RISK ANALYSIS OF FLOOD CONTROL METHOD UTILIZING RAINFALL PREDICTION

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ABSTRACT

The more effective utilization of existing dams is a growing need in Japan behind decreasing numbers of newly constructed dams despite a steady increase of extreme floods. With using numerical climate model, rainfall prediction technology has progressed remarkably. By utilizing this development, effective flood control operation which differs from existing dam operation rules is conducted at some dam sites. This flood control measure takes into consideration for risks caused by errors of rainfall prediction, that is, it assumes the occurrences of floods due to the shortages of flood control volume or unfilled water use volume.

This study analyzes the errors of rainfall prediction by using Japan Meteorological Agency's MSM and GSM, the accuracy of which have been considerably improved in recent years. Namely, the volume of rainfall prediction is divided into basin areas and rainfall duration and then it is compared with the actual rainfall amount on the ground-based observations. Furthermore, we conduct simulations concerning Kizu River Dam Group on Yodogawa River System where effective flood control was implemented in the past by over-cut, with using these upper limit on the rainfall prediction and sensitivity analysis of the over-cut volume. And the dam operation adapted in practice is verified by estimating the amount of damages in the downstream river sections.

INTRODUCTION

The standard operating procedure for multipurpose dam in Japan was established as the operation methods became regulated under the Specified Multipurpose Dam Law enacted in 1957. According to the flood control method which has been in use on dams since then, the outflow discharge rate is primarily set as a function of the inflow rate. Specifically, if a flooding occurs in the case of a dam on a well maintained river, it will release the amount of water that the river downstream can carry, as shown in Figure 1, and will store the inflow that exceeds the river's capacity. A closer examination of the dam management records, however, proves that excessive floods and unforeseen sharp floods have often caused serious damages in downstream areas. These are conceivably

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the results of climate change and of the dam plannings that cannot withstand more than a few floods, and therefore flood control method has to be improved.

The improvement of numerical climate modeling in recent years has been remarkable, especially since the integration of satellite observation data which significantly improved its accuracy. This statement also applies to the rainfall prediction by Japan Meteorological Agency which since November 2009 has been operating numerical weather prediction models known as GSM (Global Spectral Model focusing on the whole earth) and MSM (Meso Scale Model focusing on Japan and its surrounding sea).

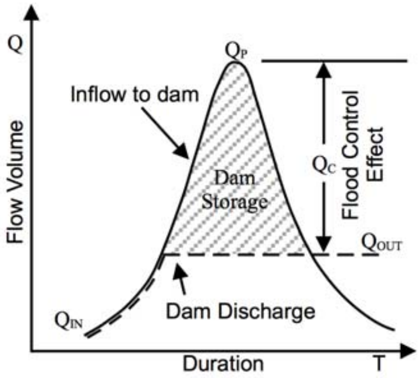

Figure 1. Example of Typical Dam Flood Control

If it is possible to forecast the flood hydrograph with high accuracy by the use of these rainfall prediction techniques, then, as Mitsuishi et al. (Mitsuishi, Sumi and Ozeki, 2010; 2011) proposed, it is also possible to proceed to the more practical flood control methods utilizing pre-emptive safe discharges or over-cuts (flood control measures exceeding the levels specified by the operating regulations). Rainfall prediction, however, is always accompanied by errors, and hence the flood control methods utilizing it are accompanied by the risk of errors. In other words, there could be a flood-control capacity shortage if rainfall exceeds the prediction, or an over-discharge of water if rainfall falls short of the prediction.

This paper focuses on and analyzes the rainfall prediction errors which needs to be apprehended by comparing the actual rainfall amount and the predicted amount provided by Japan Meteorological Agency's GSM & MSM forecast, under circumstances varying in region, in the zone size and in the cause of rain such as front, low pressure and so on and the study should play a key role in the optimum flood-control operations. Through statistical analysis, the maximum and minimum as well as the distribution of the rainfall measurement are estimated against the rainfall predictions to define the allowable prediction accuracy and then to investigate the dam risk-management in terms of the flood-control/water-use reliability. Furthermore, by referring to the case of over-cut conducted at Kizu River Dam Group, a simulation is performed to present optimum flood-control method.

