Optimal Flood Protection Level for Flood Control Infrastructure Construction in the Framework of Risk Management

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OPTIMAL FLOOD PROTECTION LEVEL FOR FLOOD CONTROL INFRASTRUCTURE CONSTRUCTION IN THE FRAMEWORK OF RISK MANAGEMENT

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***ABSTRACT*:** The objective of this study is to present a risk analysis method for flood protection level decision. The concept of "risk" is here defined as the product of flood damage and its occurrence probability. The study also presents a flood damage prediction model **FDPM** using GIS to calculate flood damages for any design storms with different return periods. The calculated monetary damages for the design storms with their occurrence probabilities enable us to quantify flood inundation risk as an **Annual Risk Density Curve** based on the concept of "risk." **FDPM** and the risk analysis method were applied to the storm design level decision of the Kanda River in the Tokyo Metropolis. One example of the applications of the risk analysis method to optimal storm design level decision is presented with cost curves: **Risk Cost Reduction Curve** and **Capital Cost Curve** given by the **Annual Risk Density Curve**.

KEYWORDS: flood risk management, optimal storm design level, urban river basin

1. INTRODUCTION

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.

Recently, the concept of "risk" has become widely accepted among researchers, engineers, and policy makers with respect to environmental problems (e.g., Field et al., 2002). The risk in the environmental engineering is generally quantified by multiplying the occurrence probability of a hazardous event by its impact on society. Risk analysis 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 analyses, deal with the relation between hazardous flood discharge and flood inundation damage as an impact on society.

The planning of flood control infrastructure system varies with several factors, but is primarily related to design capacity based on storm return frequencies. If we intend to decide the flood protection level of infrastructure system, we must consider the relationship between design storms having different occurrence probabilities and the corresponding monetary inundation damages in order to quantify the flood risk.

The objective of the present study is to present a risk analysis method for optimal flood protection level decision in the framework of flood risk management. Risk analyses for optimal flood protection level decision are used in hydraulic structure design (e.g., Kite, 1988). However, no flood risk analysis studies have been done in optimal flood protection level decision for flood control infrastructure system including diversion channels, flood control reservoirs, and infiltration facilities.

2. FLOOD RISK ANALYSIS METHOD

The procedure of the risk analysis method shown in Fig.1 begins with a set of design storms having different return periods or occurrence probabilities, as specified by a probability distribution. To explain the procedure, we properly use an example of flood prevention planning of the Tokyo Metropolitan Government.

2.1 Storm probability curve

The Tokyo Metropolitan Government (TMG) has adopted the Gumbel distribution, one of the extreme distributions. For example 75 mm/hr, adopted by TMG as a long-term storm design level, corresponds to a 15-year return period. Fig.2 shows the **Storm Probability Curve** for TMG (solid line), which relates storm level to the corresponding storm probability density. The other dotted line curve shows the relationship between rain intensity as a design storm level and its return period.

2.2 Design storm and its hyetograph

The probability distribution of the design storms relates a storm magnitude (storm level) and return period for flood prevention planning (Fig.1 (a)). In Japan, the magnitude of a design storm for urban rivers is usually expressed in terms of rain intensity per hour based on the intensity-duration-frequency (IDF) relationship.

The design storm levels plainly expressed by rain intensity per hour have their hyetographs based on the intensity-duration-frequency curve (IDF curve). To develop hyetographs, any methods can be applicable, but in the risk analysis presented in the study, the alternating block method (e.g., Ven Te Chow, 1988) is adopted as shown in Figs.3 (a) and 3(b). For a storm level 70 mm/hr (10-year return period), 155 mm/hr for 10 min, 120 mm/hr for 20 min, and 100 mm/hr for 30 min are shown in Fig.3(a) the design hyetograph is obtained using the values a, b, c, and so on.

