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ORIGINAL ARTICLE

The Value of High-resolution Climate Change Projection and Flood Simulation for Flood Control Policy as a Climate Change Adaptation Measure

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***Abstract*:** Flood prevention is important as a climate change adaptation measure, but the resolution of projection models is lower than required for impact assessment models of flood risk. To improve model resolution, in this study we analyzed whether downscale (DS) for projection model at the basin scale is a valid solution.

Appropriate DS resolution was found to vary depending on topography and watershed scale, and DS data allowed us to predict an increase in flood size at the basin scale. Detailed resolution is also needed for inundation simulations to protect the lives of citizens through government information and public awareness.

To protect the lives of citizens from disasters considered “Clear and Present Dangers,” high-resolution analysis is necessary. However, it is difficult to perform consistent simulations at high resolution because of limitations of scientific and computational resources. The DS from the current resolution to the desired resolution showed a clear resolution of this problem.

Keywords: climate change adaptation, flood control

1. Introduction

1.1 Background

Disaster prevention policies as climate change adaptation measures are important, and accurate impact assessment is important. However, there is a "resolution barrier" impacting these assessments. Figure 1 shows the spatial resolution of the climate change projection model and the impact assessment model for flood hazards.

1.2 “Resolution barrier” between climate projection model and impact assessment model

The climate change projection models, which are also referred to as global climate models (GCMs), can simulate the current climate on a global scale. Further, a model that can project the future climate scenarios based on the greenhouse gas concentrations was developed.

However, the GCM grid size is large. The GCM should be downscaled to assess the impacts at regional and watershed scales.

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1.3 “Resolution barrier” between flood prediction model and scale that citizens can experience

Citizens have to take evacuation actions based on the flood damage forecast provided by the experts.

The model will be more valuable for the citizens if it can predict the roads and homes that are in danger along with the damage in the city. Therefore, the flood forecasting models must have a high resolution.

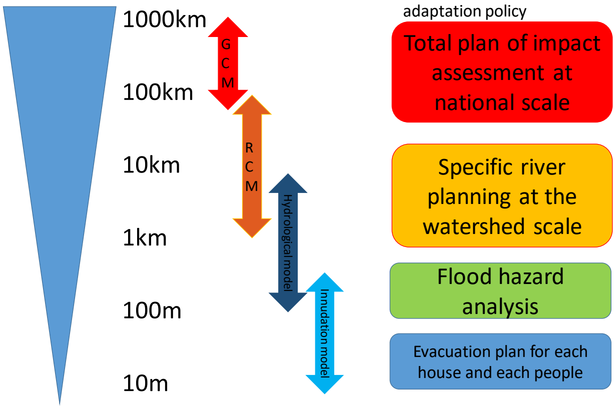

Figure. 1 Conceptual diagram of the projection Model, impact assessment model, and prevention policy

1.2 Objectives

In this study, we reviewed and assessed consistent downscaling of climate change projection and impact assessment flood models, and we enabled adaptation at the citizen level. The first step was to downscale climate change projection models to basin scale, and then the flood damage prediction model was downscaled to a useful scale at the citizen level.

2. Downscaling for GCM

There are two downscaling approaches: statistical downscaling (SDS) and dynamical downscaling , also referred to as a regional climate model :RCM.

2.1 Statistical downscaling containing bias correction

The outputs of the GCM have bias because the rainfall amounts during storms are smaller than observed. Thus, statistical downscaling and bias correction were performed simultaneously.

Figure.2 presents the abstracted probability density distribution from a log-normal field of annual maximum rainfall in GCMs and observed data. We calculated the probability year of occurrence of rainfall in a large grid climate change prediction model of present reproduction. Next, we converted rainfall values to rainfall with the same probability year of occurrence in the observed data. The same

