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DIFFERENT SKILLS OF FIVE GCMs AND THEIR IMPACTS ON AQUIFER THERMAL REGIMES

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For the purposes of estimating local changes in aquifer thermal regimes, induced by global climate change, we analyzed different performances of six general circulation models (GCMs) in the Sendai plain. Transfer function method was used to downscale the GCMs output to the local scale. GCM scenarios were evaluated based on their match with the 20th century observations and the magnitude of climatic parameter change in 21st century. Among the considered GCMs; HADCM3, MIROC and MRI models produced climate variations in a wide and consistent range (2.0 to 4.7 °C warming and -11 to 345 mm precipitation change) suggesting their applicability for climate change studies in the Sendai plain. When accounting the effects of the entire model scenarios, groundwater recharge would vary in range of 50-182 mm/year and aquifer temperature may change in 1.2-3.9 °C range in year 2080 which, according to IPCC AR4, may have critical impact on the ecological balance of the Sendai plain.

Key Words : *Climate downscaling, transfer function, groundwater temperature, Sendai plain*

1. INTRODUCTION

The unavoidable climate change impacts are often expressed through hydrological responses such as flooding and groundwater quantity depletion, but occasionally evaluated in terms of groundwater quality[1),2)]. Groundwater temperature is one of the primary parameter regulating the ecological balance of the groundwater dominated ecosystems[3)], and thus highly vulnerable to the changing climate. Assessing these impacts demand future scenarios of global climate behavior. The Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC AR4)[4)] provides a platform for climate change studies with a set of widely recognized Global Climate Models (GCMs). However, reliable assessment of anticipated climate change impacts eventually requires fine resolution projection (~10 km^2) of climate parameters at the local scale, which cannot be resolved by current GCMs. Model predictions with such high resolutions are computationally demanding and not likely to become widely available in the near future. For example, HADCM3 model has very coarse resolution, which in spatial scale, approximately equal to 90465 km^2 of the grid box containing the Sendai plain. Even though, some models like MIROC3_2-HI and CCSM3 recently produce model predictions with comparatively higher resolution (12185 km^2 and 19070 km^2 resolutions reference to the Sendai plain, respectively), they are still far behind to be used for site specific assessments. As a result, GCMs cannot explicitly account for the physical-geographic characteristics of the fine scale structure (e.g. inland water bodies, coastal lines, mountain ranges, and land use) that significantly govern the local climate. However, GCMs show a good performance in simulating large scale circulation and climatic features that affect regional climates[5)]. Therefore, statistical downscaling technique has long been used as an intermediate step between coarse resolution GCM output and fine scale climate variables[1),2),5)].

The ability to incorporate specific local information and fact that the method is computationally inexpensive, make statistical downscaling technique reliable and easy to apply over different GCMs. However, in addition to the differences in grid resolutions, each GCM scenario incorporates different model structures that produce different output. Therefore it is needed to use several GCMs and scenarios for a proper impact assessment rather than relying on single forecast[5]. To date, there has not been sufficient research to examine the different behaviors of various GCMs. A detail analysis of several GCMs and scenarios may facilitate many site specific impact assessment studies to select few significant model scenarios in a range of potential climate change in future. Therefore, our objectives are two-fold. First we will present some different performances of six GCMs for predicting the future climate change at the local scale in the Sendai plain. For the second objective, downscaled results from GCMs, which provide 18 simulations for 21st century, will be used to evaluate the range of aquifer temperature change by year 2080. These results with the potential range of impact on groundwater temperature may guide the decision makes on making resilient decisions for climate impact mitigation measures.