2.3 Flood prediction model (FDPM)

The set of created hyetographs of the design storms is used for flood damage calculation via the flood damage prediction model (FDPM). **FDPM** is composed of two models. **Model 1** calculates inundation depths for any storms, and **Model 2** computes the monetary inundation damage as a function of inundation depth calculated by **Model 1**. The two models are described in detail in Morita and Yen (2002), Morita (2005), and Morita and Yamashita (2005). The outline of the models is just explained here.

2.3.1 Model 1 for flood and inundation simulation

For **Model 1,** input design storm hyetographs are first transformed into effective rainfalls, or rainfall excess, as shown in Fig.1. Next, overland flows through sewer systems and channel flow are calculated with the effective rainfall and are then followed by two-dimensional flood inundation calculations when the channel water exceeds the capacity of the channel systems. Any flood inundation models are applicable to simulate the one-dimensional sewer and channel flows and the two-dimensional inundation.

2.3.2 Model 2 for flood damage estimation

Model 2 estimates the amount of monetary inundation damages (Fig.1). The procedure basically follows the manual of economical research of flood control (River Bureau of the Construction Ministry,

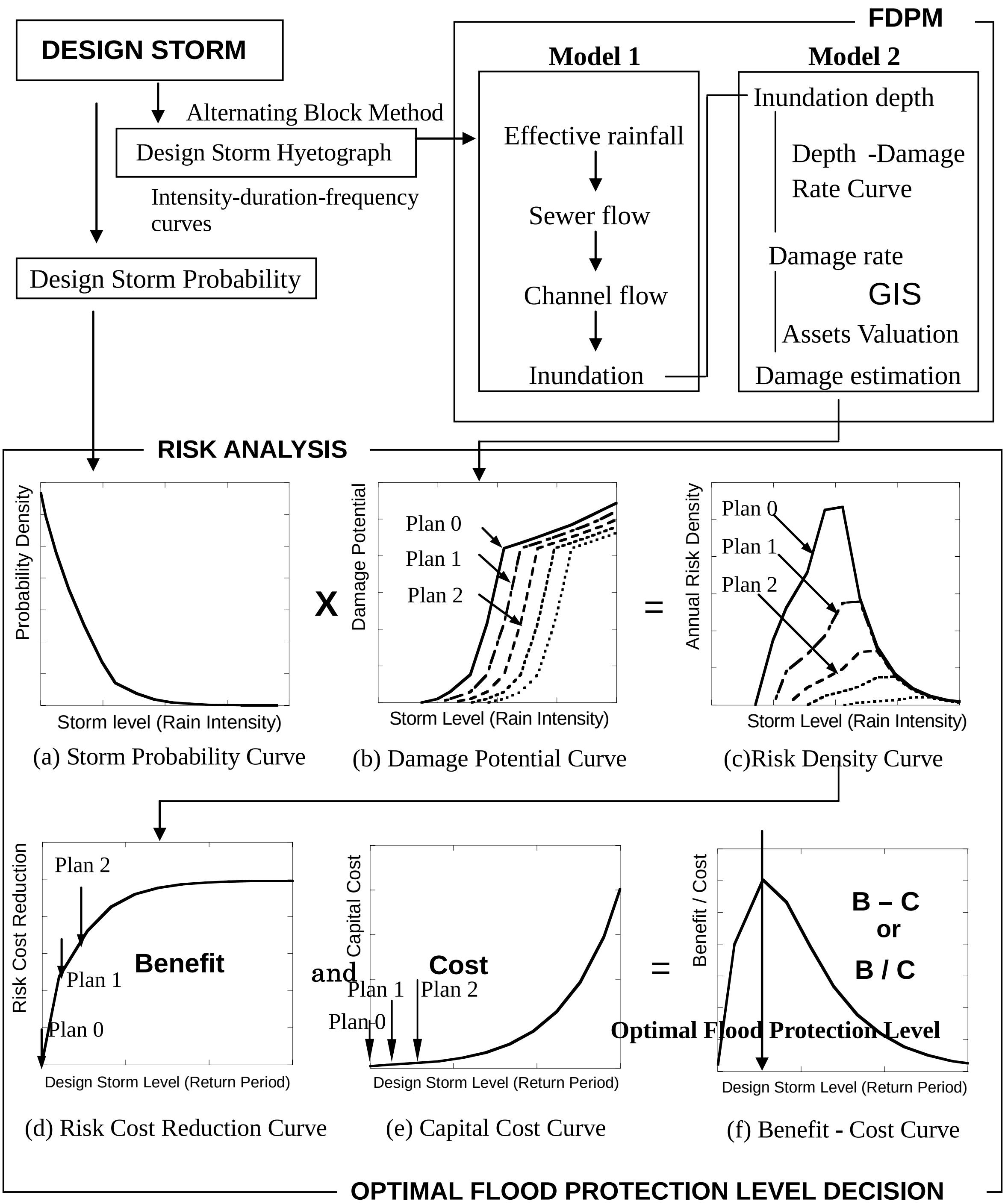

Fig.1 Procedure of risk analysis and flood damage prediction for optimal flood protection level decision

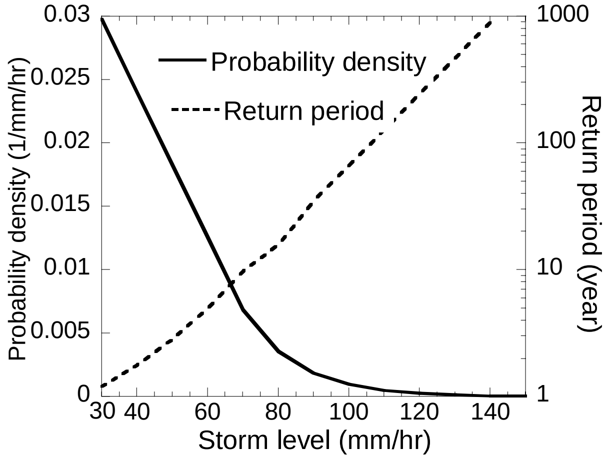

Fig.2 Storm probability curve. The curve relates storm level and its probability density. Storm level is also related to return period.

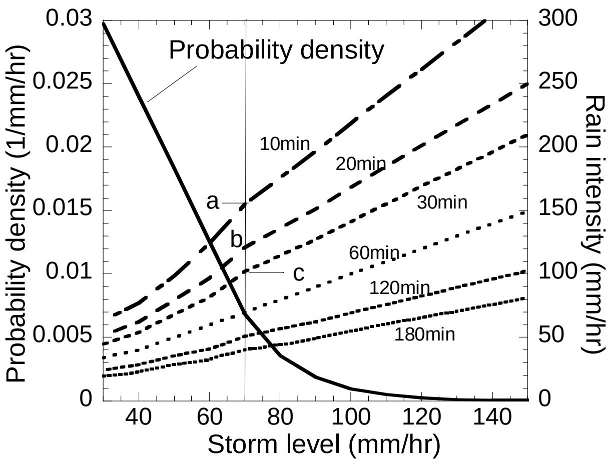

Fig.3(a) Storm probability curve

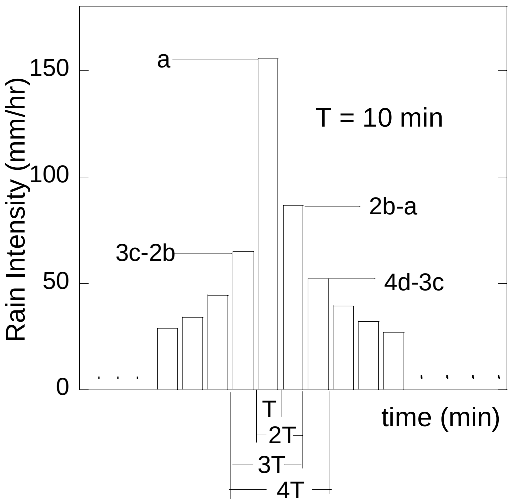

Fig.3(b) Hyetograph based on the IDF relationship and constructed by the alternating block method

2000). The damages are classified 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, as shown in Table 1. Indirect damage is caused by business interruptions related to direct damage. Business damage caused by traffic interruption is also considered in direct damage.