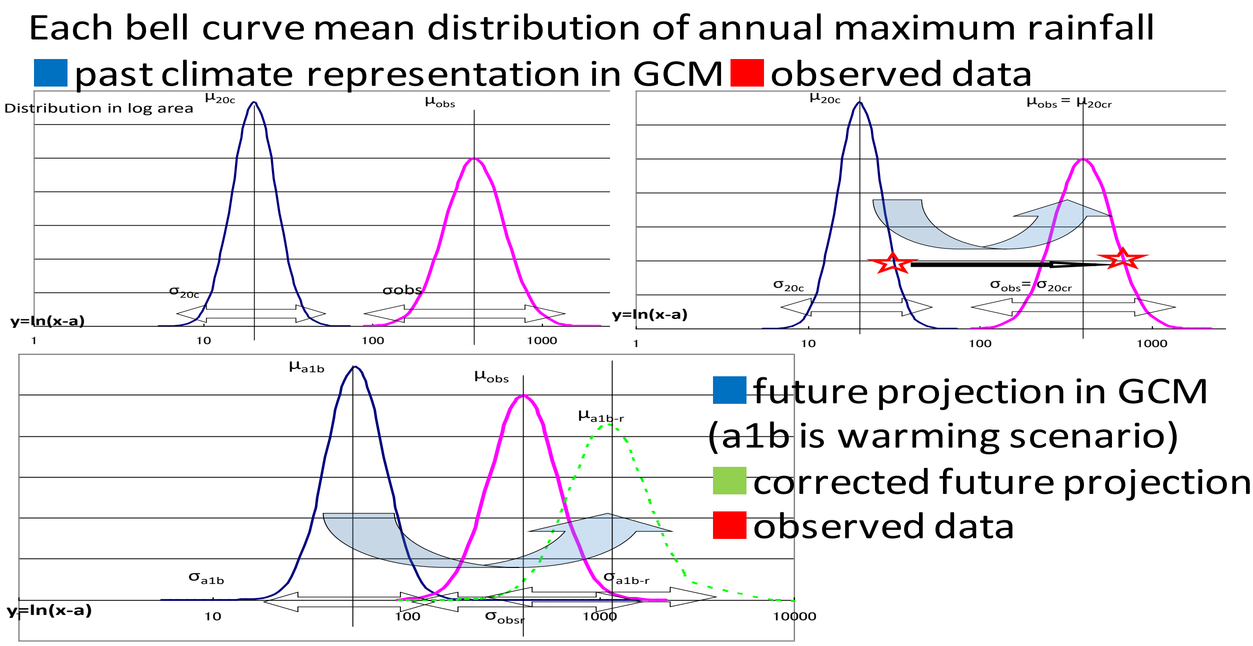

Figure.2 Conceptual figure of combination with statistical downscaling (SDS) & bias correction (BC)

transformation equation was applied to rainfall in the future projections of climate change projection models. The advantageous results of the bias correction were an absolute value suitable for the observed value and a low calculation time.

However, the limitations of statistical downscaling are that weather events not reproducible at GCM resolution are also not reproducible by statistical downscaling and no more information is available than the number of times each GCM has been run.

2.2 Dynamical downscaling

Another approach is dynamical downscaling. More detailed projections are obtained by running regional climate models (RCM) at a higher resolution, with inputs such as sea surface temperature from GCMs. Weather phenomena that cannot be reproduced by GCM, may be reproduced by RCM. Detailed topographic data can also be used to reproduce topographic affected rainfall. This requires a huge amount of computation and is difficult for individual researchers to perform.

2.3 Dynamical downscaling product: d4PDF

The database for Policy Decision Making for Future climate change (d4PDF), published by a national research institute, generated 6000 years of data by performing multiple calculations using past climate and several global future projection models as mother models. This product was first downscaled with a 60-km grid global model starting at a sea surface temperature of 6 GCMs. In addition, downscaling was done by RCM around Japan with 20-km grid.

The database contains a large number of runs over a period of several thousand years, and it enabled highly accurate statistical analysis and prediction of unusual phenomena at low frequencies.

2.4 Is the d4pdf sufficient for water disaster risk analysis?

The time resolution of the runoff model is hourly data, although daily data can also be used for hydrological statistics and analysis of long-term water supply and demand. The d4PDF output time is hourly, which is efficient for flood analysis.

