CHANGES IN INTENSITY OF HEAVY RAINFALL AND ITS IMPACT ON DRAINAGE SYSTEMS

VARIATIONS DANS L'INTENSITE DES FORTES PLUIES ET LEUR IMPACT SUR LES SYSTEMES DE DRAINAGE

Minakawa Hiroki[1] and Masumoto Takao[2]

ABSTRACT

A study was done to detect changes in heavy rainfall patterns and evaluate their impacts on paddy inundation in the Kaga three-lagoon basin in Ishikawa Prefecture, Japan.

First, heavy rainfall events (>70 mm/day or 100 mm/3-days) were extracted from 1940 – 2008 rainfall data observed near the study area. The trends in hourly rainfall in those events were analyzed. The average maximum 6-, 12-, 24-, and 48-h rainfalls in those events increased by about 4% to 9% from the past to the present. In addition, the magnitude of maximum 6-hour rainfall amounts also changed to the large side.

Next, rainfall data predicted by MIROC were examined. The results implied that monthly rainfall amount would increase with time. Additionally, the correction of bias between the observed and MIROC-generated rainfall data showed that the amount of rain in 3-day rainfall events with a 10-year return period would reach a peak of 1.23 times the present amount in the near future (an increase of about 50 mm).

Simultaneously, for the drainage analysis a model was developed consisting of kinematic and diffusive tank models for upland and inundated areas. By using these models, rainfall predicted by MIROC was used to assess the impact of climate change on drainage systems. As a result, the duration of inundation of paddies to more than 30 cm depth was estimated to increase in the future. Countermeasures, such as the improvement of pumping capacity, are suggested.

Key words: *Rainfall intensity, Drainage system, Kinematic model, Pumping capacity, Paddy inundation.*

1 Researcher, National Institute for Rural Engineering, National Agriculture and Food Research Organization, 2-1-6 Kannondai, Tsukuba, Ibaraki 305-8609 Japan; E-mail: hmina@affrc.go.jp
2 Team Leader, National Institute for Rural Engineering, National Agriculture and Food Research Organization, 2-1-6 Kannondai, Tsukuba, Ibaraki 305-8609 Japan; E-mail: masumoto@affrc.go.jp

RESUME ET CONCLUSIONS

Le réchauffement de la planète attribué aux changements climatiques laisse présager une augmentation de la fréquence de récurrence et de l'ampleur des fortes pluies dans de nombreuses régions du Japon. Il est par conséquent possible que les risques d'inondation augmentent à l'avenir, en particulier dans les basses terres. L'objectif de cette étude est de déceler les tendances passées, présentes et futures dans la manière dont les fortes pluies se modifient, ainsi que d'en évaluer les impacts sur les réseaux d'écoulement des eaux et les inondations des rizières dans les zones basses.

Le bassin à l'étude est celui des trois lagons de Kaga (environ 250 km2), qui s'étend entre les villes de Komatsu et Kaga, dans la préfecture d'Ishikawa au Japon. Il comporte deux lagons, et les zones rizicoles basses couvrent environ 4000 ha dans les parties inférieures du bassin. Le réseau d'écoulement des eaux est divisé topographiquement en deux parties, le lagon de Shibayama et celui de Kiba, et chaque réseau possède une rivière de drainage qui se jette dans la Mer du Japon.

Dans un premier temps, les événements à forte pluviométrie au-dessus d'un seuil de 70 mm/j ou 100 mm/3j ont été choisis parmi les données pluviométriques compilées à l'Observatoire Météorologique de Kanazawa (près de la région étudiée) de 1940 à 2008. Cette durée de 69 ans a été divisée en trois périodes, et les schémas de pluviométrie horaire sélectionnés à chaque période ont été comparés. En complément, les données pluviométriques réduites selon une grille de carrés de 1 km dans le bassin des trois lagons de Kaga, qui furent à l'origine générées sous la forme du MIROC3 2 HIRES (un des modèles de circulation générale - MCG), ont été compilées pour trois périodes : le présent, le futur proche et la fin du 21ème siècle. Les tendances de cet ordre chronologique ont été examinées.

Simultanément, un modèle d'analyse de l'écoulement a été mis au point, consistant en modèles de ruissellement cinématique et diffusif, respectivement pour les hautes terres (non inondées) et les zones inondables. Un événement à forte pluviométrie d'environ 300 mm au total du 16 au 19 juillet 2006 a servi à vérifier le modèle. Enfin, des études d'impact du changement climatique sur ces réseaux d'écoulement des eaux dans les zones basses ont été réalisées pour déterminer les variations des niveaux d'eau dans les lagons et dans les zones inondables. Les résultats obtenus sont résumés dans ce qui suit :

(1) La comparaison des données horaires des fortes pluies observées a montré que les précipitations moyennes maximales pour des plages de 6, 12, 24 et 48 heures lors d'événements à forte pluviométrie ont augmenté d'environ 4 à 9 % entre les premières et les dernières périodes. La distribution des précipitations maximales sur 6 heures a également varié dans le temps, tandis que les hauteurs maximales augmentaient.

