IMPACT OF GLOBAL CLIMATE CHANGE ON INFRASTRUCTURE SYSTEM FOR FLOOD CONTROL IN UNRAN RIVER BASINS

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ABSTRACT**:** Global climate change is expected to affect future storm characteristics. The change should properly be taken into account when assessing future flooding risks in urban areas. This study presents a method for quantifying the increase in flood risk caused by global climate change in the framework of urban flood risk management. Flood risk in this context is defined as the product of flood damage potential and the probability of its occurrence. The study utilizes a geographic information system (GIS) based flood damage prediction model (FDPM) to calculate the flood inundation damage caused by design storms with different return periods. Estimation of the monetary damages by these storms and their return periods are forerunners to flood risk calculations. The design storms are developed from modified intensity-duration-frequency (IDF) relationships generated by simulations of global climate change scenarios (e.g. CGCM2A2).The risk assessment method is applied to the Kanda River basin in Tokyo, Japan. The assessment provides insights not only into the flood risk cost increase due to global warming, and the impact that increase may have on flood control infrastructure planning.

KEYWORDS: flood risk management, global climate change, urban river basin

1. INTRODUCTION

Today we have a wide spread consensus that the global warming is a real threat to the future climate (IPCC, 2007). Climate change forced the decision makers to revise the flood protection plans and to consider the impact of climate change for the future flood control planning. The risk assessment for climate change is thus required to evaluate the impact on the urban drainage infrastructure and the flood protection plans.

Flood plains in Japan have rapidly been developed with concentrated population and assets and urban river basins have thus high flood damage potential after the Second World War. National and local governments have carried out infrastructure construction projects such as river improvements and construction of flood diversion channels and flood control reservoirs to prevent flood inundations. These projects in most cases have proved to be effective to decrease flood inundation damage in urban river basins. The projects, however, demand a huge deal of money and give great budget burden to small local governments. In some cases, the projects are not necessarily effective from the cost-benefit viewpoint. Effective and efficient projects are thus emphasized among decision makers, municipal engineers, and public officials in charge of flood management. Therefore, engineering methods to judge the effectiveness and reasonableness of flood control infrastructure planning should be established to support the decision-making process for an optimal flood protection level of flood control infrastructure (Morita, 2008a; Davis, 2002; Plate, 2002).

The risk assessment method should thus be developed to quantify the flood risk increase under climate change scenarios. In urban drainage managements, design storms are commonly used in the planning of urban drainage systems. The risk assessment using the design storms are thus based on the intensity-duration-frequency (IDF) relationships estimated in consideration of climate change.

The concepts of risk and risk management have become widely acknowledged among engineers and policy makers both at local levels (e.g. Guo, 2002) and within the context of climate change (DEFRA, 2003). In the risk management, the risk of a hazardous event is generally quantified by multiplying the occurrence probability of the event by its impact (National Research Council, 1989).

Risk assessment is the fundamental process for the flood risk estimation and has already been introduced and applied to flood control by the US Army Corps of Engineers (Davis, 2002). Davis and most studies (e.g., Plate, 2002), in the risk management, deal with the relation between hazardous flood discharge as a hazardous event and flood inundation damage as an impact on society. The studies used not storm but flood discharge as a hazardous event. To estimate the impact of climate change on flood disaster, storm itself should be adopted as a hazardous event in the concept of flood risk.

This study presents a methodology of risk assessment dealing with the impact of climate change for optimal flood protection planning in the framework of flood risk management. The design storms with IDF relationships are generated by a simple downscaling method for the global climate change scenario simulation results (e.g. CGCM2A2).

2. METHODS OF FLOOD RISK ASSESSMENT

The procedure of the risk assessment method shown in Fig.1 is basically the same as in Morita (2009). The procedure begins with a set of design storms having different return periods. Each design storm expressed as a design hyetograph is used as an input data in FDPM (Flood Damage Prediction Model) simulation. The results of the simulation calculations generate a damage potential curve. The multiplication of the damage potential curve and storm probability curve brings about a risk density curve which is a basis of the flood risk assessment.

2.1 Design storms and their probabilities

A design storm corresponds to a particular IDF relationship specified by a probability distribution. The design hyetographs for FDPM simulations are generated from the IDF relationships using the alternating direction method (e.g. Ven Te Chow et al., 1988). In the study, the IDF relationships determined from the Gumbel distribution, one of the extreme value distributions which the Tokyo Metropolitan Government (TMG) has adopted for flood control planning. The IDF curves of TMG and the alternating block method are illustrated in Fig.2(a) and (b). For example, 75 mm/hr (rain intensity at 60 min duration time), adopted by TMG as a long-term storm design level, corresponds to a 10-year return period.