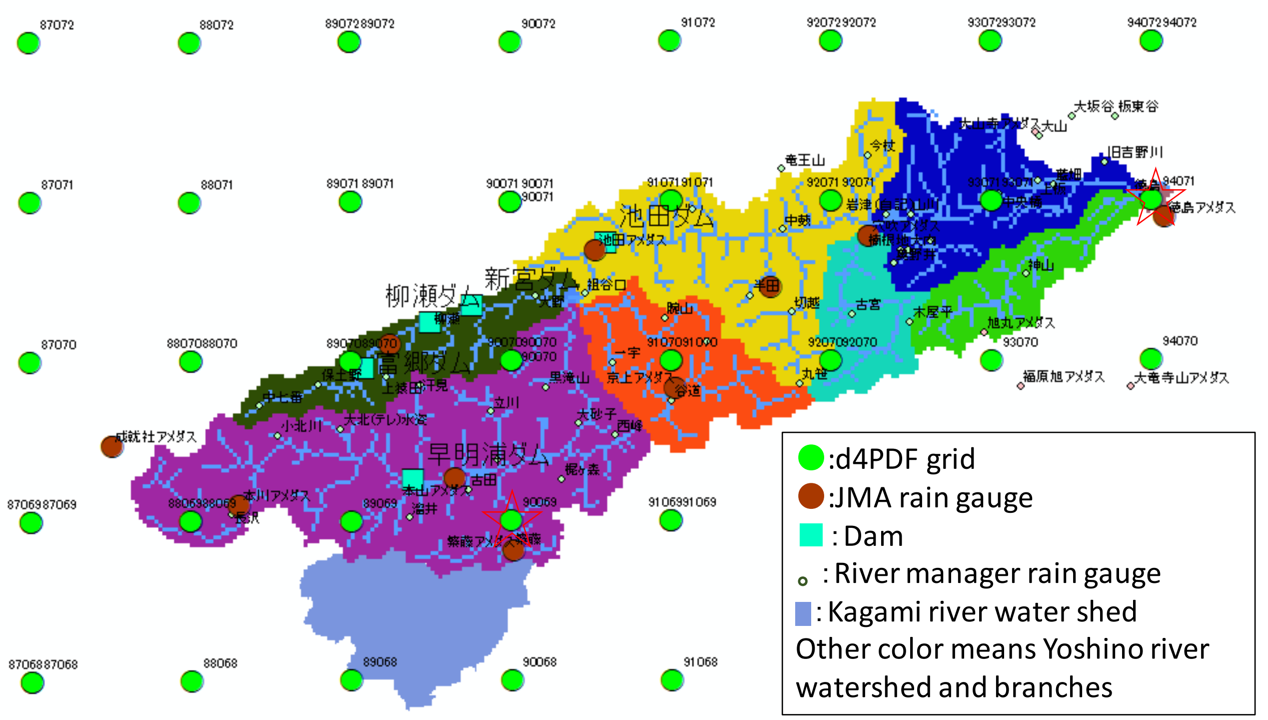

Figure.3 d4PDF grids on Yoshino river basin

The spatial resolution of a river runoff model that predicts water disasters is a few kilometers, which is similar to the grid size of rain gages and radar rainfall.

The d4pdf is a 20-km grid and is larger than the usual runoff model. Figure.3 shows the Yoshino River branch basins and the d4PDF grid.

The d4PDF grid can be matched up with branches of the Yoshino River, but it is still too large for the small river. Spatial distribution and movement of rainfall within the Yoshino River basin may be reproduced by d4PDF.

3. Impact assessment in Yoshino river with d4PDF

3.1 Reproducibility of the d4pdf in Shikoku

Shikoku is divided into northern and southern regions by the Shikoku Mountains. The southern region receives heavy rain, while the northern region receives little rain as rain clouds are blocked.

We compared the past reproduced values (HPB) of d4PDF with the observed values. Comparative points were the Shikoku Mountains where rainfall is concentrated and Tokushima in the mouth of Yoshino River where rainfall is scarce (Red star in Figure.3) The GCM HPB, future, and ground stations have different data years. The average number of days per year denotes the number of days without rainfall. The number of days of heavy rain is the number of times per 60 years.

The frequency of heavy rainfall will increase in the future(especially GF,CC and MI are weak), but the number of days of rainfall will decrease. This means indicates two types risks: floods and droughts. (Figure.4)

According to observed and HPB data in the Shikoku Mountain and Tokushima areas, d4PDF HPB could represent mountain area climates with heavy rainfall, but it did not give a good result for the Tokusima area.

The elevation of the Shikoku Mountains is approximately 2000 m, but the topographic parameters in d4PDF expressed the height as 500 m. The passage of typhoons and fronts, which are not affected by topography, was reproduced in d4PDF, but the effects of blocking rain clouds could not be reproduced. Therefore, d4pdf tended to be similar throughout the island, which was similar to the values observed in mountainous areas where rainfall is concentrated. Thus, d4PDF is suitable for analysis of the mountain and upper basin areas.

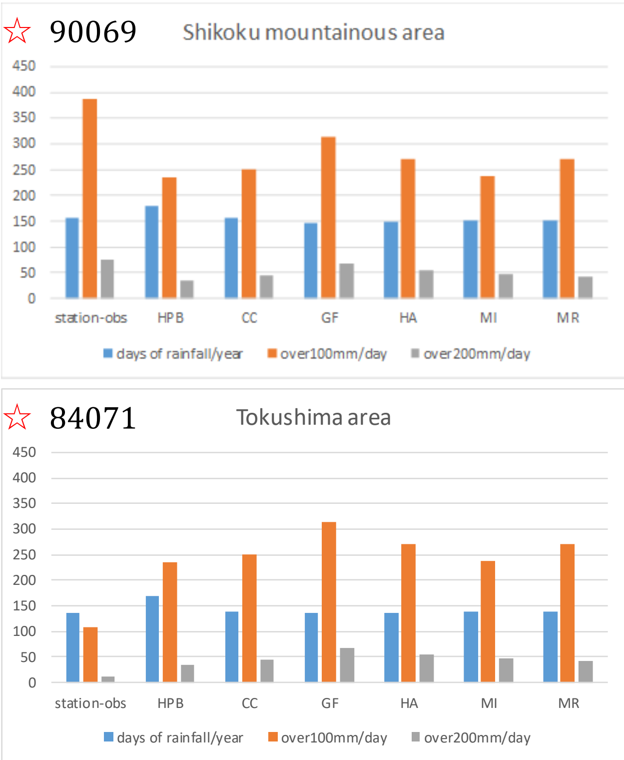

Figure.2 Number of no rainfall and heavy rainfall days (HPB: past reproduced value
CC-MR: Mother GCM name of future projection)

3.2 Impact assessment in dam management

The Sameura Dam in the upper basin of the Yoshino River contributes greatly to flood control and water supply. In the past, large-scale typhoon (NABI: Typhoon No.15 in 2005) came when dam dried up due to drought and thus the dam prevented damage in downstream with not only flood control capacity but also water use capacity used up.