ELUCIDATING RAINFALL PREDICTION ERROR

There have been several successful examples of the flood control exceeding the volume defined in the guidelines in recent years, during excessive floods and other large-scale floods at the dams managed by MLIT (Japanese Ministry of Land, Infrastructure, Transport and Tourism) or by Japan Water Agency. In these cases, while flood controls succeeded and inundations in downstream areas were prevented or at least minimized to a great extent, the decision-making process behind each case was not always scientific such as “there won't be more rain since typhoon had past and rain clouds are gone” and so forth but has the potential to be improved to ensure better risk management, regardless of the amount of rainfall. A better risk management must be reinforced by a rational and scientific analysis, and for now, in order to perfect the flood control method, it is urgent to elucidate the Japan Meteorological Agency's rainfall prediction errors, and determine the maximum and minimum possible rainfall amount.

Probability analysis on the rainfall prediction

This study uses the rainfall prediction data set which is based on Meteorological Agency's GSM and MSM, and is widely used by dam administrators in Japan from November 2008 onwards, to analyze the prediction errors by comparing the prediction and actual data of rainfall. Our analysis is based on the assumption that prediction error varies with location, zone size, cause of rain such as typhoon, weather front, low pressure and so on; in the same manner as the MLIT's Creager curve (defines the maximum possible flow rate according to the size of river basin) which divides the nation into 11 zones and calculates a separate coefficient for each zone. The subjects for this analysis are 3 dams, from zones of different climate and basin size, which carried out pre-emptive safe discharges or over-cuts in recent years: Tase Dam on Kitakami River, Kizu River Dam Group on Yodogawa River System and Sameura Dam on Yoshino River; representing Tohoku Region Pacific Coast, Central Kinki Region and Shikoku Region Pacific Coast respectively (see Figure 2).

Calculation mesh in numerical climate models generally is recommended to be kept below 1/5 of the horizontal scale of weather systems such as fronts and low pressure. Accordingly, this paper conducts analysis for fronts and low pressure systems separately, considering that the horizontal scale size as well as the prediction accuracy of GSM and MSM (which use 20 km and 5 km analytic meshes respectively) may all vary according to the cause of rain. Concerning the rainfall prediction error, the analysis tests the hypothesis that error varies according to the zone size, because the probability of error increases under heavy rain, or in other words, because the probability of spacial error tend to be larger (Yoshino, Iida and Yasuda, 2011). Since each MLIT's dam catchment area is as large as 50 to over 100 square km while the minimum mesh size in numerical climate models is 25 square km, mesh was joined together into regular squares for the analysis per 100, 400 and 900 square km. Furthermore, in the cases of over-cuts at Kizu River Dam Group and Tase Dam, those “over-cutting” were conducted at the end of rainfall. The prediction errors at the end of rainfall are presumably less than those at the start of rainfall, and this analysis treats them as 2 different types of errors. Here, “the end of rainfall” is set at the point where total predicted rainfall goes below 10 or 20 mm.

Analysis on the rainfall prediction error from the start of rainfall

Analysis method for the rainfall prediction errors. The grid mesh of a climate model as well as the locations of rainfall measurement sites for Kizu River Dam Group are shown on Figure 3.

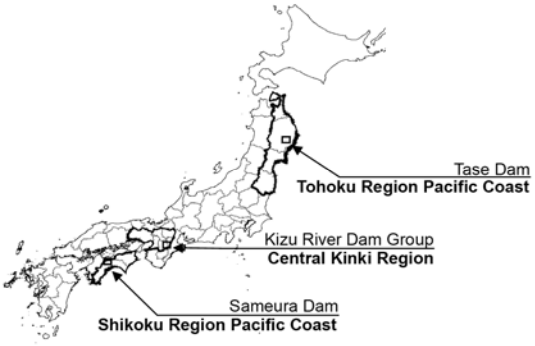

Figure 2. Regions for Analysis

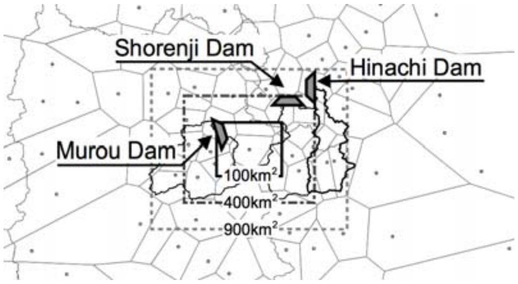

Figure 3. Thiessen Tessellation and the Meshes Different in Size (Kizu River Upper Region).