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 assets data and the calculated inundation depth for each building. In the study, the GIS assets data of the Tokyo Metropolitan Government were used.

To calculate the amount of direct damage, the assets valuation of each house or business building is basically multiplied by the damage rate determined from the inundation depth. The same method was adopted for the damage to movable objects. For these calculations, the relationships between the damage rate and the inundation depth are described as inundation-damage rate curves, which are plots of the damage rate as a function of inundation depth. The curves were obtained for the eleven types of direct damage, as shown in Table 1, based on the inundation damage statistics (Institute of Public Works of the Construction Ministry, 1995).

2.4 Damage potential curve

The monetary damage caused by the design storms is represented as a **Damage Potential Curve** (Fig.1 (b)). If the protection level of flood control infrastructure would be raised, the monetary inundation damage would be decrease under the

Table 1 Classification of direct inundation

Type	Direct Damage		
	structure	movables	
private house	wooden	household articles	
	non-wooden		
business building	wooden	depreciable	manufacturing
			commercial
			service
	non-wooden	inventry assets	manufacturing
			commercial
			service

same design storm. Different levels of flood protection, therefore, generate different damage potential curves, such as Plan 0, Plan 1, and Plan 2, as shown in Fig.1 (b). Plan 0 describes the present state of the river infrastructure system. Higher protection plans results in lower damage potentials.

2.5 Uncertainty and Risk density curve

Associated with most hydrologic data, such as flood inundation data, is uncertainty. However, uncertainty can be quantified in terms of probability distributions and the associated cost. Hence, multiplication of the Storm Probability Curve and the Damage Potential Curves for design storms having different return periods generates **Risk Density Curves** on an annual basis, as shown in Fig.1(c). Each Risk Density Curve corresponds to the Damage Potential Curve with the same flood protection level. The flood risk density decreases with higher protection plans according to the damage potential curves. The Risk Density Curve is the most important result in the risk analysis for optimal flood protection level decision.

3. OPTIMAL FLOOD PROTECTION LEVEL DECISION BASED ON RISK ANALYSIS

If a measure to raise safety with respect to inundation could be incorporated in the analysis, the risk cost could be reduced, but this would require a corresponding capital cost for flood protection.

3.1 Risk cost reduction curve

Risk cost is the cost of not providing a level of flood protection. The risk cost is computed as an expected value by the integral of the risk density curves. The risk cost reduction owing to flood protection infrastructure is the difference between the present risk cost (Plan 0) and the estimated risk cost for flood protection plans, such as Plan 1, Plan 2 in Fig. 1(d). As mentioned in **3.3**, these flood protection plans, Plan 1 and Plan 2, require the construction and maintenance costs, respectively. **Risk Cost Reduction Curve** is thus produced by the expected values of the Risk Density Curves of different flood protection levels or return periods of flood protection infrastructure plans (Fig.1 (d)). The risk cost reduction naturally means the benefit owing to flood control infrastructure construction.

3.2 Capital cost curve

The total cost for flood control infrastructure is the sum of initial cost and maintenance cost. The initial cost or capital cost means the construction cost of flood control infrastructure that should be expressed in terms of cash flow on an annual basis. Thus, to determine a financial plan, the concept of equivalence or the timing of payments and income are important. Payment and income at different times can be expressed as an equivalent total investment measured in current monetary value using discount rate (River Bureau of the Construction Ministry, 2000).

The flood control plans having risk reduction costs require corresponding annually paid capital cost and maintenance cost, respectively. The relation between capital cost and design storm level of flood control infrastructure plan is given as a **Capital Cost Curve** (Fig.1 (e)). The capital cost in the Capital Cost Curve includes the maintenance cost for simplicity.