Currently, the dam manager is planning to renovate

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the water discharge tunnel.

This tunnel enables the rapid disposal of stored water to ensure flood control capacity when flooding is anticipated. This will increase the flood control effect without building a new dam. Information on how climate change will affect the reservoir capacity of dams in the event of flooding is useful.

Using d4PDF, we compared rainfall from April to June when more than 4000 m^3/s of flooding occurred at the Sameura Dam. When the amount of rainfall in spring is low, the dam is in a drought condition and can effectively store flood water. However, dam operation will become uncertain.

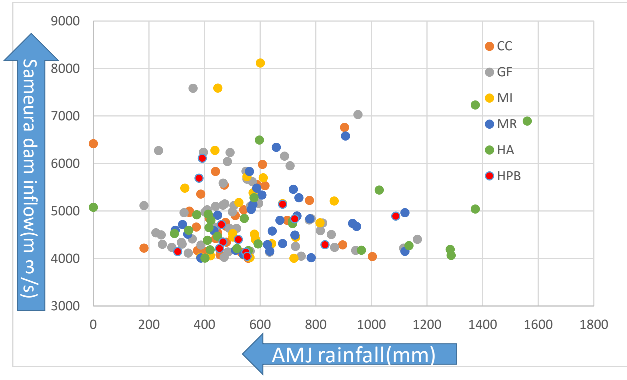

Figure.3 Relationship between flood discharge and spring rainfall amounts in HPB and GCMs in d4PDF

Figure 5 shows the relationship between flood discharge and spring (April/May/June (AMJ)) rainfall amounts. The vertical axis is the water inflow to the dam, and a dot on the upper side indicates a large flood. The horizontal axis is the AMJ rainfall; a dot on the left is a drought. Comparisons between the HPB and future projections can be made to determine overall trends. Furthermore, if there is a difference in the change per GCM relative to the HPB, the future projections might contain uncertainties.

As a result, there were significant differences in trends among each GCM. It was found that strong drought occurs more frequently in GF(GFDL-CM3) between floods and floods. HA (HadGEM2-AO) and MR (MRI-CGCM3) resulted in increased flooding and spring rainfall and reduced drought risk. Changes in the number of days of rainfall and heavy rainfall could be used to determine trends in the risk of floods and droughts. However, based on the basin scale and the characteristics of individual rivers, it was found difficult to make judgments.

3.3 Changes in flood risk in downstream areas

Downstream areas of the Yoshino River are low-lying areas that face two risks: inland flooding, which is directly caused by rainfall, and Yoshino River flooding, which is caused by rainfall in the upper mountains of the river. We compared the maximum hourly rainfall in the downstream grid when a flood of more than 15,000 m^3/s occurred downstream of the Yoshino River. For the results shown in Figure 6, the vertical axis refers to the flood flow downstream, and a dot on the upper side indicates increasing flood magnitude. The horizontal axis is the maximum hourly rainfall downstream, and a dot on the right indicates the occurrence of intensive rains leading to inner flooding.

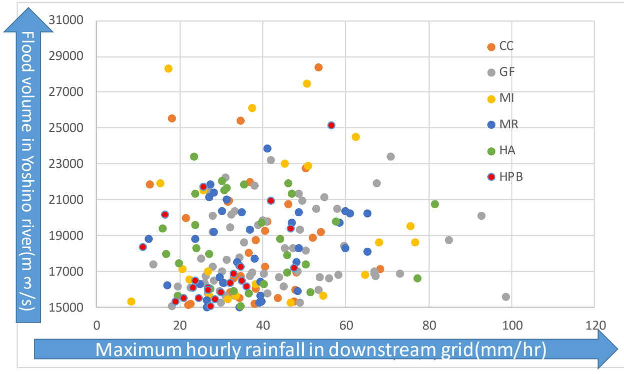

Figure. 4 Relationship between the river channel flood discharge and the maximum hourly rainfall in HPB and GCMs in d4PDF

GCMs have resulted in two types of trends, i.e., an increase in the flood flows in the main river and a large rainfall intensity downstream. The GF is observed to deteriorate in both the situations. The significant rain intensity observed in Figure 4 is consistent with the increase.

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4. Impact assessment of flood risk with high resolution RCM

This project (SI-CAT: Social Implementation Program on Climate Change Adaptation Technology) was downscaled to a 5-km grid starting with d4PDF. With this downscaling, we analyzed the change in the flood volume of two rivers in Shikoku. The topographic parameters of the Shikoku Mountains in the RCM was more than 1500 m. Therefore, it was expected that orographic rainfall would be reproduced compared with d4PDF data.