The return period T is related to the cumulative probability P as $P = 1 - 1/T$. Thus the relationship between the return period and the corresponding probability density f(T) is obtained as $f(T) = 1/T^2$. This relationship described as a storm probability curve in Fig.1(a) and in Fig.3 in detail.

2.2 Flood damage prediction model (FDPM)

The FDPM consists of two models: Model 1 and

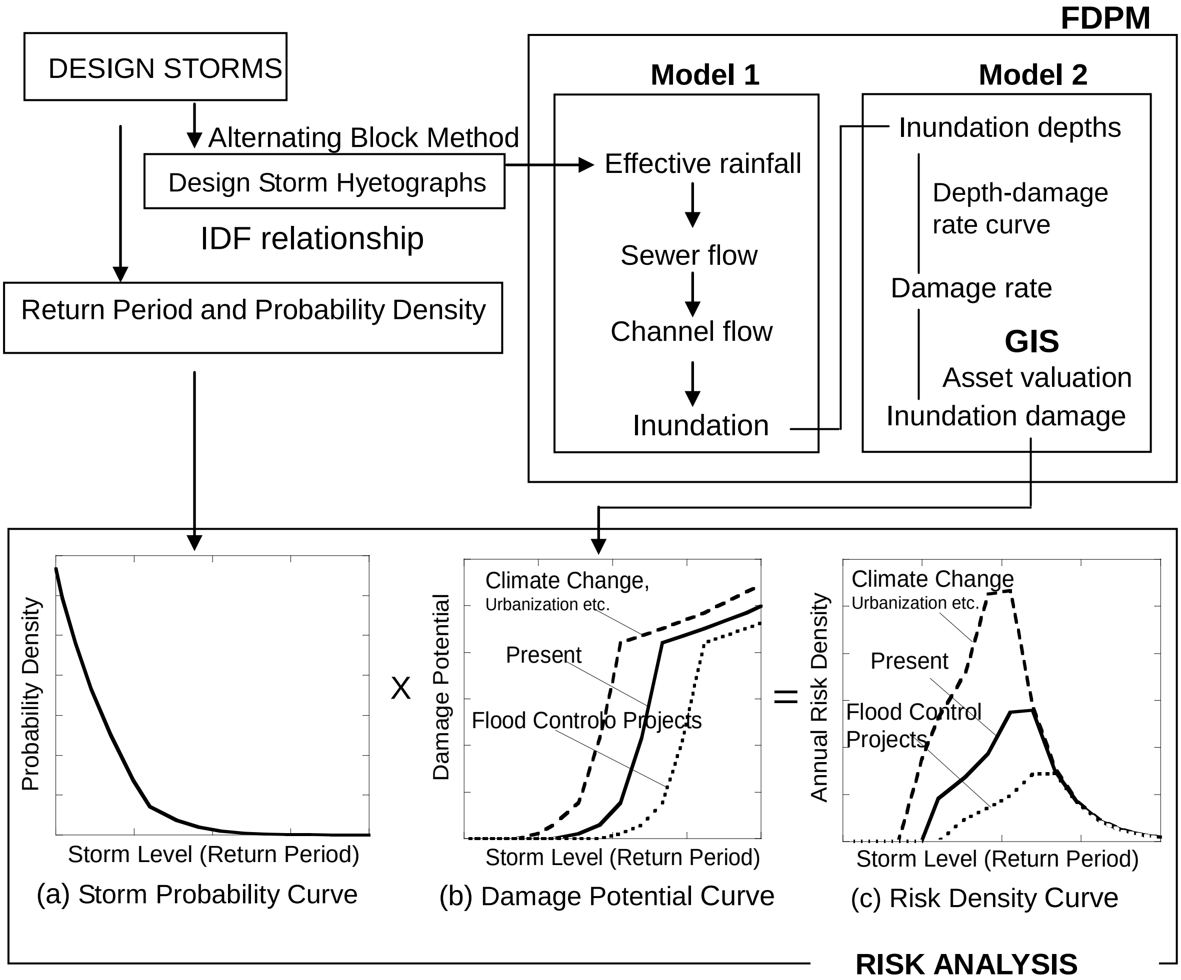

Fig.1 Procedure of flood risk assessment (Design storms, FDPM, and Risk Analysis)

