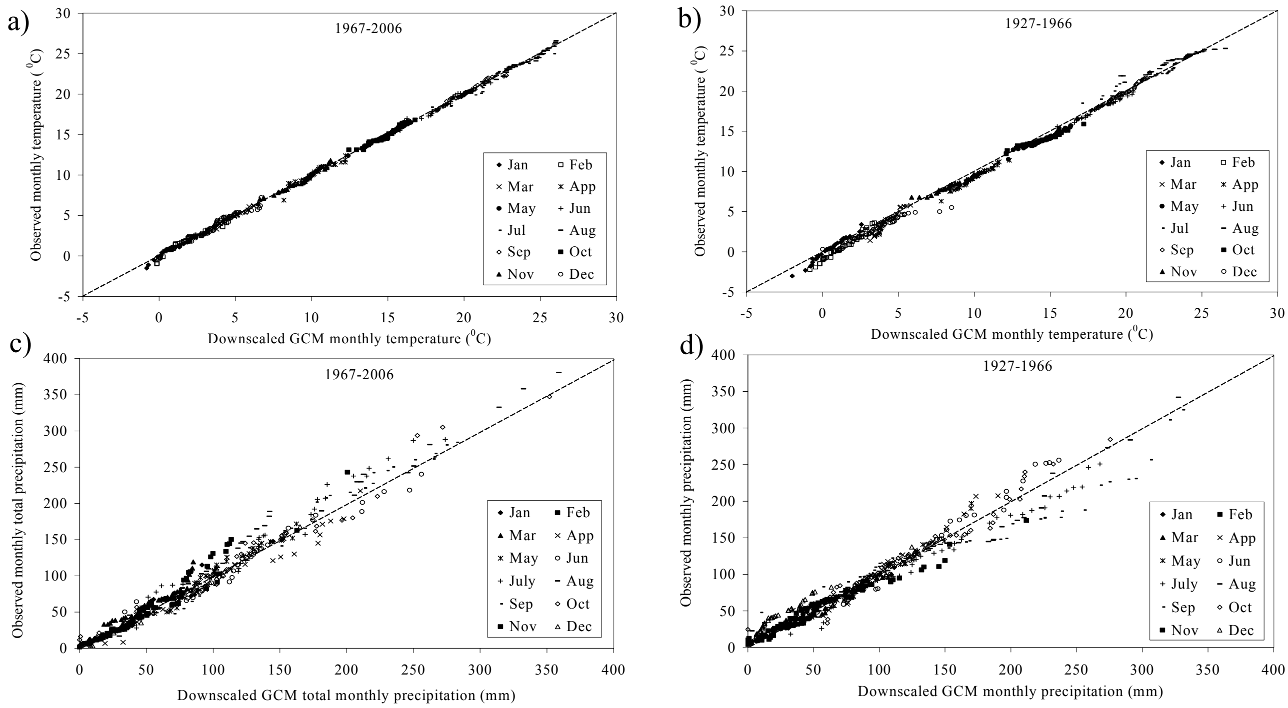

Fig.2 qq-plots of observed vs. downscaled precipitation and temperature

show lesser agreement with the observed records. Verified results during 1927-1966 indicate several significantly deviated points from the 1:1 line suggesting a poor match (**Fig. 2 d)** for February and September, while the other months show reasonably good agreement for the predictions.

c) Downscaling GCM data for impact prediction

For the impact assessment, the GCM monthly data of 2060-2099 were downscaled to the Sendai station using the fitted transfer functions for each month. Probability distributions of downscaled GCM monthly temperature for the 2060-2099 period and those of measured monthly temperature for the 1967-2006 periods are shown in **Fig.3** for January and July as an example. Compared with the baseline climate, downscaled temperature of 2060-2099 would increase by 3.7 ^{0}C for January and 5.3 ^{0}C for July. By averaging all the months of the year, downscaled monthly mean temperature would increase by 4.5 ^{0}C. Based on similar analysis, downscaled total monthly precipitation would decrease by 39% (27 mm) in November but increase by 20% (35 mm) in July. In overall, monthly total precipitation of the year would decrease by 16 mm.