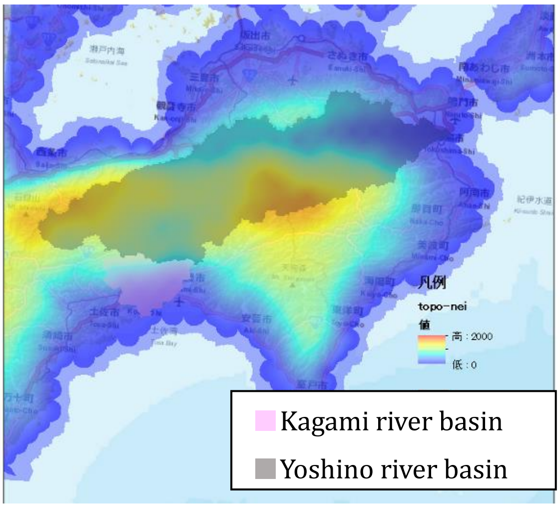

Figure.5 Topological data of 5-km RCM

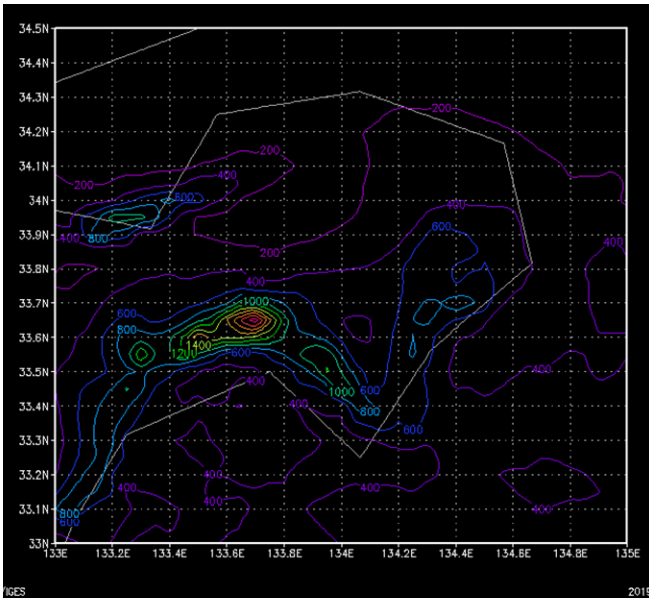

Figure.6 Distribution of rainfall in 5km RCM

Figure 8 illustrates the cumulative rainfall of the largest event, which reproduced the rainfall concentrated on the south side of the Shikoku Mountains. Although the rainfall was uniform across Shikoku in d4PDF, the 5km RCM was able to reproduce the spatial concentration of rainfall by improving the terrain parameter.

4.1 Changes in flood volume in small rivers

Changes in flood discharge to the Kagami River flowing through the Kochi Plain were analyzed. For comparison, we also entered SDS and RCM rainfall data into the discharge model. (Figure.9)

First, we compared the discharge in three types of past data (HPB) from the downscaled projection model, the actual historical maximum discharge and the target discharge in the river plan. The design flood discharge in the river plan is established by probability year. This flood volume can be validated by comparison with SDS calculated with the same probability year.

SDS was the probable discharge rate calculated statistically from the results for 36 years. Since d4PDF and 5-km RCM involved more years of execution than the probabilistic year, unusual cases should have occurred, and the observed maximum discharge was considered to be close to the maximum possible flood. The maximum value in the RCM, which calculates far more years than historical observations, can be compared to the PMF as the maximum value that can occur even at low frequencies.

SDS is the probable discharge rate calculated statistically from the results for 36 years. Since d4PDF and 5kmRCM involve a lot of years of execution than the probabilistic year, unusual cases should have occurred, and the observed maximum discharge is considered to be closed to the maximum possible flood.

The SDS values were fairly reasonable, and the d4PDF values were slightly lower than the current values even though data for several thousand years are available. For the 5-km RCM, it was close to the maximum possible flood volume. This was due to the strong influence of topographic affected rainfall on the southern slope.

In future projections, the increase in flood volume was evident. However, for the 5-km RCM, the maximum flow rate at 2 °C warming did not exceed the maximum flow rate of the HPB. This was because only the HPB's largest flood scale was isolated and large. Comparing the HPB's second largest flood scale and lower, it was shown that the 2 °C warming was larger than the HPB's flood scale.

According to the Clausius–Clapeyron equation, the saturated water vapor increases by 14% and 28% for increments of 2K and 4K, respectively. This is correlated with the maximum rainfall. However, a nonlinear relation can be observed between the increase in saturated water vapor and the increase in flood flow with respect to the Kagami River at the 5-km RCM.