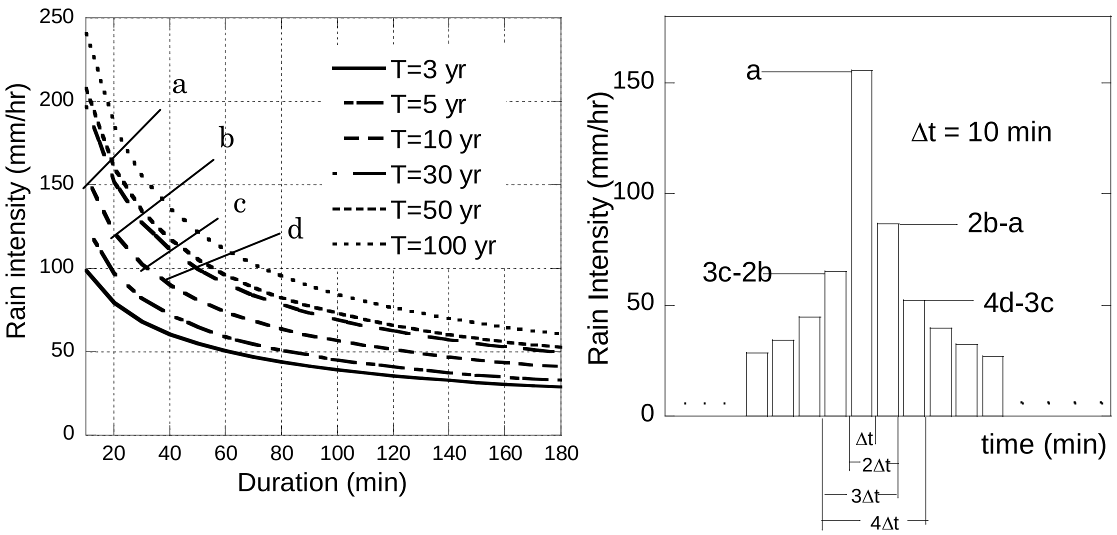

Fig.2 (a)Variation of intensity-duration-frequency (IDF) relationships with return period and (b)example hyetograph created by the alternating block method.

Model 2. The monetary inundation damage in a catchment for any given storm or hyetograph can be calculated by Model 1 and Model 2 based on GIS. Model 1 calculates the inundation depth on 50-m

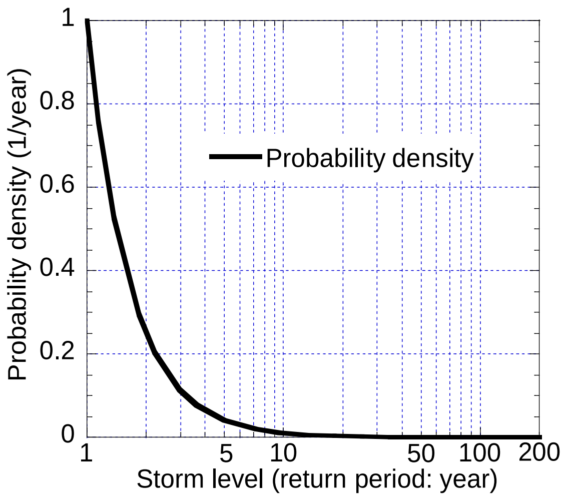

Fig. 3 Storm probability curve.

square grid for a given storm using the diffusive approximate version of the Saint-Venant equations to simulate one-dimensional sewer and channel flow, and two-dimensional unsteady surface flow or inundation (Morita and Yen, 2002). In the calculation, it is assumed that the urban catchment has a natural surface with a rough coefficient corresponding to an urban area with buildings and roads.

Model 2 estimates the amount of monetary inundation damage as a function of the inundation depth calculated by Model 1. The procedure basically conforms in general to the manual of economical research of flood control (River Bureau of the Construction Ministry, 2000) and is described in detail in Morita (2008a). The monetary damage falls into two categories: direct damage and indirect damage. Direct damage means physical damage related to a house, household articles, corporation assets, and so forth, and is classified into eleven types. Indirect damage is caused by business interruptions related to direct damage.

2.3 Damage potential curve

The monetary damages caused by the design storms are estimated using Model 1 and Model 2 for any given storm having their own return periods. The relationship between the return period of a design storm and the corresponding monetary damage is expressed as a damage potential curve (Fig. 1(b)).

