FLOOD RISK FORMULATION ON LOW-LYING PADDY REGIONS AS AN IMPACT ASSESSMENT TOOL FOR EXTREMES

Hiroki Minakawa¹ and Takao Masumoto¹

ABSTRACT

This paper discusses a flood risk assessment procedure applied to low-lying paddy areas using risk curves to show the relationship between flood damage and heavy rainfall scales. The damage in paddies denotes the amount of rice yield reduction, and damage estimation entailed three steps. First, a drainage analysis model that enabled us to reproduce the inundation process in low-lying paddy areas. Next, a rainfall pattern generator, which requires daily and hourly observed rainfall data. Finally, the scale of rice yield reduction was investigated through pseudo-flooding experiments with rice plants. Those scales provide the relationship between duration of inundation and the reduction of rice yields. These three components were combined to formulate risk curves. A low-lying paddy area, the Kaga three-lagoon basin in Ishikawa Prefecture, was chosen as an experimental target. Based on drainage analyses, the water depth and inundation period in the paddies were extracted, and reduction scales were used to estimate the yield reduction ratio of each paddy. Damage in paddies was calculated by multiplying the reduction ratio and normal yields in the area, and these results were employed as fundamental data in the risk assessment. As a result, we formulated risk curves for the relationship between the probability of rainfall amount and the damage in the region at present and in the future. The shift between these two curves was defined as the change in the risks in the region due in part to climate change. Sustainable countermeasures for flood prevention would rely on schemes and strategies based on this assessment method.

Keywords: Regional flood risk, Yield reduction of rice, Inundation on low-lying paddies, Impact of climate change.

1. INTRODUCTION

Due to climate change, the intensity and frequency of rainfall are to increase in many regions (Minakawa and Masumoto, 2010). Intense rainfall often triggers flooding. According to data compiled by the Ministry of Agriculture, Forestry and Fisheries (MAFF), there are about 2.5 million ha of paddy fields in Japan, much of which is in low-elevation areas and vulnerable to flooding. Although rice plants can tolerate submergence, rice yield decreases with long-term or extreme inundation. In fact, flooding damage accounts for a large percentage of the rice yield reduction observed in Japan, and MAFF statistics indicate that the annual damage amounts to billions of yen (tens of millions of U.S. dollars). However, drainage plans for low-lying paddy areas have not been revised for decades, and changes in rainfall patterns associated with climate change are not reflected in the current guidelines. Measures such as increasing drainage capacity are urgently needed to minimize the damage caused by more frequent flooding. On the other hand, paddy fields also provide an important water storage function and can retain part of any flood. This function can mitigate or prevent flood damage in downstream regions, and it might therefore be an important countermeasure against more frequent flooding in residential and urban areas. To support this function, it is necessary to gain a better understanding of the potential

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flooding by means of flood analysis, because rice plants are cultivated in these paddies and must be protected as well.

In this paper, we describe a quantitative method for evaluating the relationship between the risk of flood damage in rice paddies and heavy rainfall events. We used three components—a diurnal rainfall pattern generator, a flood analysis model, and a scale of rice yield reduction—to assess the effects of prolonged rainfall on flood risks in low-lying paddies. These quantitative flood risk assessments will help farmers and land managers to develop protective measures against the impacts of climate change.

2. STUDY AREA

The Kaga three-lagoon basin in Ishikawa Prefecture includes low-lying paddy areas that are vulnerable to flooding due to increase in rainfall frequency and intensity (Figure 1). The basin catchment is 250 km², and it is divided into upland areas (mostly forested) and flooded areas (in the downstream). The lower parts of the basin are covered by paddy areas and by two lagoons (Shibayama and Kiba). In this basin, the drainage system is topographically divided into two networks: one passes through the Shibayama Lagoon and the other passes through the Kiba Lagoon. Low-lying paddy fields cover 2,600 ha in the Shibayama network and 1,350 ha in the Kiba network. Both networks have drainage rivers that flow from the upland area in the south into the low-lying areas in the north: the Youkaichi River (catchment area 5.0 km²) and the Iburihashi River (88.9 km²) in the Shibayama network, and the Hiyou River (12.0 km²) in the Kiba network.