The average rainfall of each mesh was calculated from the rainfall measurements using Thiessen method, and for 51 cases after 2010, that is to say after the substantial improvement of the weather prediction by the advent of satellite-based observations, in which total rainfall measurement of more than 50 mm in 48 hours were recorded, rainfall volume ratio was calculated as follows:

$$\text{Rainfall volume ratio} = \text{Rainfall measurement} / \text{Predicted rainfall amount} \qquad (1)$$

Flood risk management is a fundamental issue in actual dam operation, and the data should logically be analyzed using probability and statistics. Hence here, frequency distribution of the rainfall volume ratio is approximated with the probability density function of the gamma distribution, against the rainfall measurements in 6, 12, 24, 33 and 48 hour time periods. When selecting function type, the lower limit of rainfall volume ratio was arranged to be zero, and the SLSC (Standard least-square criterion) value was arranged to be below approximately 0.04. Figure 4 shows a scattergram of various predicted rainfall amount and rainfall measurements in a dam basin. Figure 5 shows an example of probability density and probability density function. The formula for the probability density function is as follows:

$$f_x(x) = \frac{\nu(\nu x)^{k-1}}{\Gamma(k)} e^{-\nu x} \quad x \geq 0 \tag{2}$$

Here, $\Gamma(k) = \int_0^\infty x^{k-1} e^{-x} dx$, $k > 0$ $k > 0$, k and ν are calculated with the sample average μ and variance σ^2 as follows:

$$\mu = k / \nu \ , \ \sigma^2 = k / \nu^2 \tag{3}$$

When determining the specific flood-control volume, it is necessary to consider the risks of actual rainfall to be heavier or lighter than predicted. With these two risks in mind, the maximum and the minimum rainfall amount should be estimated against the predictions.

PL: Rainfall volume ratio, multiplied by pre-emptive discharge frequency, error within the water-use reliability factor.
PS: Rainfall volume ratio, multiplied by over-cut frequency, error within the flood-control reliability factor.

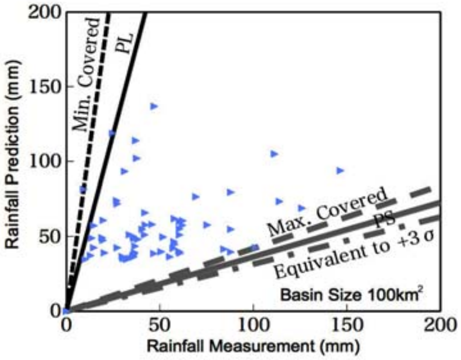

Figure 4. Scattergram of Predictions and Measurements (Kinki / Low Pressure / MSM / 33 hrs).

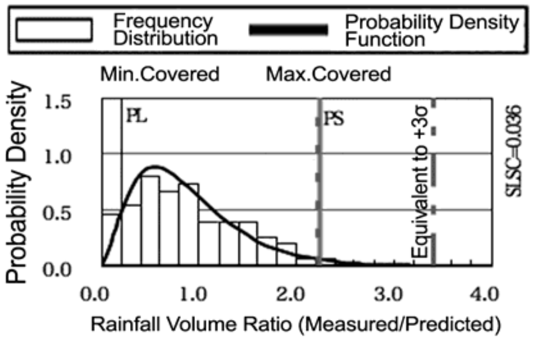

Figure 5. Probability Density Function of Rainfall Volume Ratio (Kinki / Low Pressure / MSM / 24 hrs).

1) Risk of rainfall being heavier than predicted. Over-cutting brings a risk of flood-control capacity shortage. Strict risk-management is required since the conduct could lead to loss of lives and properties in the downstream area. To encounter this error, maximum rainfall amount can be specified, as shown in Figure 5, according to the 3 possible cases listed below:

Case 1: Define the maximum value to include all rainfall measurements. An option to decrease the risk by including all false predictions found in records.

Case 2: Define +3σ (3 standard deviations) as the maximum value. An option to decrease the risk by applying the design criteria used in the field of aerospace engineering (Japan Aerospace Exploration Agency, 2010).

Case 3: Define the flood-control reliability factor of river as the maximum PS value. A task of keeping the multiplication of exceedance probability of probable maximum and over-cut frequency within the flood-control reliability factor as specified in the river project. Here, the over-cut frequency is calculated on the premise that over-cuttings were conducted during the floods in which the necessary flood storage was less than half of flood-control capacity.

2) Risk of rainfall being lighter than predicted. Pre-emptive discharge can bring a risk of water shortage after flood, if rainfall falls short of the prediction. To encounter this error, 2 cases are presented as follows:

Case 4: Define the minimum value to include all rainfall measurements. An option to decrease the risk by including all false predictions found in records.