2. METHODOLOGY

(1) Study area and data collections

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[6]. Similar to Fukushima and Yamagata cities near by study area, 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 (e.g. 2.0, 1.8, and 1.7 °C/century in Sendai, Yamagata, and Fukushima, respectively). 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 (**Fig. 1**). 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. Some significant differences in land use types exist at the local scale surrounding the wells. Wells W2, W3 and W4 are located in paddy field areas and have similar surface characteristics and land use

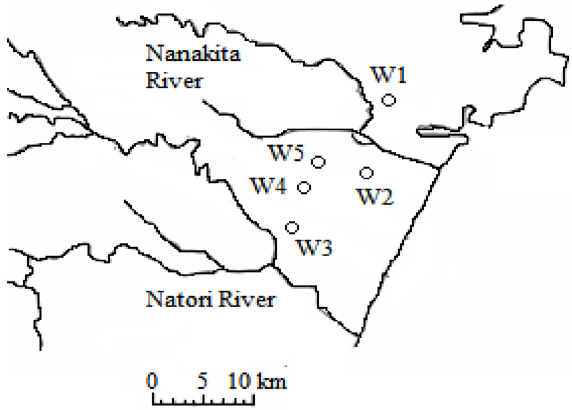


Fig.1 Study area.

histories. Well W1 is located in a residential area and well W5 is located at the city center, which is more urbanized than all other well locations. All well locations are situated within seven kilometers of the city center and the Sendai meteorological station. In all wells, there is clear evidence of a temperature profile inversion from the general geothermal gradient. 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.

(2) Analytical model for sub-surface heat flow

Horizontal water flow in a semi–confining aquifer can significantly affect the vertical temperature distribution in the basin. Monthly averaged water level records in 2007 produced vertical hydraulic gradient in 0.077~0.169 m/m and horizontal hydraulic gradient in 0.0008~0.0014 m/m ranges. According to that, averaged vertical hydraulic gradient is notably higher than the averaged horizontal hydraulic gradient, which may confirm the appropriateness of the one-dimensional heat transport model for the study area.

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

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

where T is temperature, z is depth from the ground surface, t is time, α (= $k/c\rho$) is the thermal diffusivity of the aquifer and β = $vc_0\rho_0/c\rho$, where v is the vertical groundwater flux (positive is downward), $c_0\rho_0$ is the heat capacity of the water and $c\rho$ is the heat capacity of the porous medium. Assuming that the heat capacity is constant and that the groundwater and aquifer are in thermal equilibrium, the initial boundary conditions for a linear increase in ground surface temperature can be written as

$$T_{(z,0)} = T_0 + az \qquad (2)$$

$$T_{(0,t)} = T_0 + bt\,, \tag{3}$$

where T_0 is the ground surface temperature at $t = 0$, a is the general thermal gradient, and b is the rate of surface warming. Under the above initial boundary conditions, Carslaw and Jaeger[7] obtained an analytical solution for the temperature distribution as a function of depth and time:

$$T = T_0 + a(z - \beta t) + \{(b + \beta a)/2\beta\} \times [(z + \beta t)\exp(\beta z/\alpha)$$
$$\mathrm{erfc}\{(z + \beta t)/2(\alpha t)^{1/2}\} + (\beta t - z)\mathrm{erfc}\{(z - \beta t)/2(\alpha t)^{1/2}\}] \tag{4}$$

3. RESULTS AND DISCUSSIONS

(1) Model calibration and verification

The undisturbed depths of the aquifer (e.g., below 60 m at W5) exhibit an approximately linear T−D profile. Extrapolation of this linear portion to the ground surface yields the intercept temperature (T_0). If thermal conductivity is assumed to be uniform over the representative depth interval, the general geothermal gradient (a) can be estimated from the gradient of the undisturbed portion of the T−D profile. Therefore, the parameters a and T_0 in Eq. (4) can be estimated with reasonable accuracy (±0.002ºC /m, ± 0.1ºC, respectively) from the estimated T−D profile in each observation well. A series of synthetic T−D profiles over different values of b, t and v were then formulated and compared with the observed T−D profile in the Sendai plain for a preliminary approximation of the parameters in Eq. (4). The parameter t was calibrated to be 60 years (1947-2007), which reasonably agrees with the starting time of SAT warming in the Sendai plain. The parameter b was calibrated for each observation well, which spans in 1.5~2.1 °C/100years. It shows good agreement with the land-use type and depth of departure from the steady state temperature in all well locations. Moreover, observed linear trend of SAT warming in the Sendai plain (2.0 °C/100years) lays in calibrated range suggesting a fine match with the local climatic conditions. Considering the potential uncertainties of groundwater recharge estimation, Gunawardhana and kazama[2] estimated the groundwater recharge rate by three other techniques (the water balance method, the water level fluctuation method and Darcy's method) that produced groundwater recharge rates over a consistent range of 105-210 mm/year in the Sendai plain. The calibrated groundwater recharges by the T-D profile method in different well locations respect to various land-use types range 105-215 mm/year, showing a good match with the previous studies. Simulated results with constrained parameters are shown in **Fig. 2**, which shows good agreement with the observed T-D profiles.