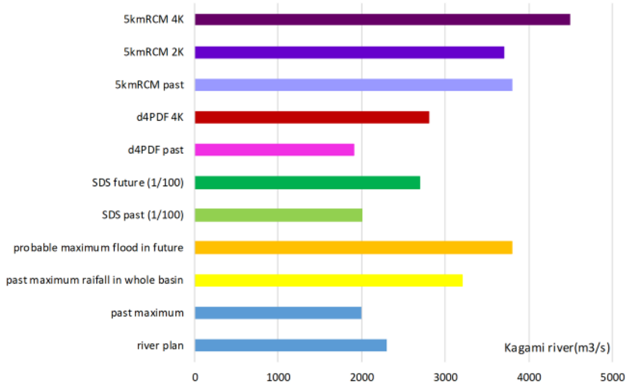

Figure. 7 Relation of previous flood scale and changes in flood scale with each forecast data in Kagami river

Purple bars: 5km RCM, red bars: d4PDF, and green bars: SDS, are calculated current and future maximum flood discharge. The yellow bars indicate the maximum flood flow that could occur if the worst rainfall ever recorded covered the entire basin (PMF). The orange bar is the PMF due to rainfall increased by climate change. The two blue bars are the design flood discharge in the river plan and the maximum flood flows that have occurred in the past

4.2 Changes in flood volume in large rivers

In Figure 10, results of various downscaling data at the Ikeda Dam in the middle reaches of the Yoshino River are compared. The meaning of the bars is the same as in Figure 9.

The SDS for the same probability year (150 years) was overestimated for the discharge of the river plane. There was still a difference in discharge in spite of the same probability absolute amount of rainfall. This was likely because the temporal downscaling was carried out with rainfall waveforms that would increase the flood scale if the rainfall were the same or because of the spatial distribution of rainfall. Not all areas in the Yoshino River basin receive heavy rainfall, but each rainfall event determines whether the rainfall is concentrated in the upper or middle streams or other tributaries. However, the SDS overestimated rainfall because it gave the same probability year to the entire basin.

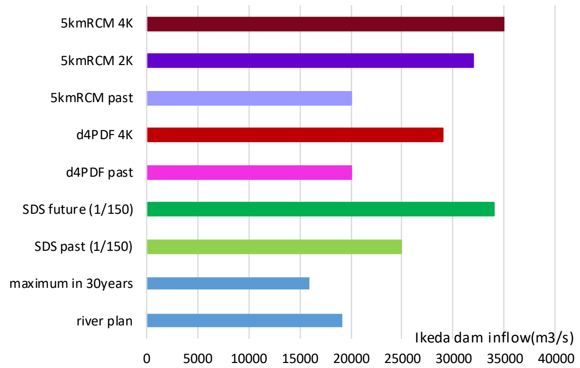

Figure.8 Relationship between the previous flood scale and changes in flood scale with each forecast data of the Ikeda Dam on the Yoshino River

A comparison between the RCMs showed that the HPB of d4PDF and the 5-km RCM were reasonable. This was because the effect of orographic rainfall on the southern slope did not have a significant effect