Fig.1(b) represents a damage potential curve for the present catchment condition by a solid line and illustrates the upper and lower damage potential. Global warming or urbanization causes the inundation damage potential to increase as shown by the dashed line. Conversely, flood control projects decrease the potential as shown by the dotted line.

2.4 Risk density curve

The concept of risk is defined as the product of flood damage and its occurrence probability. According to the definition, an annual risk density curve is computed by multiplying the damage potential curve and storm density curve. As shown in Fig.1, the increasing damage potential curve (Fig.1(b)) and the decreasing storm probability curve (Fig.1(a)) are combined to form the risk density curve having a peak in the middle (Fig.1(c)). Parallel to the damage potential curve, the present risk density curve shifts upward for estimating assuming global climate change, as shown by the dashed line, and shifts downward with the application of flood control projects as shown by the dotted line.

2.5 Risk cost for flood disaster

Risk cost is an expected value of the annual risk density curve is the annually-averaged monetary expenditure over time for flood inundation damages. The risk cost is obtained by using the integral of the risk density curve with respect to return period.

The risk cost would increase with global climate change because heavy storms are expected to become more frequent due to global warming. The risk cost at the present catchment condition and that at assuming global warming condition are expressed as $RC_{present}$ and $RC_{climate\ change}$, respectively. The risk cost increase caused by the global warming is the difference between the two risk costs, $\Delta RC = RC_{climate\ change} - RC_{present}$. This risk cost increase can be compared with capital cost to improve the infrastructure for flood control coping with global climate change.

3. DESIGN STORMS FOR GLOBAL CLIMATE CHANGE

Global warming would change the characteristics of storms in Tokyo area. To evaluate the risk cost increase due to global climate change, design hyetographs based on IDF relationships are required for the FDPM simulations and the flood risk assessment.

3.1 Change in storm characteristics due to global warming

Many studies in the fields of Hydrology and Meteorology are now working on predicting the change in the characteristics of storms due to global warming. Few studies, however, deal directly with the change in magnitude and frequency of heavy storm in the Tokyo Area. Only two studies have predicted the change based on General Circulation Models (GCMs): National Institute for Land and Infrastructure Management (NILIM) (2004) and Saita (2005) of the Institute of Industrial Science (IIS). Table 1 shows the outline of the two studies.

The resolution of the GCMs output is so coarse (280km) that some downscaling should be done to predict GCM climate changes for heavy storm impact studies. NILIM (Study A in Table 1) focused on the variation of rainfall characteristics in Japan region related to global warming and then downscaled the output of CGCM2A2 spatially and temporally to 20km and a 3-hour duration using a regional climate model (RCM20) developed by the Meteorological Research Institute. They gave the result that the maximum 3-hour rain intensity could increase by more than 20%.

Study B by Saita (2005) of IIS estimated the annual maximum daily precipitation for the 20th and 21st centuries in the Tokyo Metropolis through probability analysis using the output of the K-1 model developed by a joint research group including the Center for Climate System Research of Tokyo University (CCSR).

3.2 Return period shift (RPS) method to estimate flood damage for global climate change

The risk assessment in this study (Fig.1) uses design hyetographs created by IDF relationships as shown in Fig.2(a) and (b). The impact of climate change on the design storms for an urban catchment can be assessed using the currently used IDF relationships as shown in Fig.2(a) and estimated IDF relationships for the 21th century. The forecast IDF relationships should be estimated incorporating the results of the above two studies that deal with changes in storm characteristics due to global warming.

Some important studies have been done for estimating the forecast design hyetographs based on IDF relationships. Nguyen et al. (2007) gives a detailed description of a spatially and temporally downscaling method and the deviation of the resulting IDF curves. The derived IDF curves are used to create the design storms for the 21st century and to calculate flood damages for global warming.

In this study, we present a simple method, Return Period Shift (RPS) method to estimate flood damages for the 21st century based on the relationship between

Table 1 Outline of the two studies on global warming

	Research Group	verification	prediction	model	predicted change in rainfall
Study A	NILIM	1981 – 2000	2031 – 2050	RCM20	maximum 3-hour rain intensity
Study B	W.Saita(IIS)	1900 – 2000	2000 – 2100	K-1 Model	annual maximum daily precipitation

the return periods for the 20th and 21st centuries. This method enable us to calculate the flood damages for the 21st century with global warming without using the IDF curves for the 21st century.