(2) Assessment of climate model and scenarios

To assess the performance of the different models in capturing local climate in the Sendai plain, we compare the time series of each model against the observations during 1927-1999. **Fig. 3a)** shows the linear trends of temperature of different GCM scenarios with a comparison of observed trend over 73 years. Many researches from IPCC AR4[4] suggested that global averaged warming in 20th century ranges from 0.5-0.7 °C/century. Of the six GCMs analyzed, four of them (HADCM3, MRI, ECHAM5, and CSIRO) simulate warming trend in 20th century (black color boxes in **Fig. 3a)** for the grid box containing the Sendai plain. CCSM3 model simulates very little trend while MIROC exhibits negative trend. Even though the temperature trend is less dependent on grid resolution, GCMs usually unable to capture the local effects of urban heat island of the size of Sendai city. This may explain the mark of significantly higher warming rate in the Sendai plain than the simulations from six GCMs (Observed warming rate is over two times higher than the HADCM3 model, which simulates the highest warming rate among six GCMs). According to the warming trends in the future, HADCM3 model predicts the highest warming rate in the end of 21st century while MRI model shows the smallest trend, which is almost similar to the present trend of warming rate in the Sendai plain. However, in accordance with the IPCC AR4[4], magnitude of global warming in later part of the 21st century expects to be significantly higher than the 20th century. Thus, it is reasonable to assume that the simulations from HADCM3 may not over predict the future but a possibility and therefore, can be used as a potential impact predictor for the future studies in the Sendai plain.

Even though there are some significant geographical variations of climate change, particularly with respect to precipitation, globally mean precipitation is projected to increase in future. According to IPCC AR4[4], high latitudes countries (e.g. Japan) likely experience high precipitation events. As depicts in **Fig. 3b**, five GCMs predict

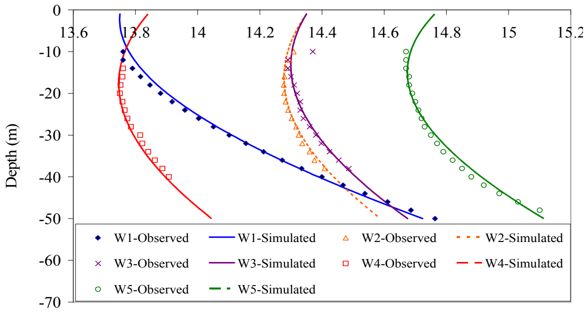


Fig. 2 Model verification with observed T-D profiles

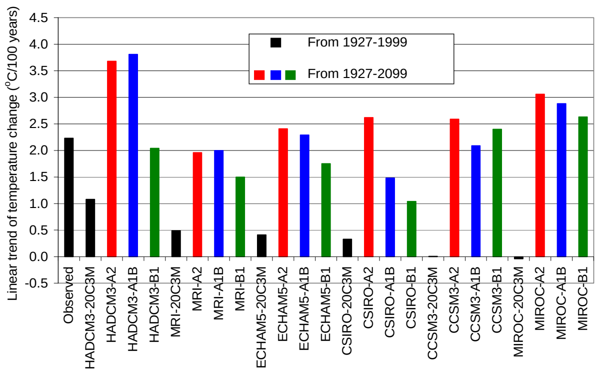
potential of increasing precipitation in the 21st century while only MRI model predicts decreasing trend. HADCM3, MIROC and CCSM3 models simulate significant precipitation change, which predict over 300 mm of annual total precipitations rise in 21st century relative to the observations in 20th century. When comparing GCM simulations with observed precipitation in same time horizon (1927-1999 in black color in **Fig. 3b**), CSIRO and HADCM3 exhibit comparatively smaller biases (55mm and 149mm, respectively) while CCSM3 shows the strongest wet bias (601 mm). In contrast, MRI model shows dry bias, but similar to the decreasing pattern of precipitation in future.