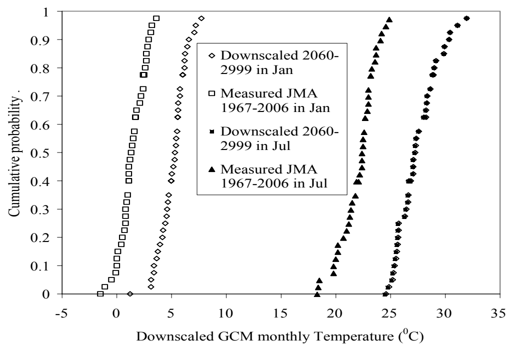

Fig. 3 Cumulative probability distributions

(2) Recharge estimation

a) Recharge estimation from T-D profiles

The seasonal change of ground surface temperature has a strong influence on the groundwater temperature. However, the amplitude of temperature oscillation attenuates with depth, and in general, it does not have a significant effect below 15-20 m[6]. Long term 1-hour observations (May, 2007-February, 2008) in W1-W4 at different depths show that the groundwater temperature below 12-30 m remains constant throughout the observation time. Therefore, temperature depth-profiles (T-D profiles) within this range can be used to estimate the recharge or discharge rates based on the curvature of the profiles[17].

The annual mean air temperature in the Sendai plain has increased by about 1.71 ^{0}C during the last 80 years. Therefore, considering the linear trend of temperature rise from 1927 to 2006, b is set as 0.0221 ^{0}C/year and t is 80 years. Further, it is assumed that a is 0.045 ^{0}C/m in W2, W3 and W4 and 0.075 ^{0}C/m in W1[15]. Considering α is 5.8×10^{-7} m^2s^{-1}, the T-D profiles were computed for different β values. Taniguchi et al.[18] examined the sensitivity of recharge and temperature variation in change of α and concluded that α does not significantly affects to the final result. Therefore, same α vale was considered for the saturated and unsaturated zones.

This conclusion further justifies the zero storage change assumption in simple water budget method (Eq. (3)), even though the possible storage change may result for different α values as a particular depth become saturated or unsaturated. **Fig. 4** shows the estimation of β value for W4 by matching the measured T-D profile. Different β values indicate different recharge rates; the higher the β vale is higher the recharge rate is. Assuming that the specific heat (c_0) and density (ρ_0) of water are 4.18×10^3 $\mathrm{Jkg^{-10}C^{-1}}$ and 10^3 $\mathrm{kgm^{-3}}$, respectively, and the specific heat (c) and density (ρ) of the porous medium in the Sendai plain are 930 $\mathrm{Jkg^{-10}C^{-1}}$ and 2500 $\mathrm{kgm^{-3}}$, respectively, we calculated the recharge rates from the obtained β values ($\beta = vc_0\rho_0/c\rho$) to be 100, 135, 120, and 125 mm/year at W1, W2, W3, and W4 respectively. In a similar manner, the calculated recharge value at W5 is 90 mm/year. Based on the observed water level records, 0.08 m/m, 0.17 m/m and 0.15 m/m of hydraulic gradients were estimated in the W1, W2 and W4 respectively for shallow sub surface layer. According to the Darcy's low, high hydraulic gradient represents large water flow and therefore, estimated hydraulic gradients further verify the slight changes of recharge values estimated from the T-D profiles. In order to estimate the representative recharge rate for the whole catchment, the Thiessen polygon method was applied. The approximate annual recharge rate in the Sendai plain was estimated to be 120 mm.

(b) Recharge estimation from water budget

Monthly average air temperature and monthly total precipitation from the Japanese Metrological Agency (JMA) were obtained. In the estimation of surface runoff, monthly rainfall is assumed to be a single storm event in the particular month[2]. The entire catchment was divided for six types of land use categories with 250 m × 250 m grid size based on the GIS and land use map data. Furthermore, three soil types were considered based on the available geological maps[16] and past bore-hole results. In summery, 18 sub-categories were used.

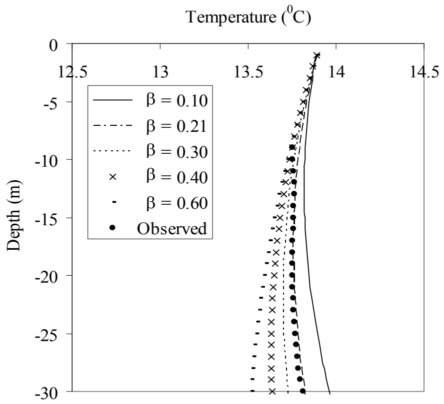

Fig.4 Temperature depth-profile at W4

Various CN values from the National Engineering Handbook[12] and effective parameters based on the Bagrov relation were assigned for each land use category. Summations of the monthly averaged evapotranspiration and runoff values within the year were used in Eq. (3) to estimate the annual recharge. The calculated recharge was 135 mm/year. The estimated recharge rate from the water budget method reasonably matches the one estimated from the T-D profiles. Therefore, it can be assumed that the assigned CN and effective parameter values reasonably agree with the real site characteristics in the Sendai pain.