The IDF relationship for the 20th century are those currently employed by the Tokyo Metropolitan Government as shown in Fig.2(a). Fig.4 shows the relationships between the periods for the 20th and 21st centuries. Saita (2005) obtained the relationship shown in the dashed line in Fig.4 by analyzing the probability of precipitation change forecast for global warming conditions. The relationship for the NILIM (2005) study, which is shown by the solid line in Fig.4, was also derived from the comparison between the 3-hour extreme rain intensity and that for the 21st century.

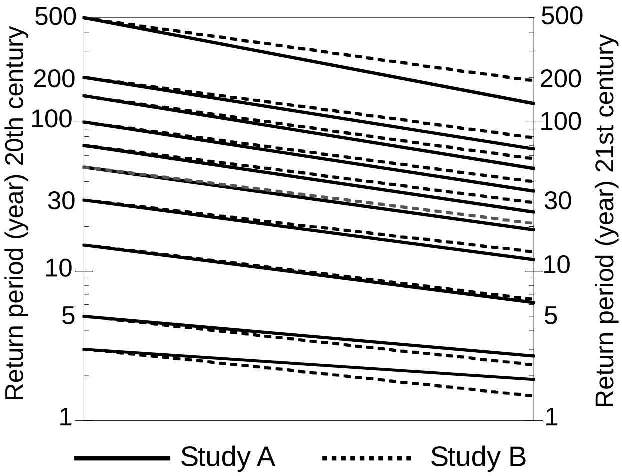

Fig.4 Return periods for 20th and 21st centuries

The Return Period Shift method (RPS method) uses the calculated results of flood damages for the 20th century to determine those for the 21st century directly. For example, return period 30-years for the 20th century corresponds to 15-years for the 20st century as shown in Fig.4. The calculated damage for return period 30-years of the 20th century corresponds to or can be interpreted as that for 15-years, 21st century. Accordingly, the flood damages for the 21st century are determined for the corresponding return periods. The shifted values of flood damage for the 21st century are used to depict damage potential curve for the 21st century as shown in Fig.7.

4. APPLICATION OF RISK ASSESSMENT FOR URBAN RIVER BASIN

The flood risk assessment was applied to simulations of the Kanda River basin in the Tokyo Metropolis. The Kanda River basin with an area of 105.0 km^2 is a typical urban river basin characterized by high population density and numerous assets. The basin has two tributaries: the Zenpukuji River and the Myoushouji River. The basin is extremely urbanized and has as impervious area of 65%. The outline of the Kanda River Basin is shown in Fig.5.

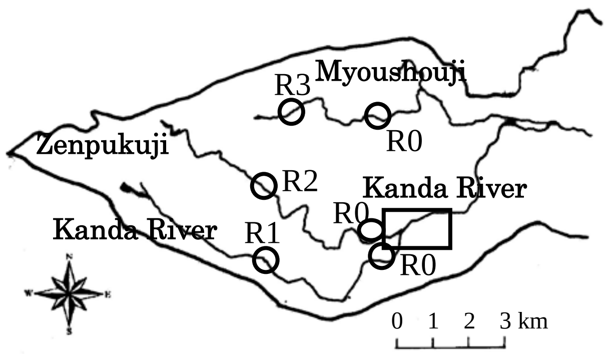

Fig. 5 Outline of the Kanda River basin

Three R0s are the inlets of the reservoir under Loop Road 7. R1, R2, and R3 are hypothetical reservoirs.

In 1997, the government constructed a flood control reservoir for the Kanda River, the underground flood control reservoir under Loop Road 7, the lowest R0 out of three R0s in Fig.5. In 2006, the other two reservoirs were completed and the connected three reservoirs R0 had a total capacity of 540 000 m^3 for storage of flood water from the river channel. Other than the Loop Road 7 reservoir, five flood control reservoirs have been implemented by the government as a flood control project over the past two decades. The FDPM incorporates overflow modeling of all the reservoirs in Model 1 calculation. The flood risk assessment method presented in Fig.1 is thus applied to the simulations in a typical urban river basin.

4.1 Flood control infrastructure projects

If a measure to raise safety against flood disasters could be implemented, then inundation damage and flood risk cost could be reduced owing to the flood control project. For the Kanda River basin having extremely urbanized land use, flood protection plans using flood control reservoirs and storm infiltration facilities could be applicable within the limitation of time and budget.