(3) Spatial downscaling of GCMs output

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 all 6 models, which produce 6 and 18 time series for each climatic parameter for the 20th and 21st centuries, respectively. Model results containing the target station in the Sendai meteorological station (38.26 ^{o}N and 140.9 ^{o}E) were spatially downscaled using the transfer function method (more details in Gunawardhana and Kazama[1),2)]). Transfer function method builds a regression relationship between GCM output (predictors) and local climate variable (predictand). Among the parameters of concern, sea level pressure has significant influence to govern the local precipitation. However, many studies found that the direct use of GCM precipitation as the sole predictor produce better local precipitation than introducing multiple predictors[5)]. Similarly, GCM scale surface air temperature is a robust predictor for regional temperature. Therefore, we considered large scale climatic parameter as the only predictor governing the representative climate variable at the local scale. Projected GCMs data of 1967-2006 were used as the control to developed transfer functions in conjunction with measured data of the same period. Those transfer functions were then used to downscale the 1947-1966 GCM data to the Sendai plain and later verified with the observed climatic parameter. For climate prediction, those transfer functions were further used to downscale 2060-2099 GCM precipitation and temperature. **Fig. 4** shows the comparisons of cumulative probability distributions of temperature and precipitation. According to **Fig. 4a,** the highest warming was projected by MIROC-A2 scenario (about 5.0 °C in January and 6.6 °C in July), which cause average of 4.7 °C warming in 2060-2099 time periods relative to 1967-2006. For the same model scenario, precipitation is projected to increase by 18% (217 mm) relative to observed precipitation during 1967-2006 time periods in the Sendai plain.

Model bias in GCM simulations weakens the magnitude of GCM predictions at the local scale. Therefore, when considering several GCM models, scenario that predicts the highest warming rate at the GCM grid scale will not necessarily predict the utmost impact in the local scale. According to **Fig. 3a**, HADCM3 model predicts the highest warming trend at the GCM grid scale, but at the local scale it was dropped to the second by MIROC model, which predicts 0.8 °C warming than the HADCM3 in 2080. This change was occurred due to bias difference between two models relative to the observed trend. Therefore, the criteria of selecting the GCMs to produce extreme impacts must include not only the magnitude of climatic parameter change in the future (e.g. annual precipitation change during 2000-2099 relative to 1927-1999 in this study), but also the bias of GCMs relative to the observations at the local scale. Therefore, two indexes with accounting the model bias and the magnitude of climatic parameter change in future were considered for assessing the performance of different GCMs in the local climate predictions. As example, for the temperature, relative difference

a)



b)

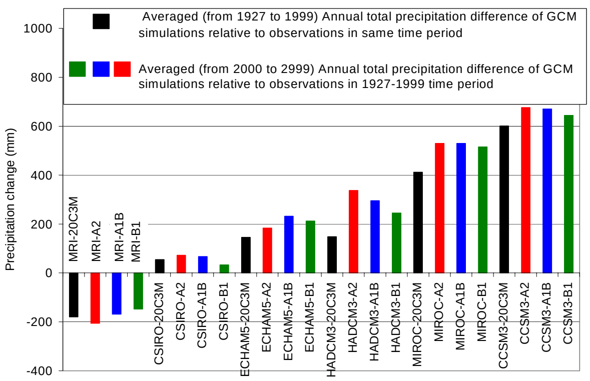


Fig. 3 Comparisons of observed climatic parameters with the different GCM scenarios; a) linear trend of temperature change and b) averaged annual total precipitation change relative to the observations during 1927-1999.