(3) Impacts from climate change

Two climate change scenarios were considered. In the first scenario (S1), b in the Eq. (2) was set as 0.0221^0C/ year, assuming the same magnitude of surface temperature warming in the past (from 1927 to 2006) will be continuing in future. In this case, only the change of temperature was considered but the recharge rates at each well were remained constant. In the second scenario (S2), downscaled temperature for 2060-2099 was considered and the mean annual average temperatures of the each time periods (1927-1966, 1967-2006, and 2060-2099) were plotted to find b. The estimated b value is 0.0411^0C/ year. Moreover, the monthly precipitation change in the future were used with the calibrated CN and effective parameters values in the Eq.(3) to estimate the recharge rate change in all the well points. Estimated recharge rates together with the predicted b value were used in the Eq.(2) to estimate the probable effects of climate change on temperature distribution. Groundwater temperature change at the depth of 30 m was considered as the reference depth to compare the significance of each scenario. The results are shown in **Table 1**.

Table 1: Groundwater temperature change by both scenarios

Scenario	Temperature change (^{0}C)		
	Ground surface	Groundwater	
		Max	Min
S1	1.6	1.11 (at W5)	0.93 (at W1)
S2	4.5	2.36 (at W5)	2.31 (at W1)

The difference between the maximum and minimum temperature change is caused by the differences of the recharge rate. However, the sensitivity analysis indicted that the ground surface temperature change is more significant than the variations of the recharge rate for the shallow groundwater temperature change. When compare the significance of the two scenarios, A2c scenario (S2) predicts more temperature change (average of 2.34 ^{0}C by year 2080) than the first scenario (S1, average of 1.02 ^{0}C by year 2080). According to the IPCC[1)] even with the current climate change mitigation policies and related sustainable development practices, global greenhouse gas emission will continue to grow over the few decades and therefore the magnitude of the global warming rate will definitely increase than today. Therefore, S1 results can be used as the bottom line for the decision making and the figures of the S2 can be accounted for the impact assessments of the groundwater temperature change. This study did not consider the possible effects of land use change that can be likely happened in future on the recharge change. Therefore, the combine effect of urbanization and climate change may even more and will be significant from the ecological point of view.

5. CONCLUSIONS

In this study, potential impacts of climate change on groundwater temperature were estimated. Recharge rate, estimated from the T-D profiles (average 120 mm/year) reasonably match with the one estimated from the water budget method.

HadCM3 A2c scenario monthly data were downscaled to the Sendai station using linear and non-linear regressions. Observed records of 1967-2006 were considered as the base for estimating the transfer functions and they were verified with the observations of 1927-1966. Developed transfer functions for both precipitation and temperature shows good agreement with the verified results. Verified transfer functions were then used to downscale the GCM data from 1960-2099. Compared with the baseline climate, downscaled temperature of 2060-2099 would increase by 3.7 ^{0}C for January and 5.3 ^{0}C for July. By averaging all the months of the year, downscaled monthly mean temperature would increase by 4.5 ^{0}C. Moreover, downscaled monthly precipitation will decrease by 31% (12 mm) in January but increase by 20% (35 mm) in July. In overall, monthly total precipitation will decrease by 16 mm.

Furthermore, downscaled GCM data were used for the impact analysis. Probable magnitudes of Groundwater temperature change by the A2c scenario was compared with a scenario which assumed that the same magnitude of the present global warming will continue to the future. A2c scenario shows significant effect which will increase the groundwater temperature in average of 2.34 ^{0}C by year 2080. These results will be significance for the ecological balance of the eco-system in the Sendai plain and the developed methodology in this study will be useful especially in arrears where limited hydrological and climatic data are available.

ACKNOWLEDMENT: This work was supported by the Global Environment Research Fund (S-4) of the Ministry of Environment, Japan. The GCM data were provided by the UK Hadley Centre. We are also grateful to Mariko Izumi in Sendai city office, and Dr. Seiki Kawagoe, for support in observations.

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(Received September 30, 2008)