Table 2 shows the flood protection plans with flood control reservoirs and storm infiltration facilities. Plan A0 means the present state of the catchment. Fig. 5 shows the completed reservoirs R0 and the hypothetical reservoirs R1, R2, and R3. Plan A1, A2, and A3 are flood protection plans using flood control reservoirs shown in Table 2. All of the hypothetical reservoirs have a storage capacity of 300 000m^3. Plan D1, D2, D3, and D4 are intended to decrease the rate of impervious area introducing storm infiltration facilities. Although roof surfaces of buildings are impervious, they would be pervious if the infiltration facilities would collect all of the rainfall on them. The assumed impervious area rates are shown in Table 2.

Table 2 Flood control plans for flood risk assessment

Plan	Flood control reservoirs			
	R0	R1	R2	R3
A0	✔			
A1	✔	✔		
A2	✔	✔	✔	
A3	✔	✔	✔	✔

Plan	Impervious area rate				
	0.65	0.60	0.55	0.50	0.45
A0	✔				
D1		✔			
D2			✔		
D3				✔	
D4					✔

4.2 Flood inundation damage simulations by FDPM

Flood inundation depths were two-dimensionally calculated under the present condition or under the 20th century condition by Model 1 for a 50 m x 50 m grid for design storms having different storm levels of 2-, 3-, 5-, 15-, 30-, 50-, 70-, 100-, 150-, 200-, 300-, and 500-year return periods. The input hyetographs were created on the basis of the IDF curves for these return period storms. The 50-m square grid was adopted mainly because the digital geographical data available fro Geographical Survey Institute of Japan are commonly represented at a scale of 50m. The time increment Δt was set to be 1.0s for calculation stability. The water pathways in the area were not taken into account, and the inundation water was assumed to flow according to the 50-m digital elevation model (DEM).

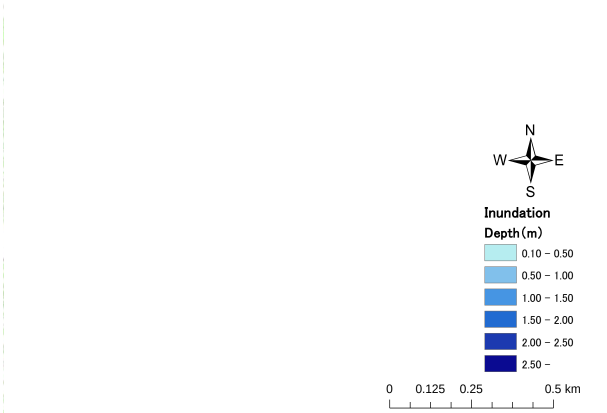

Fig.6 Calculated inundation depth with GIS data superposed for the onset area shown in Fig.5

The inundation damages for the design storms were also computed by Model 2. To conserve space, the detailed explanation of the two models is omitted. In order to estimate the inundation damage using Model 2, GIS with data of the private and corporation assets of the catchment is effectively utilized for flood damage calculations to overlay the asset data and the calculated inundation depth for each building. In the study, the GIS asset data of the Tokyo Metropolitan Government were used.

The two models are described in Morita (2008a). Examples of flood inundation calculations are shown in Fig.6 for 15-year return period storm under the present catchment condition.

5. RESULTS AND DISCUSSION

The inundation depths and related monetary damages for all grids were calculated by the FDPM using the design hyetographs for the 20th century. Besides, the monetary damages for the 21st century under global warming were computed using the RPS method. The damage potential curves and the annual risk density curves were obtained form the risk assessment procedure as shown in Fig.1.

5.1 Damage potential curve

The total monetary damages associated with the present (20th century) and the shifted damages with global warming (21st century) are shown in Fig. 7. The damages are relatively low when storm levels are low, increasing markedly when specific storm level threshold----30 years for the 20th century are exceeded. Those specific storm levels inundate the first floor levels of buildings. Fig. 7 also indicates that the basin would experience no damage due to inundation by a storm level with a return period of < 5 years for the 20th century and <3 years for the 21st century. The threat of flooding becomes greater under global warming.

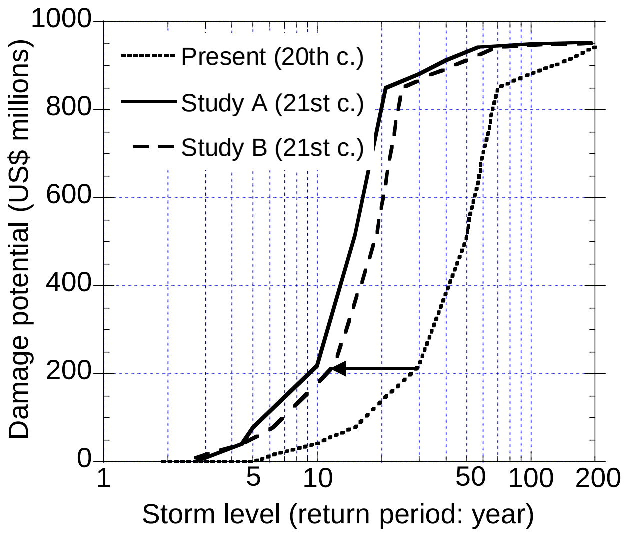

Fig.7 Damage potential curves for the 20th and 21st centuries.