(2) L'analyse des données du MIROC indique que les précipitations mensuelles ont augmenté avec le temps. De plus, les données corrigées établies à partir des précipitations observées et générées (par le MIROC) montrent qu'un événement pluviométrique décennal futur de 3 jours correspond dans le présent à une période de retour de 25 à 35 ans.

(3) Les résultats des analyses de propagation des crues pour des événements à forte pluviométrie correspondent aux hydrogrammes observés des niveaux des eaux des lagons.

On peut en déduire que les rizières situées dans les lagons avoisinants et les zones basses ont été endommagées par les inondations.

(4) Les prévisions des précipitations (probabilité d'une période de retour de 10 ans et plus) proposées par le MIROC ont été appliquées dans l'évaluation de l'impact des variations climatiques sur les réseaux d'écoulement des eaux. On a estimé que les surfaces inondables augmenteraient à l'avenir et suggéré un certain nombre de mesures, comme le réaménagement des réseaux d'écoulement en fonction des normes et des capacités des pompes d'évacuation, et l'amélioration des capacités de pompage.

Mots clés: *Intensité de pluie, système de drainage, modèle cinématique, capacité de pompage, inondation des rizières.*

1. INTRODUCTION

An increase in flood risk, especially in low-lying areas, is predicted as a result of the climate change that will accompany global warming. In various regions of Japan, heavy rainfall events are often observed and can seriously damage paddies. Immediate measures to minimize the damage are needed. On the other hand, capacities of drainage canals and pumps have been planned by using design rainfalls—for example, a 3-day rainfall event with a 10-year return period—in accordance with drainage plans for paddy areas. However, the standards on which the design rainfall is based have not been reviewed for a long time, and changes in the rainfall pattern associated with climate change are not reflected in any drainage planning. If rainfall is influenced by climate change, then the intensity of heavy rainfall is projected to increase. It is important to determine the trends of change in heavy rainfall intensity so that existing drainage facilities can be improved to meet the necessary standards.

This paper discusses the detection of trends of change in heavy rainfall events from past to present and in the future, and it evaluates the impacts of these changes on drainage facilities and paddy inundation in low-lying areas.

2. THE STUDY AREA

The Kaga three-lagoon basin, which is located in a low-lying area and stretches over the cities of Komatsu and Kaga in Ishikawa Prefecture, Japan, was selected as a study area (Fig. 1). The catchment has an area of about 250 km^2 and is divided into inundated and uninundated areas. In the lower reaches of the basin are two lagoons, Shibayama and Kiba Lagoons, as well as low-lying paddy areas covering about 4000 ha. Additionally, in the city of Komatsu (around Kiba Lagoon) urbanization has recently been expanding.

In this basin, the drainage system is topographically divided into the Shibayama and Kiba Lagoon networks, and each network has a drainage river flowing into the Sea of Japan. There are three rivers flowing from the upland uninundated area into the low-lying area. The Youkaichi River (catchment area, 5.0 km^2) and Iburihashi River (88.9 km^2) lie in the Shibayama Lagoon network, and the Hiyou River (12.0 km^2) is in the Kiba Lagoon network. These drainage networks are usually separated from each other by sluice-gates, but in emergency situations (e.g., in heavy rainfall events) they are operated simultaneously.