between warming rate (WR) in future and bias of GCM prediction compared to observed warming rate was applied ({GCM $WR_{2000-2099}$ – [GCM $WR_{1927-1999}$ – Observed $WR_{1927-1999}$]}/ Observed $WR_{1927-1999}$). This index produces the highest value for MIROC (3.2 for MIROC-A2), which clear explains the highest impact prediction of MIROC-A2 than the HADCM3 model in the local scale. Similarly, even though HADCM3 produces moderate change for precipitation at the GCM grid scale (**Fig.3b**), HADCM3-A2 scenario gives the highest index value (0.15) than the MIROC-A2 (0.1) or CCSM3 (0.06). This is again due to its low bias of HADCM3 relative to the observed precipitation than the MIROC or CCSM3 models. As a result HADCM3-A2 makes the highest prediction of future precipitation change from the downscaled results at the local scale (345 mm/year).

(4) Potential climate change impacts at the local scale aquifer thermal regimes

To account the climate change effects on hydrology in the Sendai plain, we substituted the projected precipitation and temperature to water budget technique, which was previously developed by Gunawardhana and Kazama[1),2)] for the Sendai plain. The possible variations of groundwater recharge were estimated with respect to the change in surface runoff and evapotranspiration due to changing climate in future. When comparing the different GCMs performances, HADCM3 estimates decreasing trend of groundwater recharge (1-26% reduction from 2007 estimation) for its all scenarios. As a result of its projected decreasing trend of precipitation and moderate warming, MRI-A2 scenario predicts the strongest hydrological impact, which reduces the groundwater recharge to 50 mm/year by year 2080 in the Sendai plain. According to MIROC-A2, anticipated groundwater recharge would decrease by 32 mm/year, despite the projected 18% increase in precipitation, due to higher degree of evapotranspiration resulting from a 4.7 °C increase in surface air temperature. However, due to its slow rate of warming (the second lowest among 5 GCMs) and moderate precipitation rise, ECHAM5 model predicts 11-35% of recharge increment in 2080 for all model scenarios. Moreover, combined effects of groundwater recharge variation (as β) and ground surface temperature change (as *b*) were applied in Eq. (4) to estimate the potential aquifer temperature change. **Fig. 5** depicts the potential range of aquifer change by 2080. The strongest effect is produced by MIROC-A2 scenario, which causes approximately 3.9 °C warming in aquifer temperature at 8 m depth (the deepest depth for the water table among five observation wells). MRI-A2 scenario exhibits a moderate effect on aquifer temperature change near to the ground surface (2.8 °C at 8 m depth), but it is the robust in terms of carrying the climate change impacts to the deeper aquifer depths. As depicts in **Fig. 5**, by year 2080, depth of departure from steady state T-D profile will approximately extend to 120 m. 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. When MRI-A2 scenario produce substantial groundwater recharge reduction (about 63% from 2007 estimation), it results to decelerate the cooling process of infiltrating water flow and carry the climate change signatures earlier than other scenarios. When accounting the effect of the entire model scenarios, aquifer temperature may change in 1.2-3.9 °C ranges which may have critical impact on the ecological balance of the Sendai plain[4)].