Case 5: Define the water-use reliability factor of river as the minimum PL value. A task of keeping the the multiplication of exceedance probability of probable minimum and pre-emptive discharge frequency within the water-use reliability factor (1/10, as water shortage is expected to occur once in 10 years) as specified in the river project. Here, the pre-emptive discharge frequency is calculated on the premise that pre-emptive discharges were conducted during the floods in which the necessary flood storage was more than 0.8x of flood-control capacity.

Analysis on the rainfall prediction errors. The followings are the results of the analysis method presented in the next preceding subsection. Figure 6 uses the data from MSM rainfall predictions (MSM forecast for low pressure in Tohoku Region) on a rainfall duration axis to show the maximum and minimum values over Cases 1 to 5.

The flood control of Japanese dams, in general, attaches importance to the rainfall measurements at the 24 hour and the 33 hour time points after the beginning of rainfall. When looking at the error on the maximum value in Figure 6, Case 1 and 2 accompany magnification of 3x to 4x, and the $+3\sigma$ value being higher than the total inclusion of all rainfall measurements. The prediction accuracy is still unsatisfactory, as at present at Kizu River Dam Group, over-cuts are conducted by a method which multiplies the predicted maximum value with 1.5x (i.e. expecting rainfall to be 1.5 times heavier than predicted) to encounter the risk of flood-control capacity shortage. The PS value in Case 3 is about 2x. The error on the minimum value, on the other hand, is as insignificant as about 0.2 in Case 4, while the PL value (equivalent to water-use reliability factor) in Case 5 is about 0.5. Although these risk management methods need to be further investigated by analyzing each dam's rainfall prediction errors, Case 2 and 4 which emphasize flood-control/water-use reliability factor may suit the case of low pressure-induced rainfall at Tase Dam. Yet, all dam administrators who may exceed the regulation should be aware of the risks caused by prediction error, especially the risk of flood-control capacity shortage, or in other words, rainfall of maximum intensity. Hereafter the analysis is focused on the PS value of Case 3.

Figure 7 compares the GSM and MSM prediction errors in low pressure-induced rainfall. Of the two weather prediction models, MSM generally has lower magnification (i.e. higher accuracy) in all 3 regions, especially in Shikoku. GSM can serve this purpose as well since fronts and low pressure has horizontal scales as large as 200 to 2000 km, but the downscaling seems to have increased the MSM's accuracy to some extent. Hereafter the analysis is focused on MSM.

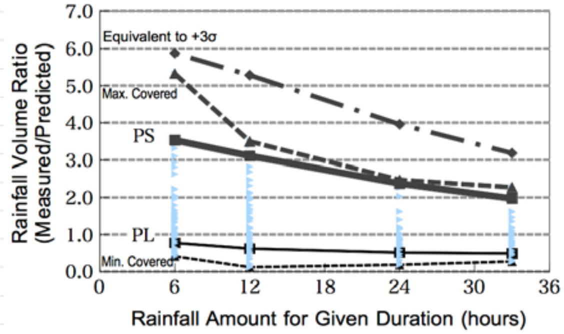

Figure 6. Error in Max and Min Values, Rainfall Volume Ratio and Duration

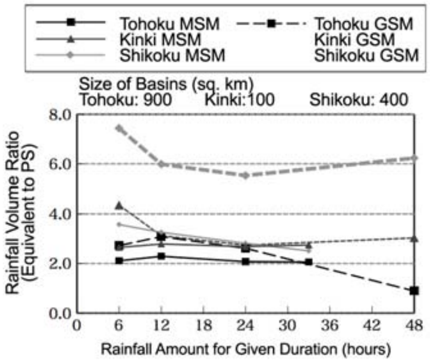

Figure 7. Rainfall Volume Ratio (PS) by Prediction Model

Figure 8 shows the rainfall volume ratio in low pressure-induced rainfall. Note that accuracy is slightly higher in larger regions. This is presumably because, as Yoshino et al. (2011) observed, the larger the target area, the smoother the spatial prediction errors. Figure 9 compares the prediction accuracies by the cause of rainfall, i.e., front and for low pressure system. It is obvious that low pressure-induced rain has lower rainfall volume ratio, hence higher prediction accuracy. Although this requires further analysis of more data, the values at 24 and 33 hour time periods in MSM forecast data of the rainfall induced by low pressure are relatively reliable having accuracies as high as 2.0x to 2.8x. Note that, as for the duration of front induced rain, the longer the duration, the less the rainfall volume ratio.