3.3 Optimal flood protection level

When the benefits of a flood control infrastructure construction exceeds the cost, economic feasibility are the maximum of (benefits – costs) or the maximum of (benefits/costs). The benefit-cost comparison equations can be used to determine the optimal flood protection level of flood control infrastructure. By combining the Risk Cost Reduction Curve with the Capital Cost Curve, we obtain the **Benefit-Cost Curve**, as shown in Fig.1 (f). Finally, the flood protection level (return period) having the maximum B/C ratio or the Maximum value of B – C is determined as the optimal flood protection level.

4. APPLICATION OF RISK ANALYSIS TO OPTIMAL FLOOD PROTECTION LEVEL DECISION AND DISCUSSIOIN

The flood risk analysis method presented in Fig.1 is applied to the optimal flood protection level decision in a typical urban river basin.

4.1 Urban river basin for flood risk analysis

Risk analysis was applied to the flood control infrastructure planning of the Kanda River basin in the Tokyo Metropolis. Fig.4 shows an outline map of the Kanda River basin. The figure also gives the results of inundation depth calculation using **Model 1** of **FDPM**, under 120 mm/hr, 300-year return period design storm. The basin, having an area of 80.6 km^2, has two tributary rivers, the Zenpukuji River and the Myousyouji River. The Tokyo Metropolitan Government constructed a flood control facility, the Kanda River underground flood control reservoir under Loop Road 7 (Loop-7 Reservoir) in 1997. Since the Kanda River is a typical urban river, it is almost impossible to widen the section of the river channel. Flood control infrastructures of reservoirs and infiltration facilities are thus alternatives to raise the flood protection level.

4.2 Damage potential curve

Flood inundation depths were calculated by **Model 1** for a 50 m x 50 m grid for the design storms having different storm levels of 30, 40, 50, 60, 70,75, 80, 85, 90, 100, 110, 120, and 150 mm/hr. 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. The two models are described in Morita and Yamashita (2005) and Morita (2005).

The total damage amount for the present river basin condition is shown as a solid line in Fig.5. The damage occurs under design storm level more than 60 mm/hr. The potential damage remains very slight with lower storm levels and then increase markedly

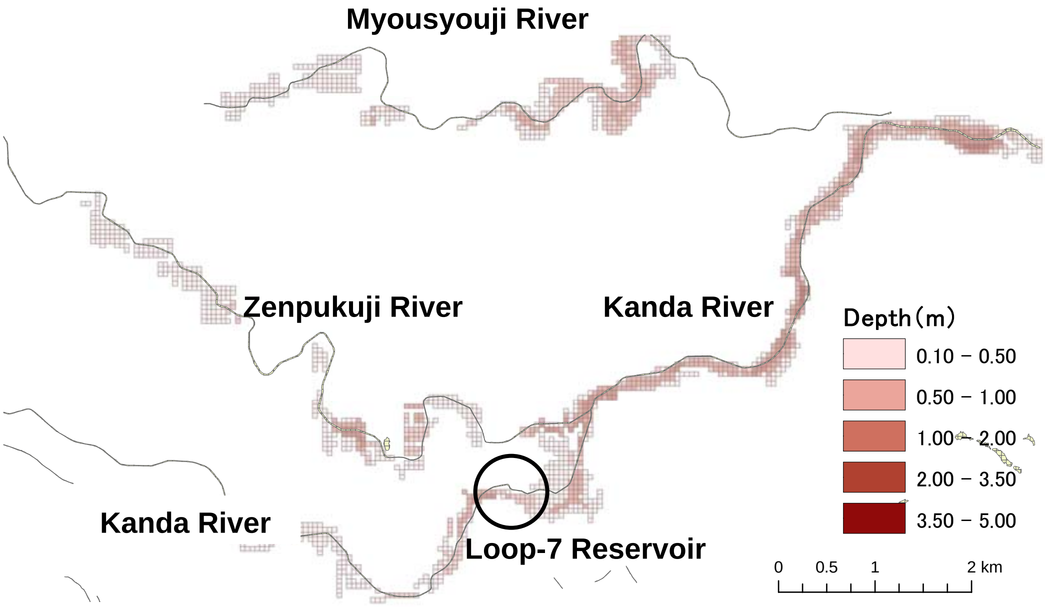

Fig.4 Outline of the Kanda River and Result of inundation depth calculation under 120 mm/hr, 300-year return period design storm with GIS data superposed.