3. RAINFALL DATA COLLECTION AND HANDLING

3.1 Observed rainfall data

Long-term rainfall data from the Kanazawa Meteorological Observatory (near but outside of the study basin) were analyzed (Minakawa and Masumoto, 2010). The data spanned 69 years (from January 1940 through December 2008) and were used for stochastic analysis. From the daily data, a maximum 3-day rainfall event in each year was extracted, and 10 patterns with different return periods (2-, 3-, 5-, 8-, 10-, 15-, 30-, 50-, 100-, and 200-year rainfalls) were derived with a Gumbel distribution. These results were used as input rainfall amounts for the flood analysis. The hourly data were used to clarify characteristics of rainfall intensity and frequency in the region. Results of the rainfall analysis were employed in a rainfall generation method, as described in the following sections.

![Figure 1. Map of the study area](image-url)
3.2 Data predicted by global climate models

We collected future rainfall data, as predicted by the global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Features of collected data are shown in Table 1. GCMs with high spatial resolution were chosen, because reproducibility of regional climate phenomena, such as heavy rainfall events and tropical typhoons, arises from the spatial resolution of the model. The spatial resolution of collected GCMs was ranged approximately 120 km to 200 km (as shown in the third column in Table 1). Before using the data, these were downscaled to a 5-km resolution with the interpolation method described by Kudo et al. (2016), and the data around the study area were clipped.

All models have daily rainfall data in the historical (1970–2005) and projected period (2016–2100). Moreover, there are three types of data series according to the Representative Concentration Pathways (RCP) scenario employed, namely RCP2.6, 4.5, and 8.5, in the projected period (Van Vuuren et al., 2011). Typically, the prediction data by the climate model includes variations in the results arising from the initial value of calculation, so, ensemble run members in historical and future projection were collected (Table 1). Therefore 15 kinds of data in historical period and 11 kinds of climate projection data were available for climate change projections under each RCP scenario.

Calculation of the probabilistic 3-day rainfall events was performed with data from each GCM, as with the observed data. Here, annual maximum 3-day rainfall events extracted from 1981 to 2000 and from 2081 to 2100 were used to calculate the rainfall amounts for the present and future periods, respectively. Finally, we identified changes in rainfall intensity due to climate change by comparing the results of the present and future periods.

<table>
<thead>
<tr>
<th>Name of GCM</th>
<th>Development country</th>
<th>Data resolution (degrees)</th>
<th>Number of data</th>
<th>Extracted range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSIRO-Mk3-6-0</td>
<td>Australia</td>
<td>1.875x1.875</td>
<td>3</td>
<td>136.31°E - 136.56°E</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>The United Kingdom</td>
<td>1.875x1.241</td>
<td>3</td>
<td>36.13°N - 36.42°N</td>
</tr>
<tr>
<td>MIROC5</td>
<td>Japan</td>
<td>1.406x1.406</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>Japan</td>
<td>1.125x1.125</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

4. DEVELOPMENT OF COMPONENTS FOR FLOOD RISK ANALYSIS

We developed a tool for flood risk assessment that consists of three components. In this section, we describe the development of the components and use of the assessment tool.

4.1 Development of a diurnal rainfall pattern generator

Heavy rainfall events that cause flood disasters are low-frequency events, and many meteorological stations have been collecting rainfall data for periods that are too short to provide detailed information on extreme events. In addition, even if enough samples can be obtained at a daily resolution, data with hourly (or shorter) resolution are rarely available. To provide the data required for planning, rainfall simulations (e.g., Woolhiser and Osborn, 1985; Hershienord and Woolhiser, 1987) can be used to generate many patterns of rainfall data. The generated data, which reflect both the amount and temporal pattern of the observed rainfall, are useful input data for various studies, including flood analysis. Thus, we proposed a rainfall simulation method (the
“diurnal rainfall pattern generator”) that can generate short-time-step patterns of the amount and temporal pattern of rainfall (Minakawa et al., 2014a; Minakawa and Masumoto, 2015). We applied the generator to long-term rainfall data observed at the Kanazawa Meteorological Observatory. Parameters for the generation were defined from the observed data, and the generated data were verified by comparison with the observed data. The results produced by the generator reproduced the observed statistical characteristics of heavy rainfall in the study area, and thus can be used to estimate the risk of flooding for a given rainfall pattern.

The generator is based on the Markov-chain Monte Carlo method, and it can perform any one or all four of the following calculations. In calculation 1, the generator describes the monthly event frequency using a Poisson distribution. In calculation 2, it generates the total rainfall for each daily event using a gamma distribution based on historical rainfall data for the study area. In calculation 3, the generator disaggregates the daily total rainfall into hourly data using a beta distribution. In calculation 4, it rearranges the disaggregated data series by correcting for autocorrelation. Because these four calculations are independent, we used only calculations 3 and 4 (disaggregation and rearrangement) to generate the input rainfall data, as described later in this paper.