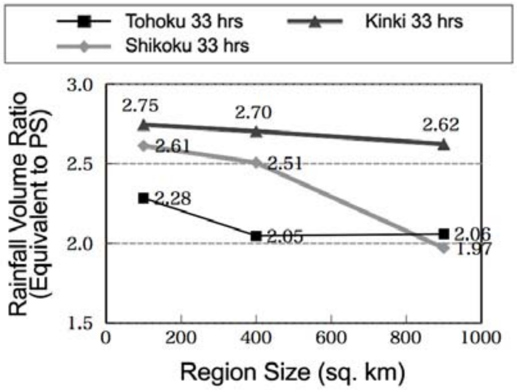

Figure 8. Rainfall Volume Ratio (PS) by Region Size

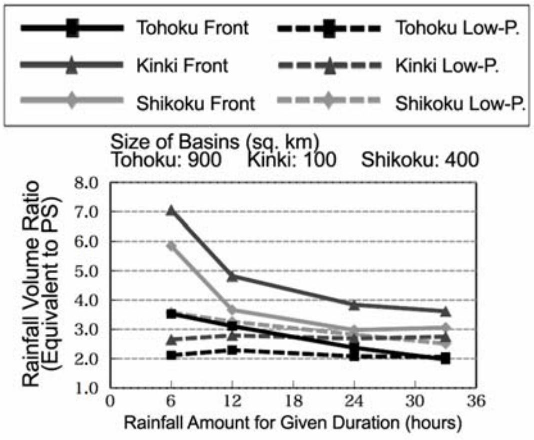

Figure 9. Rainfall Volume Ratio (PS) by the Cause of Rain

Analysis on the rainfall prediction error at the end of rainfall

An analysis similar to that of the next preceding section is performed here on the rainfall prediction at the end of rainfall. At Kizu River Dam Group and Tase Dam, over-cuts were conducted when there seems to be no chance of more heavy rain, under the sky with no rain clouds in sight, such as after a typhoon. This method, although does not always guarantee the desired result at the flood peak, seems to be reasonable since it is expected to demonstrate high level of rainfall prediction accuracy, make good use of the flood-control capacity and, to some extent, lower the river level. Here, rainfall amount differences were used instead of rainfall volume ratio, because the predicted rainfall amount is too low at the end of rainfall.

Rainfall amount differences = Rainfall measurement - Predicted rainfall amount (4)

Figure 10 shows the predicted rainfall amount and rainfall measurement of a low pressure-induced rainfall in Central Kinki Region. Deviations from the 45 degree line indicate rainfall amount differences. As a result, rainfall amount differences for PS are found to be less than 15 mm, and considering that the flood-control capacity of MLIT's dams are equivalent to about 100 mm rainfall in dam basins, the accuracy is satisfactory.

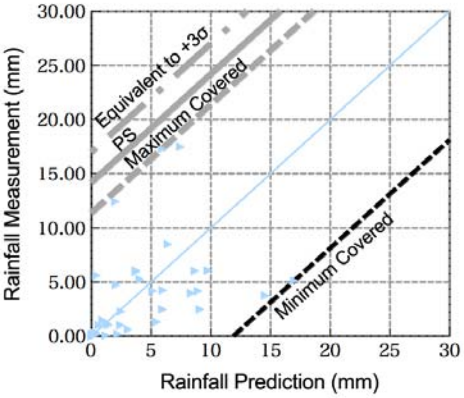

Figure 10. Scattergram of Predictions and Measurements at the End of Rainfall

SIMULATION OF A REASONABLE FLOOD CONTROL METHOD

To conduct an over-cut, one must figure out a method to determine specific flood-control volume while considering the risk of rainfall prediction. This section introduces a method to determine the appropriate flood-control volume, by using actual flood control conducted at Kizu River Dam Group as case example. For this purpose, rainfall prediction error is rendered as rainfall volume ratio, over-cut volume ΔQ is defined as 50 m^3/s rate, and water level of the flood inflow to the dam is defined as initial water level, to generate hydrographic curves including the 1.0x case as shown on the Figure 11.

Here, considering that the size of each MLIT's dam catchment area is 100 square km, the probability density function of rainfall volume ratio is presumed to conform to the error distribution of MSM 33 hours forecast data for an 100 square km section (typhoon rainfall within Central Kinki Region). Note that, in the case when the value of ΔQ is small, the river water level at the low-flow section in the downstream Nabari city will reach the estimated maximum level and the said area may eventually suffer flood damage. And if, on the other hand, the value of ΔQ increases, then, although the river water level will inversely decrease, the dam may suffer flood-control capacity shortage during the final stage of the flood.