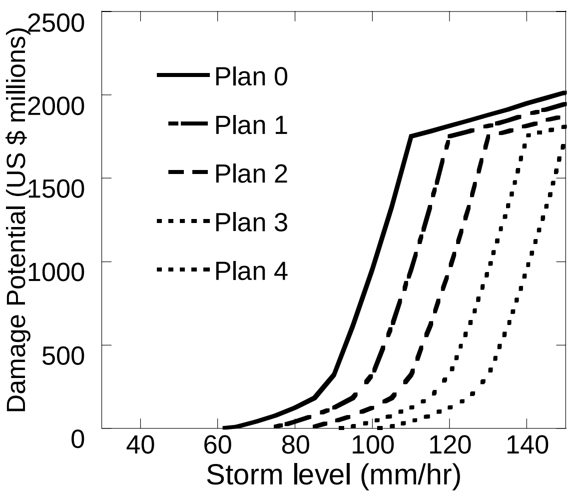

Fig.5 Damage potential curves for several flood protection plans with different return periods.

when a certain threshold value of storm level, 90 mm/hr, is exceeded. The damage curve has an inflection point at 110 mm/hr with a damage potential of about 1,700 million US$.

If an infrastructure construction for flood control is adopted in order to make the river basin safer with respect to inundation, the potential damage becomes lower. In Fig.5, the initial damage storm level or the flood protection level is 60 mm/hr for the present river basin condition (Plan 0) as shown in a solid line. With higher flood protection measures, the initial damage storm level becomes higher and the damage potential curve moves to the right as shown in dotted lines. Plan 0 signifies the present condition and Plan 1 means the flood protection infrastructure plan with the initial damage storm level 70 mm/hr. Moving the curve to the right by 10 mm/hr gives Plan 2, Plan 3, and so on. Actually, the damage curves of different flood protection levels have different shapes. Strictly speaking, the damage potential curves should be calculated for each safer river basin condition with higher flood protection level. In this study, however, the potential damage curves are assumed to have the same shape for simplicity.

4.3 Risk density curve

The annual risk density curve is computed by multiplying the monetary inundation damages by the probability densities of storm levels having different return periods. In other words, multiplying Fig.3 (solid line) by Fig. 5 (solid and dotted lines) generates the annual risk density curves, which are shown in Fig.6. The risk density curve (solid line) is the risk density curve of the present river basin condition. Some extrapolation was performed to complete the curve for the entire range from 60 mm/hr to 200 mm/hr. Figure 6 shows that, at present, the basin would have no inundation damage under storm level 60 mm/hr (5-year return period), No flood control in the future would bring about the maximum annual risk cost RC_{max} computed as the integral of the curve from 60 mm/hr to 200 mm/hr.

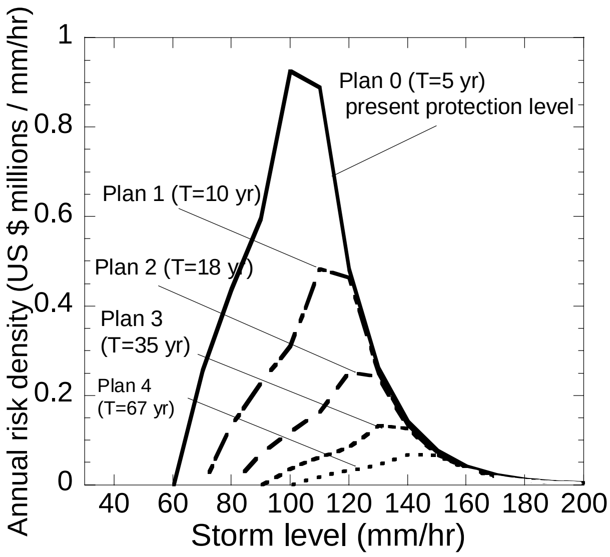

Fig.6 Annual risk density curves for several flood protection plans with different return periods.