4.2 Setup of the flood analysis model

In Japan, the land in low-lying areas is mainly used for paddy fields. To analyze the flood characteristics of low-lying areas, such as the storage effect of the paddy fields, it is necessary to develop a model that can manage water movement between the channels and the paddy fields. Therefore, we developed a flood analysis model consisting of a kinematic wave runoff model, which was applied to the uplands, and a drainage analysis model, which was applied to the flooded low-lying areas.

For the drainage model, we chose a diffusive tank model (Hayase and Kadoya, 1993), which is a simplified runoff and drainage model, for analyzing channel flow and flooding in paddies (Minakawa and Masumoto, 2013a). The model was constructed by connecting the channels with the paddies (here, represented as “channel tanks” and “paddy tanks”, respectively), the paddy and channel tanks were connected by weirs, and the flows between them were expressed as non-uniform flows. Because it is a distributed model, we can estimate the water level and discharge for every channel and paddy tank. Here, discharges from the uplands calculated by the kinematic model were used for the upper boundary conditions for discharge. Moreover, drainage pump stations and floodgates were included in each network. In the model, they were automatically switched to ON/OFF or OPEN/CLOSED in accordance with each operational rule as part of a system of controlling water levels.

The model was applied to the study area, and was verified by using a heavy rainfall event (about 300 mm) that occurred from 16 to 19 July 2006. We compared the observed hydrographs with the calculated hydrographs for water levels in the Shibayama and Kiba Lagoons. Both of the calculated results were consistent with the hydrographic observations (Minakawa and Masumoto, 2013).

4.3 Formulation of an assessment tool of flood risk

4.3.1 Design of reduction scales of rice yields

The degree of flooding damage to rice plants depends on various aspects of the flooding conditions and the flooding duration, making it difficult to accurately estimate the damage. We attempted to formulate damage scales based on rice yields that account for the relationship between flooding conditions and rice yield (Minakawa et
al., 2014b). The scales were developed through a pseudo-flooding experiment under real inundation conditions in a rice paddy and a yield survey. We conducted the experiment from 2012 to 2014 to collect fundamental data on the effects of flooding conditions (i.e., timing of flooding, submergence duration, water depth, water turbidity) on the damage ratio of rice yields. Details of the experimental methodology were described by Minakawa et al. (2013) and Minakawa et al. (2014b).

Figure 2 illustrates the scales formulated by using 3 years of the experimental data (Minakawa et al., under review). The japonica rice cultivar ‘Koshihikari’, which accounts for about 36–38% of total rice acreage in Japan, was used. The scales were formulated based on the results of the yield survey, in particular the normal grain weight, which incorporates decreases in both weight and quality of brown rice. The reduction ratio was estimated by comparing the value with the standard value from the control plot. Finally, data were arranged according to the developmental stage to create the scales. The reduction ratio in the scales was clearly related to the flooding condition, especially the growth stage and submergence duration.

4.3.2 Structure of the flood risk assessment tool

Three components form the tool for assessing flood risk in low-lying areas. Here we describe the methodology by which the components are used.

The flood risks vary greatly depending on the hyetograph pattern for the input rainfall amount at hourly or shorter intervals. Therefore, it is important to first describe the patterns of heavy rainfall in any flood risk assessment. Although the rainfall generator can provide many pattern data sets as input for the assessment, we only used calculations 3 and 4 (disaggregation of daily rainfall and rearrangement of the internal pattern of the hyetograph) to generate the input rainfall data. Any value for the total rainfall amount (daily) and generation number can be set. In this case, the target rainfall amounts input into the generator were the 3-day rainfall probability calculated from the observed data (here, 10 patterns with different return periods reported in section 3.1).

![Graph showing reduction scales in rice yields focusing on flood damage](image-url)
Second, calculations by the flood model are performed with all generated rainfall. Next, the time series of inundated water depth in each paddy tank is examined from output of the model. The criteria for allowable inundation (i.e., paddy inundation >0.3 m for less than 24 h) are occasionally included in regional drainage planning in Japan. Basically, the paddies that meet these criteria are assumed to be undamaged, and data for paddies inundated for longer than the allowable limit (24 h) are all extracted to estimate the reduction in rice yield caused by flooding in the paddy. The number of hours in which the water level exceeded this depth is calculated and that value is used to represent the flooding duration.