The damage potential curves indicate that the damage for the 21st century is significantly larger than that of the 20th century. The effect of damage increase due to global warming can also be more clearly understood from the three damage potential curves. The two damage potential curves for the 21st century have almost the same trend in terms of damage potential increase with return period, although the damage potential of Study A is a little larger than that of Study B for the storms with greater than 5-year return periods. This is explained by the fact that the estimated return period of Study A over 5-year (y-axis) is a little smaller than that of Study B for the same return period of the 20th century (x-axis) as shown in Fig.4.

5.2 Annual risk density curve

The annual risk density curve was calculated by multiplying the damage potentials due to inundation by the probability densities of storms of different return periods. As shown in Fig. 8, annual risk density curves peak at approximately 10 years for the 20th century and 4 to 5 years for the 21st century. The annual risk density curve is thus computed from the decreasing storm probability curve in Fig.3 and the increasing damage potential curves in Fig.7. The peak of the annual risk density curve can be considered to be a design storm with the highest flood risk.

Global warming causes a marked increase not only in flood damage potential but also in flood inundation risk. The risk density of Study A is smaller than that of Study B for return periods of <4 years, but larger for return periods of >5 years. This can be explained in the same way as the case of the damage potential curves in Fig. 7.

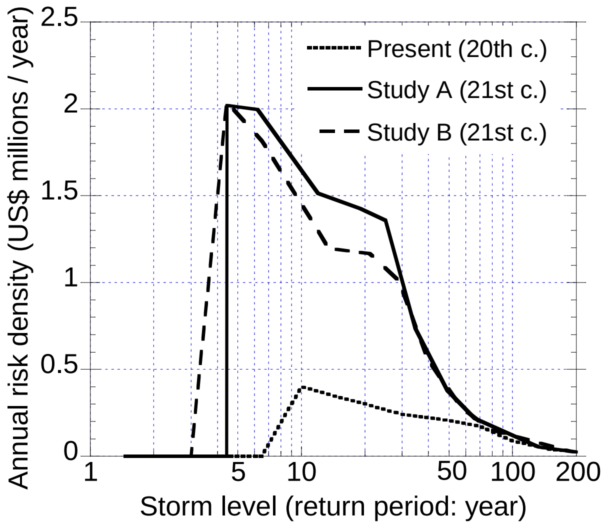

Fig.8 Annual risk density curves for the 20th and 21st centuries.

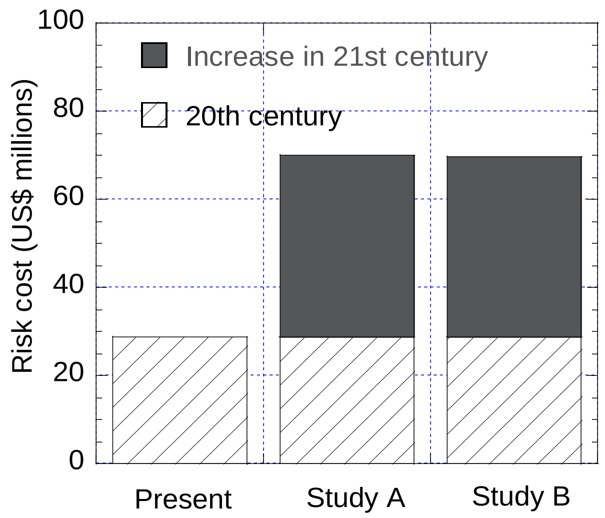

Fig.9 Risk cost increase due to global warming

5.3 Risk cost and risk cost increase

The risk cost can be calculated by integrating the annual risk density curve shown in Fig. 8 over 1- to 200-year return period of. The risk cost for the 20th century, for the present design storm, was computed to be approximately 28 million US$. As mentioned before, this figure represents the average monetary expenditure for flood inundation damages. The risk costs of the two studies for the 21st century were calculated, integrating the two projected annual risk density curves. Fig. 9 shows the calculated risk costs for the 20th and 21st centuries. The risk cost increases due to global warming were computed form the difference in risk cost between the 20th and the 21st centuries. The risk cost increase thus estimated is approximately 41 million US$ for Study A and for Study B.