If the higher level of flood protection of 70 mm/hr (Plan 1; 10-year return period) is adopted, the risk density becomes lower, as shown in Fig.6. The expected risk cost for a flood protection level of 70 mm/hr or 10-year return period, RC(70 mm/hr) or RC(10-year), can be computed as the integral from 70 mm/hr to 200 mm/hr for the 70 mm/hr risk density curve in Fig.6. Accordingly, the expected risk costs of 80 mm/hr (Plan 2), 90 mm/hr (Plan 3), and 100 mm/hr (Plan 4) are obtained.

4.4 Application of risk density curve to optimal flood protection level decision

4.4.1 Risk cost reduction curve

If the design flood protection level is r_d or return period T_d, the risk cost reduction with the higher flood protection, $RCR(T_d)$, is RC_{max} minus $RC(T_d)$ calculated as the integral of the risk density curves in Fig.6. The relationship between flood protection level T_d and risk cost reduction $RCR(T_d)$ is described as a risk const reduction curve (solid line) in Fig.7. In the figure, the flood protection level is expressed as a return period.

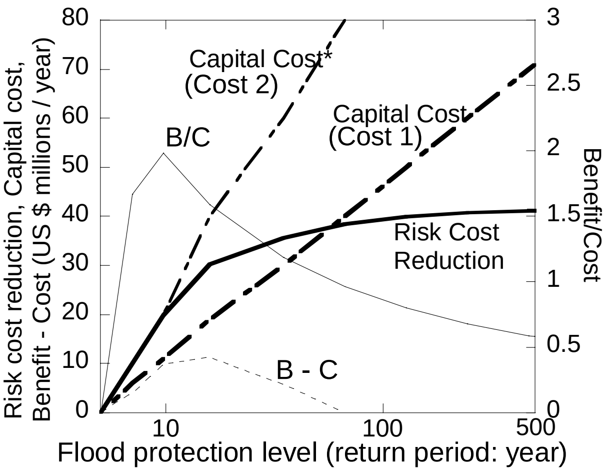

Fig.7 Risk cost reduction curve, capital cost curve, benefit/cost curve, and benefit – cost curve for optimal flood protection level decision.

4.4.2 Capital cost curve

If an infrastructure construction such as river improvement is undertaken to increase the safety for inundation, a corresponding capital cost is required for the flood protection. The capital cost curve is basically obtained based on flood protection infrastructure plans, Plan 1, Plan 2, Plan 3, and so forth. Unfortunately, the acquisition of the capital cost data is very difficult and thus the capital cost $CC(T_d)$ is, in this study, temporarily set by referring to the construction cost of the Kanda River underground flood control reservoir under Loop Road 7, as given in Fig.7 (Cost 1). The costs of a flood control infrastructure system vary according to many factors, but primarily related to flood protection level based on planned storm return period. The cost function has no linear relationship to return period (Heaney et al., 2002).

4.4.3 Optimal flood protection level

The optimal flood protection level can be determined by the two indexes: the maximum benefit-cost ratio B/C and the maximum difference B – C. Here, the benefit "B" refers to the expected annual risk cost reduction $RCR(T_d)$ and the cost "C" refers to the capital cost $CC(T_d)$. From the figure, the flood protection levels, 10-year return period and 15-year return period are supposed to be an optimal flood protection level using the index B/C and B – C, respectively. The two indexes have different meanings. The maximum B/C means the most effective performance of the capital cost. On the other hand, as shown in Fig.8, the maximum B – C (point A) means the minimum total cost of risk cost plus capital cost (point D).