Finally, the reduction ratio is estimated from the reduction scales. First, we have to determine the growth stage of rice to select the appropriate scale shown in Figure 2. The stage is identified based on the timing of occurrence of flooding (i.e., the tillering stage extends from June to mid-July, the booting and heading stages occur from mid-July to late August, and then the maturing stage begins). Especially during the booting and heading growth stage, yield eduction ratios under incomplete and complete submergence were recorded separately by using the scales, according to the relationship with submergence duration. In some cases, a paddy had both submergence situations. After the booting stage, the plant height of 'Koshihikari' is about 0.9 m, so when the water depth exceeded 0.9 m, the situation is defined as complete submergence. If the water depth is between 0.6 and 0.9 m, then the top of the rice will be above the water surface and this is defined as incomplete submergence. The durations of both conditions are counted in each paddy, respectively, and used to estimate the reduction ratio from the scales. A total reduction ratio was calculated to aggregate each reduction ratio, by using eq. (1):

\[ R = \left( r_i + (100 - r_i) r_c \right) / 100 \]  

(1)

where \( R \) is the total yield-reduction ratio on a target paddy, and \( r_i \) and \( r_c \) are the reduction ratios (%) under incomplete and complete submergence, respectively. The decrease in rice yield in the basin was calculated by using eq. (2):

\[ D = Y \cdot \sum (R_j \cdot A_j) \]  

(2)

where \( D \) is damage to a paddy in the basin (i.e., loss of rice yield, tons); \( Y \) is the normal rice yield per unit area in the basin (according to MAFF data, the nationwide normal yield in Japan is 5,300 kg/ha); \( R_j \) is reduction ratio in paddy tank \( j \) determined by eq. (1); \( A_j \) is the area of paddy \( j \) (ha); and \( j \) is the number of paddy blocks in the flood model. We prepared a variety of rainfall data patterns for the analysis, and then the expected value of the damage with a target rainfall was evaluated (Eq. 3):

\[ E[D] = \frac{\sum D}{P} \]  

(3)

where \( E[D] \) is the statistical expectation of damage with a target rainfall amount (tons) and \( P (=1,2,3,\ldots n) \) is the generation number of rainfall pattern input into the flood model. The assessment tool was used with all target rainfalls repeatedly to explain the characteristics of flood damage on the basin.
5. RESULTS AND DISCUSSION

5.1 Variation in intensity of extreme events due to climate change

The impact of climate change on extreme rainfall events was assessed from the data based on 11 climate projections in each RCP scenario. Figure 3 shows a comparison of the probability of 3-day rainfall events for the present and future periods, resulting from each RCP scenario of the GCMs. Compared to the present trend, the change in extreme rainfall was greatest for RCP8.5. In addition, the results were affected by uncertainties in the climate projection, even within the same scenario. As a result, the ratio increase in the future probability of extreme rainfall events ranged from 0.9 to 1.4 for RCP2.6, from 1.0 to 1.6 for RCP4.5, and from 1.1 to 1.7 for RCP 8.5 compared with the present period.

Generally, any GCM has inherent bias between the generated and observed data, and several methods for bias correction have been proposed (e.g., Ines and Hansen, 2006; Kudo et al., 2014). In this study, we employed an easy method for bias correction focused on the use of a probabilistic rainfall amount between the observed rainfall and that generated by a GCM. The fold increase of the rainfall amount in each return period was used as an index for correction coefficients of the GCM bias. The probabilistic 3-day future rainfall amounts were estimated by multiplying the correction coefficients by observed data for every return period. Assessment of the impact of climate change on this low-lying paddy region was conducted based on the bias-corrected rainfall amounts.

5.2 Flood damage estimation in the basin

We created the input rainfall data using the diurnal rainfall pattern generator, with a rainfall duration fixed at 3 days and the total rainfall fixed at an arbitrary amount by using a probability distribution based on historical rainfall data for the study area (Minakawa and Masumoto, 2015). Here, we derived the 3-day rainfall amount for 10
return periods, ranging from 2 to 200 years. Each rainfall amount was input as the total rainfall for the generator. The disaggregation of rainfall into an hourly series was repeated 300 times for each rainfall event, so that a given total rainfall amount had a range of different temporal patterns. The generated data were all used as inputs for the flood analysis model, thereby providing 300 flood patterns for each rainfall amount.

Our simulations suggest that the time series in the hydrographs depended on the rainfall patterns and therefore resembled the water level trends in the channels. Figure 4 illustrates an example of the distribution of peak water depths in paddies for a single rainfall pattern with a 10-year return period. The paddies that are vulnerable to flooding during heavy rainfall are easily visible. Our analysis also revealed that the flooding duration varied widely from maximum to minimum as a function of rainfall amount based on the results of 300 simulations. Figure 5 compares the frequency distributions of evaluated paddy damage in the Shibayama network for rainfall with 30- and 100-year return periods. The average damage was estimated as 48.0 t for a 30-year rainfall and about 252.2 t for a 100-year rainfall. In addition, the results had a large variability arising from changes in the temporal pattern of rainfall, even if the total amounts were the same. The results indicated that this uncertainty would increase with total rainfall amount. Thus, extreme events, such as a rainfall larger than that with a 100-year return period, may trigger an unexpectedly huge flood.