5.4 Capital cost of flood protection projects

In case flood control reservoirs or storm infiltration facilities are constructed, corresponding capital costs would be required for flood protection. In other words, flood protection plans, such as plans A1 to A4, all have an associated capital cost.

In the present study, the capital cost for a specific return period T_p, $CC(T_p)$, are estimated relative to the construction cost of the Loop-7 Reservoir for plans A1 to A4 and the average equipment cost of storm infiltration facility for plans D1 to D4. The construction cost of reservoirs R1, R2, R3, and R4, was assumed to be 20 million US$ / 10,000m^3 and to have a lifetime of 50 years. For the storm infiltration facilities, the cost was estimated at approximately 2,000 US$ / household with a lifetime of 10 years. The operating costs were not considered for the reservoirs or infiltration facilities. Discounting and cash flow studies were reluctantly omitted from the present study.

5.5 Evaluation of global warming impact on flood control infrastructure system

If measures that reduce the likelihood of inundation could be implemented, the inundation damage and flood risk would be reduced by these flood control projects. For the Kanda River basin, flood control projects using flood control reservoirs and storm infiltration facilities could be feasible within time and budget limitations. Morita (2009) estimated the risk reduction effects of construction of hypothetical reservoirs R1, R2, and R3 as shown in Fig.5 (flood control plans: A1, A2, and A3) and of introduction of storm infiltration facilities intended to reduce the rate of impervious area of the basin from 0.65 to 0.45 (flood control plans: D1, D2, D3, and D4). The estimated risk cost reduction for the flood control plans and corresponding capital costs are quoted from Morita (2009) in Fig. 10.

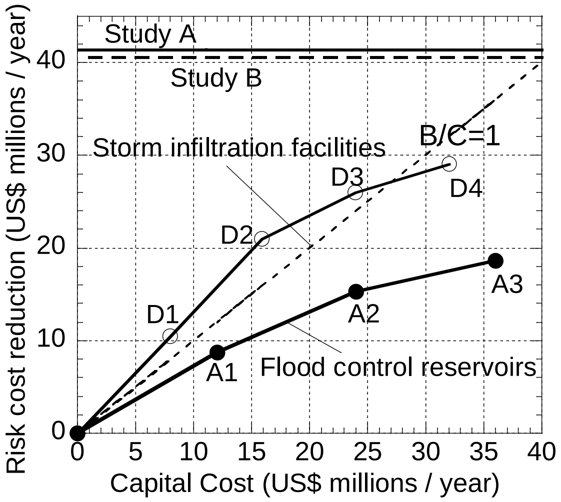

Fig.10 Risk cost reduction and capital cost for flood control projects.

The risk cost reduction and corresponding capital cost for each flood control plan are plotted along with the B/C=1 line. Plans using the flood control reservoirs fall below the B/C=1 line, whereas most of the storm infiltration plans fall above the line and more cost effective. The risk cost increase due to global climate change would be approximately 41 million US$ for Study A and for Study B. The risk cost increases owing to global change are greater than the risk cost reductions of the flood control plans as shown in Fig. 10. The B/C ratios of both the reservoir plans and the plans to reduce impervious area increase more moderately against capital cost and turn out to be less effective from a cost-benefit viewpoint. Generally, the cost function does not exhibit a linear relationship with return period (Heaney et al. 2002).

Thus, the assessment shows that the risk loading effect of global warming on flood control infrastructure could overbalance the risk reducing effect of currently envisioned future flood control projects.

6. CONCLUDING REMARKS

The objective of this study was to develop and present a quantification method for the assessment of flood risk increase caused by global climate change. The most important results are as follows:

(1) A framework for a risk assessment method employing a FDPM with GIS data for quantifying the impact of climate change on the local river basin system has been developed.

(2) The Return Period Shift method was introduced to estimate the flood inundation damage of the 21 century from that of the 20th century without creating modified IDF curves for global warming.

(3) The risk assessment method was applied to estimate the risk increase effects of global warming on flood control in the Kanda River basin in Tokyo. The risk analysis quantified the flood risk, producing two curves each for the 21th and 21st centuries: the damage potential curve and the annual risk density curve.

(4) The estimated risk cost could double in the 21st century. The risk loading effect of climate change on flood control infrastructure could be greater than the risk cost reduction effect of envisioned flood control projects.

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