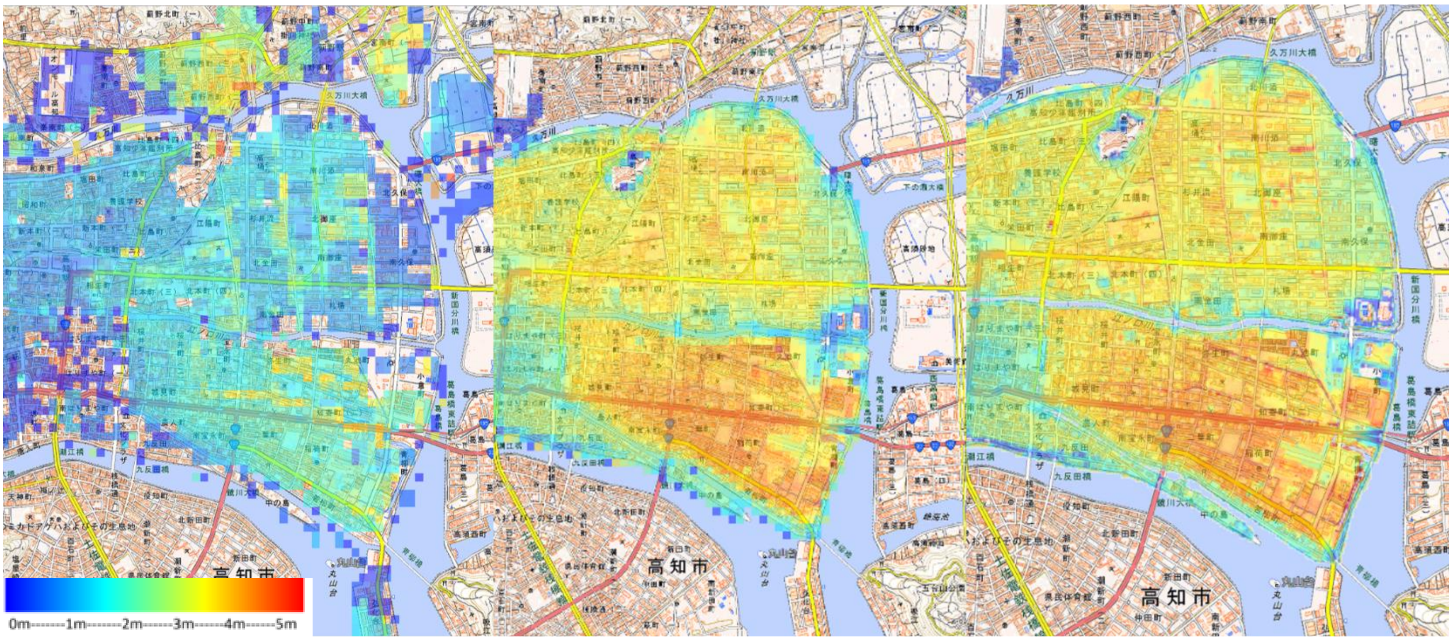

Figure 11. Improvement of flood analysis (old DEM 50-m grid/new DEM 50-m grid/downscale to 10-m)

on the entire catchment area.

5 Improvement of flood analysis

5.1 High-resolution flood analysis

To protect the lives of citizens, it is necessary for citizens themselves to recognize flood risks on a routine basis and to evacuate. Conventional flood analysis is usually on a scale of several tens of meters, making it difficult to identify detailed risks of individual roads and buildings. In recent years, the Geographical Survey Institute has released high-precision elevation data of a 5-m grid using a laser profiler in urban areas and around major rivers. High-resolution inundation analysis has disadvantages in terms of computational cost and stability. Therefore, it is more reasonable to consider downscaling the results of low-resolution inundation analysis that could achieve a lower resolution with computational cost.

5.2 Downscaling of flood analysis

Conventionally, digital elevation maps (DEM) generated from topographical maps have been microtopography was not reproduced because the data was generated from a point-based survey. The precision was also in 10-cm units. The new DEM was generated by a laser profiler, and the precision was also 1-cm units. Even with inundation analysis of a 50-m grid, the new DEM was useful for accurately calculating the mean elevation.

First, from the 5-m DEM, we generated a 10-m grid DEM for terrain modification and 50-m averaged DEM for inundation analysis. Then, it was necessary to confirm whether microtopography, such as embankments and small rivers, had been reproduced.

Next, the inundation analysis of the 50-m grid was performed. The results of the 50-m flood analysis were corrected using a 10-m DEM with the assumption that the capacity of water was the same whether it was a 50-m grid or a 10-m grid. The three maps in Figure 11 show the results using old DEMs, new DEMs, and high-resolution inundation depths in Kochi City. The accuracy was improved only by switching to the new DEM. Further downscaling indicated the risks to individual roads and buildings. Thus, citizens will have information about whether their homes will be in danger and whether the roads to the shelter are safe.

6. Consideration

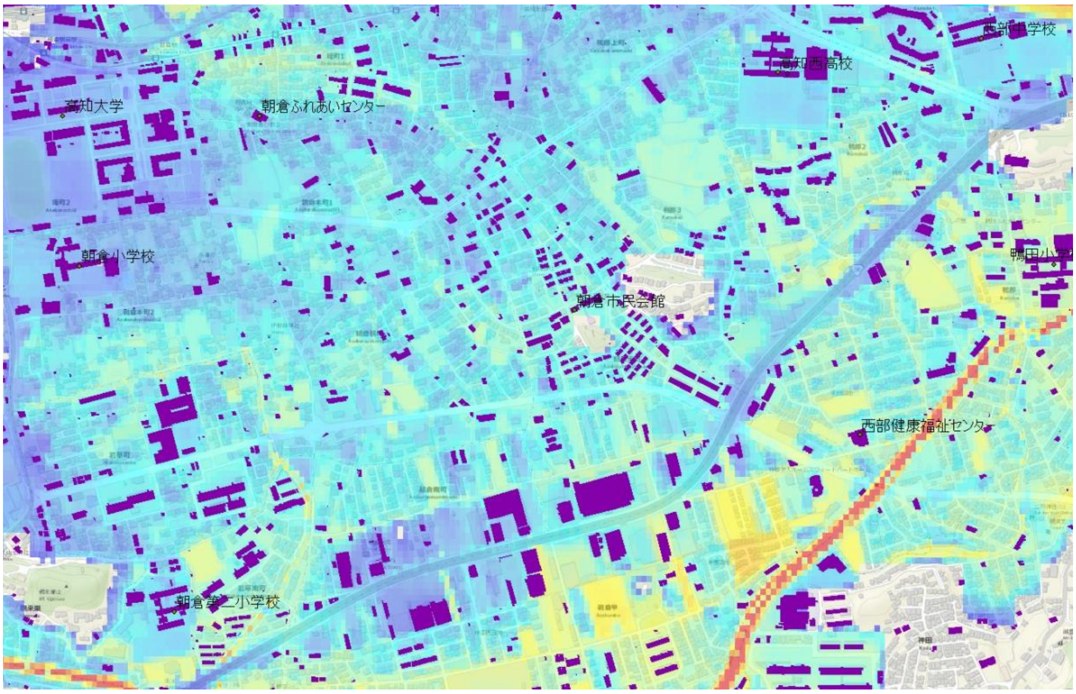

Figure.12 Overlay map :high resolution inundation depth

Japanese kanji name dot: official shelter facilities ■Solid buildings that could be used as a shelter:

6.1 Effectiveness and limitations of RCM

This paper shows that high-resolution RCM is effective for flood risk analysis with climate change. However, the results can vary greatly depending on the downscaling approach. Therefore, there remains a problem in determining the flood discharge to be specified in the disaster prevention policy under climate change.