![Figure 4. Distribution of peak water depth in the paddy fields (example based on simulation results for rainfall with a 10-year return period)](image)

5.3 Evaluation of increment on flood risk in future climate

Based on the estimated damage from each probabilistic rainfall amount, the relation between rainfall amount and average damage in the two basins were calculated by using eq. (4):

\[ D(X_T) = \exp(a \cdot X_T + b) \]  \hspace{1cm} (4)

Where, \( D(X_T) \) is the average rice yield reduction with rainfall \( X_T \) in the basin (tons); \( X_T \) is the rainfall amount with a \( T \)-year return period (mm/3 days); and \( a \) and \( b \) are parameters determined in each basin depending on the growth stage of rice. The estimated parameters at each growth stage are listed in Table 2, and the contributing
rate of these equations fell within 0.983–0.996. The results calculated using eq. (4) showed a strong correlation with the results of damage estimation.

![Graph showing frequency distribution of damage](image)

**Figure 5.** Frequency distribution of damage to paddies in the Shibayama network

**Table 2.** Fitting parameter for eq. (4) and correlation coefficient in each growth stage of rice plants

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Kaga three-lagoon basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Tillering stage</td>
<td>5.340E-03</td>
</tr>
<tr>
<td>Booting stage</td>
<td>6.981E-03</td>
</tr>
<tr>
<td>Maturing stage</td>
<td>6.753E-03</td>
</tr>
</tbody>
</table>

Furthermore, the flood damage caused by future rainfall events was evaluated by using eq. (4). Here, bias-corrected rainfall data, which were estimated by multiplying a 3-day rainfall amount in the present period by an index of climate change in the future with the same return period, were used to assess the future risk curve. Finally, the risk curves in present and future periods were formulated. Figure 6 shows an example of the target basin in the RCP4.5 scenario at the booting stage of rice. In the graph, the vertical axis is occurrence probability of the event \((=1/T)\), and the horizontal axis shows total damage in the basin. The uncertainty of present and future projections is shown as the shaded regions. In addition, the amount of damage can also be assessed in terms of economic losses by considering the purchase price of rice. For example, recent value of the transaction price of a 60-kg bag of rice was about 13,000 yen on the basis of the price of ‘Koshihikari’ grown in Ishikawa Prefecture in 2015 (from MAFF data).
In this study, we built on our previous research to formulate the tool for damage assessment in the basin for predicting the risk of flooding in low-lying paddy areas, with the goal of supporting planning to mitigate the effects of climate change. Our results showed that the frequency of extreme rainfall events will increase in the future. However, the degree of increment depended on the type of GCM and the scenarios employed. According to our results, the flood damage in paddies would depend both on the amount and the temporal pattern of rainfall. The risk curves for the present and future periods are a useful tool for predicting and mitigating the effects of future flooding. The results might serve as fundamental data for the revision of drainage planning in low-lying paddy regions, such as reconsidering the rainfall amount for design standards of drainage pump capacity, as well as the strengthening of pumping capacity.

Because climate change will have other effects on the Kaga three-lagoon basin’s water resources, it will be necessary to perform a more holistic evaluation of the impacts of climate change on agricultural water use. Extreme events such as flooding and drought strongly affect agricultural water use in monsoon Asia, as has been shown in Thailand (Vongphet et al., 2014). Coupling of an analytical model for agricultural water use with a flooding model has been done to develop a model that can calculate the effects of flooding and drought simultaneously (Vongphet et al., 2015). The methodology described here is useful for estimating damage to paddy fields spread across a large basin, although some problems, such as the accuracy of the scales, remain to be clarified. It can also be applied to risk assessment of climate change in low-lying areas or used for planning countermeasures against more frequent floods due to heavy rainfall in the future. In particular, active use of the water storage function of paddies is one way to reduce the damage to urban areas during flooding. It is therefore also necessary to assess the potential damage to paddies so that cost-benefit analyses can be performed for this proposed countermeasure. For more accurate estimation, future studies should be conducted to modify the drainage analysis model to better reproduce the flood conditions in paddies and to validate the results by using data based on real flooding damage.
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