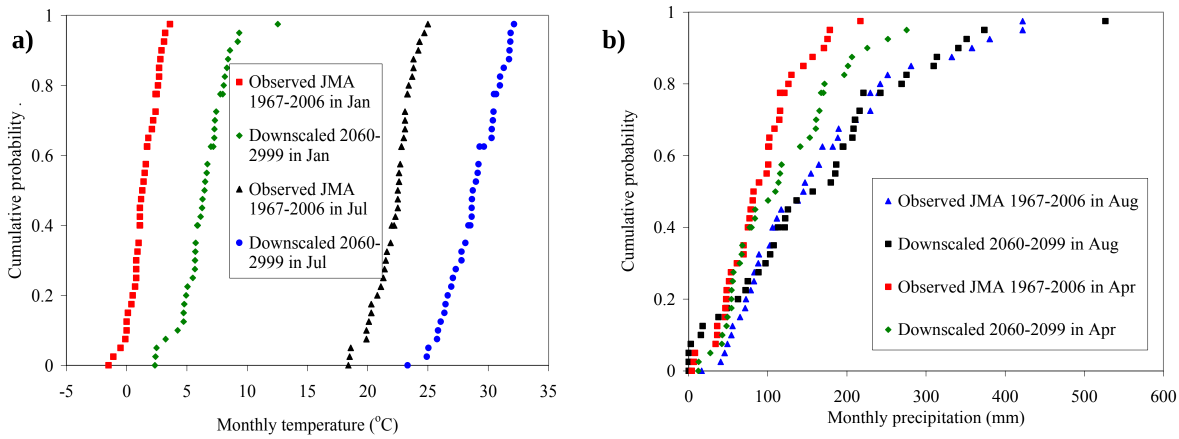


Fig. 4 Cumulative probability distributions of observations and MIROC-A2 predictions; a) temperature, and b) precipitation

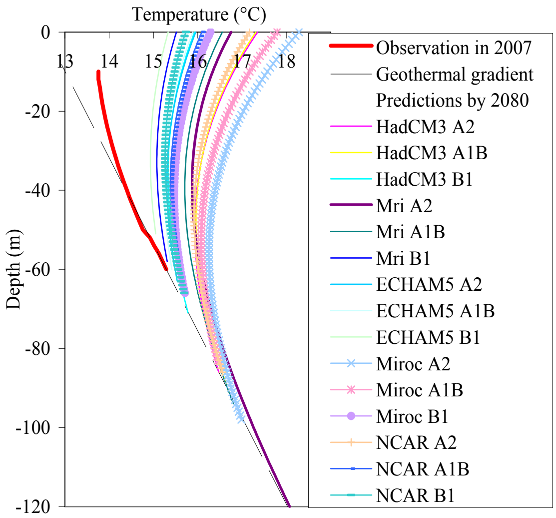


Fig. 5 Range of aquifer temperature change by different GCMs

4. CONCLUSIONS

GCMs output with various downscaling techniques link the global scale climate features to the local scale and make a platform for climate change studies. However, different model structures with various grid resolutions produce different result for the same area of interest, which makes the use of single model with few scenarios realistically critical. We considered six GCMs with three scenarios in each and examine their behaviors with respect to temperature and precipitation in the grid box containing the Sendai plain. Magnitude of the climate parameter change in the future at the GCM grid scale did not necessarily indicate the same order of magnitude in downscaled results due to existent model bias with observations at the local scale. However, model bias may arise from various effects, and may not necessarily indicate that the model cannot correctly capture the large-scale climate change signals. Therefore, two indexes were introduced that accounts the combined effects of model bias and the magnitude of climatic parameter change in the future and we conclude that HADCM3 and MIROC models may suitable for climate change studies such as flood forecast due to its moderate bias and higher precipitation arising trend in future in the Sendai plain. Then again, MRI model would suite for the quantity and quality aspects of the water resources anticipated to climate change. Selection of these three models (HADCM3, MRI and MIROC) will simulate the potential climate change impact in highest and lowest extreme events, which may minimize the computational cost of using several models.

The use of 18 scenarios from six GCMs in our study generates a consistent range of impact on the hydrology in the Sendai plain. With respect to 1.8-4.7 °C surface air temperature rise (minimum in CSIRO-B1 and highest in MIROC-A2), 11 mm/year precipitation reduction in MRI-A2, and 345 mm/year precipitation rise in HADCM3-A2, groundwater recharge would vary in a range of 50-182 mm/year. When, different degrees of groundwater recharge and ground surface warming rates were incorporated, aquifer in the Sendai plain may warm in 1.2-3.9 °C range by 2080.

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 Sendai plain. Land-use practices, such as reforestation have the potential to decrease aquifer temperature by increasing shading. Therefore, estimations in this study will be important for mitigating climate change impacts, where aquifer temperature increases due to ground surface temperature change would likely compensate by lowering aquifer temperature with the effect of reforestation program.

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