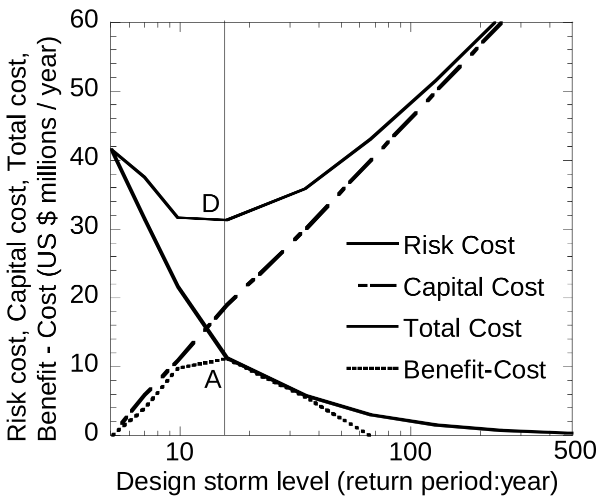

Fig.8 Optimal flood protection level using the index of Benefit – Cost. The maximum B – C means the lowest total cost.

In Fig.7, the other capital cost curve (Cost 2) does not intersect the risk cost reduction curve, which means that there are no effective flood protection infrastructure constructions to reduce the flood inundation risk. Any other measure such as risk finance should be introduced into flood risk management schemes.

5. CONCLUDING REMARKS

The objective of the present study was to present a decision support measure for flood protection level of flood control infrastructure. The important results are as follows:

(1) The framework of the risk analysis method is presented for decision-making process of flood protection level in flood control infrastructure planning.

(2) The useful curves were introduced for the risk analysis and the optimal flood protection level decision: Storm Probability Curve, Potential Damage Curve, Risk Density Curve, Risk Cost Reduction Curve, Capital Cost Curve, and Benefit-Cost Curve.

(3) Benefit-cost analysis was applied to optimal flood protection level decision by using the annual risk density curve. An example of the risk analysis applications is shown for the management of the Kanda River basin in the Tokyo Metropolis.

The combination of risk analysis and benefit-cost analysis will be a strong tool to support decision-making processes in flood control planning.

REFERENCES

Chow, V.T., Maidment, D.R, and Mays, L.W., 1988. *Applied Hydrology*, MacGraw-Hill, International Edition, New York, 466 p.

Davis, D. W., 2002. Risk analysis in flood damage reduction studies – The Corps Experience, *Proceedings of. EWRI* in CD-ROM, ASCE, Philadelphia, Pennsylvania, USA.

Field, B.C. and Field M.K., 2002. *Environmental Economics: An Introduction*, Third Edition, MacGraw-Hill/Irwin, New York.

Heaney, J.P. and Sample, D. and Wright, L., 2002. Costs of Urban Stormwater Control, USEPA Report EPA/600/R-02/021, Urban Watershed Management Branch, Edison, NJ, USA.

Institute of Public Works of the Construction Ministry, 1995. Estimation of damage rate for private and public properties based on actual damage investigation.

Kite, G.W., 1988. Risk: Frequency and risk analyses in Hydrology, Water Resources Publications, Highlands Ranch, Colorado, 235 p.

Morita, M and Yen, B.C., 2002. Modeling of conjunctive two-dimensional surface- three dimensional subsurface flows, *Journal of Hydraulic Engineering*, ASCE, **128**(2): 184-200.

Morita, M. and Yamashita, K., 2005. Decision Support System for Storm Design Level Based on Inundation Damage Simulation and Risk Analysis Using GIS, *Proceedings of 10th ICUD*, CD-ROM , Copenhagen, Denmark.

Morita, M., 2005. Flood risk analysis on storm design level decision for urban flood control, *Proceedings of International symposium on fluvial and coastal disasters*, Kyoto, Japan.

Plate, E. J., 2002. Flood risk and flood management, *Journal of Hydrology*, **267**, 2-11.

River Bureau of the Construction Ministry, 2000. The manual of economical research of flood control.