The grid size of RCMs must be sufficiently small relative to the size of the basin for RCMs to be used. In addition, if the RCMs do not replicate the phenomena that cause flooding in the region, they cannot be used for evaluation.

Since the absolute value cannot be reproduced, it possible to present the expansion of the relative rainfall intensity and the change of the occurrence probability year. An additional future study should use SDS for RCM. However, only the Japan Meteorological Agency stations have reliable and high-quality rainfall data over a long period. AMeDAS stations of JMA exist only on a 20-km grid and can only be used to correct d4PDF of a similar resolution. Although more detailed analysis is possible by including rain gage data from river administrators, electric power companies, and local governments, this would require a great deal of effort to collect and interpolate the data.

The resolution and accuracy of radar AMeDAS have improved since 2000, but it is of limited use for correction. Although more detailed downscaling will be promoted in the future, it is desirable to analyze the climatic characteristics of the target watershed before using it.

6.2 Significance of downscaled inundation analysis

We are assisting local governments in planning climate change adaptation measures. The river administrator has published a hazard map that overlays the maximum values of inundation data from multiple levees break.

However, for local governments, static hazard maps are not sufficient for specific evacuation guidance. For this reason, we provided local governments with moving image data and detailed data for each time step. In addition, by increasing the resolution, the risk at a road or building scale can be understood and can contribute to evacuation guidance.

Figure 12 is an example of the data provided to the city office. Based on detailed inundation depth data for each building and road, we overlaid the official shelter location of the city and the building information that could be a shelter against floods. The city office could designate additional shelters based on the data. In addition, by utilizing the video data of the flood flow, evacuation guidance to citizens can be generated. By obtaining detailed information, citizens can become more aware of risks and be able to take safe evacuation actions.

In the future, it will be easier to analyze inundation at high resolution that can represent each road and building risk, but there is a need to respond to immediate hazards to protect citizens. The downscaling of flood analysis could be useful for supporting the evacuation of each citizen using the coarse resolution computational models that already exist.

7. Conclusions

Historically, flood control measures have not had any hard measures but were mainly self-help assistance such as evacuation for each citizen. In modern times, when it became possible to construct embankments and dams, the government designated measures using hardware. In recent years, local governments have been promoting software measures, such as the release of hazard maps and evacuation guidance. However, the worsening of the scale of floods caused by climate change in recent years is a situation in which "Moving the goalposts".

Thus, as shown in Figure 13, for government hardware and software measures, the residual risk is greater during the increased flood risk. In the case of this excess risk, citizens must evacuate on their own. In this study, we showed consistent simulations can be performed using climate change projection model on a scale at which each citizen can be aware of risks. Currently, it is difficult to estimate absolute rainfall and flood discharge in the RCM. However, the possibility of large-scale damage exceeding the threshold or exceeding the largest flood in the past can be presented. At each stage, as research develops, integrated simulations will become possible.

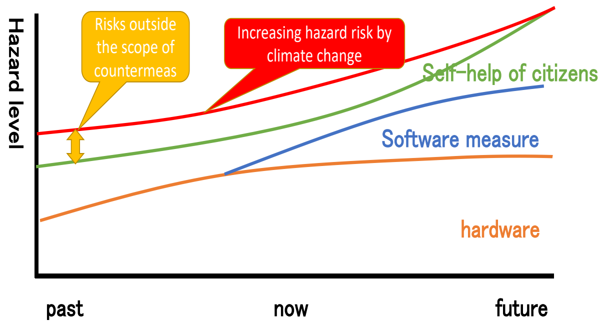

Figure. 11 Relationship between flood counter measure and risk

Due to the limitations of scientific knowledge and computational capacity, the global and civil scale resolution of simulations will continue to be difficult to perform in the future. However, since climate change-related disasters are considered a “Clear and Present Danger,” we cannot wait for accuracy to improve.

It is useful to perform partial downscaling of the currently available simulations, and two examples of downscaling of RCMs and flood models were provided to illustrate how the global scale to citizen framework for consistent simulation to scale was presented. The steps in the RCM allow the expansion of flood flows to be assessed, making it clear that larger floods than the current design goals can be reliably assessed, and that further disaster prevention policy planning is needed. High-resolution inundation models have also made it possible for citizens to understand the hazards of each street and building and protect themselves.

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