Following the idea described above and using available rainfall prediction data, we have calculated the estimated damage for the over-cut volume ΔQ. This was done by estimating the flow rate on the populated Ieno district in Nabari city for each rainfall amount, on the assumption that flood-control will be conducted by discharging a certain amount of water via ΔQ over-cut, and then by referring to the research on the relevance between flow rates and inundation damage costs. The damage costs were calculated by multiplying the costs in each case by the probability of rainfall prediction error, and then added to their total costs. The ΔQ which causes the least damage is obviously the optimal option.

To prove the validity of this method, analysis was performed on the assumption that it was possible to predict the inflow hydrograph, by defining the value of ΔQ for every 50 m^3/s from 0 m^3/s to 450 m^3/s. The result demonstrates that the optimal value is 150 m^3/s, as shown on the Figure 12, and any other value will increase the inundation damage cost. The 150 m^3/s over-cutting actually is used in flood-controls, and this simulation proved the flood-control operations at Kizu River Dam Group to be statistically valid. Similar simulations should be done on other cases to further examine its validity and, furthermore, should be implemented at dam control centers to enable operators with or without experience to perform optimum flood-controls.

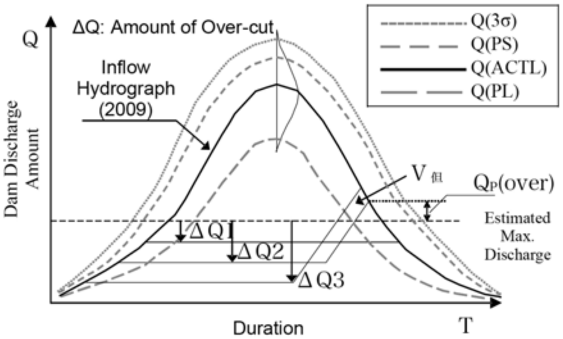

Figure 11. Over-cut Operation Diagram

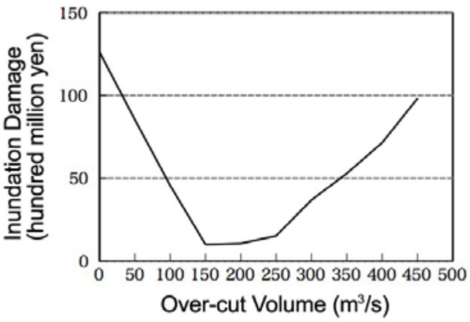

Figure 12. Over-cutting and Inundation Damage

CONCLUSION

This study has compared, through statistical analysis, the predicted rainfall amounts and actual rainfall measurements under various conditions, such as different in rainfall duration, time of prediction, zone size and the cause of rain, which were collected in 3 domestic regions to determine the nature of prediction errors, for the benefit of the flood-control operations using Japan Meteorological Agency's GSM & MSM forecast. Moreover, 5 methods of risk-management were presented through the employment of theory in other fields, and by carrying out further analysis, the maximum and the minimum rainfall amount were estimated against the predictions to define the allowable prediction accuracy.

Although the prediction accuracy must be improved through the collection of more data on rainfall, mainly typhoon rainfall, this study discovered the following:

1) Rainfall prediction accuracy can be demonstrated by the probability density function of the gamma distribution. The comparison with actual rainfall measurement proved that MSM's prediction accuracy, which has been increased by downscaling, is superior to GSM's, and that the longer the rainfall duration, or the larger the basin size, the smaller the rainfall volume ratio. In terms of the cause of rain, low pressure-induced rainfall tends to bring higher prediction accuracy than frontal rainfall.

2) As for risk-management of rainfall prediction error, this study presented 3 methods, one is to define the maximum value to include all rainfall measurements, one is to define $+3\sigma$ as the maximum value, and the other one is to define the flood-control reliability factor and water-use reliability factor as maximum (PS) and minimum (PL). The analysis on the data of 3 regions proved that the method employing PS has an accuracy high enough for the dam operations.

3) The flood-control volume of over-cut may be determined by the method of integrating the inundation damage cost into the probability density function of rainfall prediction error. The method proved the flood-control operations at Kizu River Dam Group in November 2009 to be valid. After undergoing examinations during floods, this method is expected to be applied for optimum flood-controls.

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