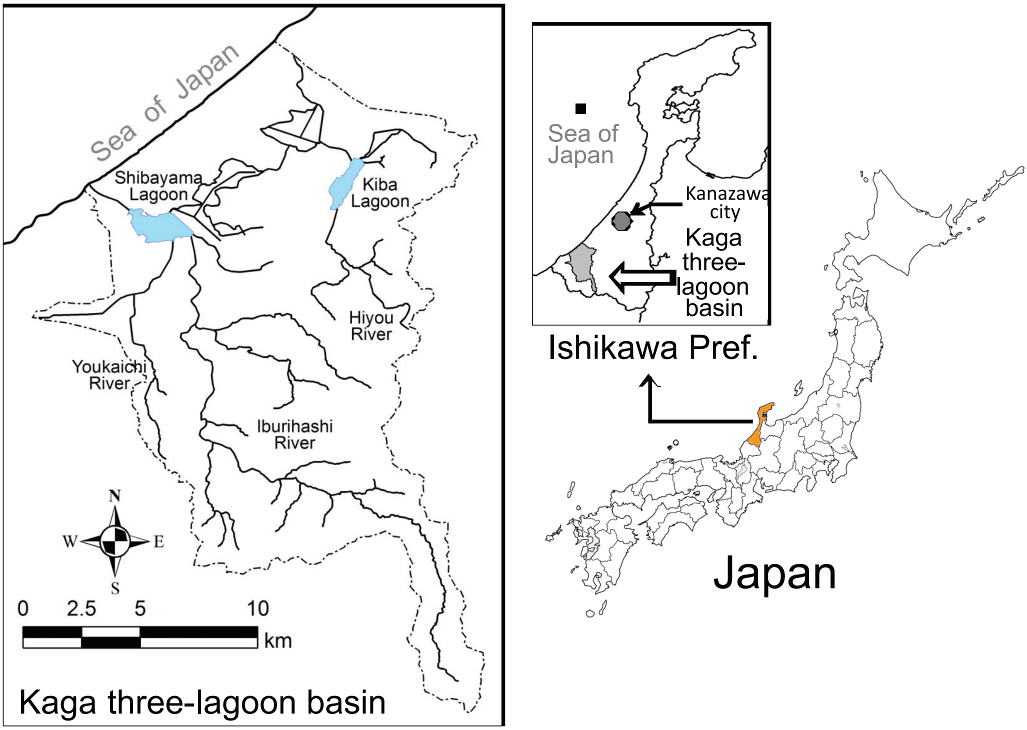


Fig. 1. The study area (Zone d'étude)

3. ANALYSIS OF RAINFALL DATA

Observed rainfall data and data predicted by a general circulation model (GCM) were analyzed (Minakawa and Masumoto, 2010). The observed data were used to explain real trends of change in the pattern of heavy rainfall in the long term, and the predicted data were used to generate future trends in heavy rainfall pattern.

3.1 Observed rainfall data

Long-term rainfall data from the Kanazawa Meteorological Observatory (near, but outside, the study basin) were analyzed. The data span was 69 years (January 1940 through December 2008), and daily and hourly rainfall data were collected.

Heavy rainfall events in which the 3-day rainfall exceeded 70 mm/day or 100 mm/3-days were extracted from the daily rainfall data in order to check for changes in the pattern of heavy rainfall. Each extracted event was examined in terms of hourly rainfall (72 h), and the average maximum 1-, 3-, 6-, 12-, 24-, 48-h rainfalls (in millimeters) in each of three periods in the 69 years namely, period I (1940–1962), period II (1963–1985), and period III (1986–2008), were calculated. A comparative analysis of the frequencies of occurrence of heavy rainfall and of the rainfall patterns in terms of hourly rainfall in each period was then performed.

3.2 Rainfall data predicted by GCM

Data generated by a GCM were used to predict future rainfall values (Table 1). MIROC (Model for Interdisciplinary Research on Climate) is a GCM developed by the Center for Climate System Research at the University of Tokyo in cooperation with several institutes in Japan. A dataset downscaled to a 1km mesh scale in and around the study basin was used; this dataset was originally generated as MIROC3_2_HIRES (Meehl *et al*., 2007 and Okada *et al*., 2009), which is based on SRES A1B (a scenario in which there is a balanced emphasis on all energy sources). There were three data periods: Present (1981–2000), Near Future (2046–2065), and End of the 21st Century (2081–2100); the changes were examined on the basis of this timeline.

Table 1. Attributes of rainfall data predicted by the GCM (Attributs des données pluviométriques calculées par le MCG)

Name of GCM	Resolution	Range of extracted data	Data Period
MIROC 3_2_HIRES (SRES A1B)	1 km×1 km (45" × 30")	136.17°E–136.31°E 36.27°N–36.8°N (Kaga three-lagoon basin)	Present (1981–2000) Near Future (2046–2065) End of 21st Century (2081–2100)

3.3 Bias correction of GCM data

It is common knowledge that any GCM has inherent bias influenced by the observed data. The method of bias correction focused on the use of a design rainfall between the observed rainfall and that generated by MIROC. The procedure is shown below:

1) As predictive values of the design rainfall, probabilistic 3-day rainfalls were calculated by using MIROC data with the Gumbel distribution (Eq.1). Here, the 3-day rainfalls in 12 patterns with different return periods (2-, 3-, 4-, 5-, 8-, 10-, 15-, 20-, 25-, 30-, 40-, and 50-year) were derived. Simultaneously, they were also calculated by using observed data and MIROC Present (1981–2000) data.

$$f(x) = \exp\left\{-\exp\left[-\frac{(x-l)}{a}\right]\right\} \qquad l, a: \text{parameter} \qquad (1)$$

2) Correction coefficients (Table 2) were obtained from the ratios of the observed Present values to the predicted (MIROC) Present values for the probabilistic 3-day rainfall in each return period.

3) Probabilistic 3-day future rainfalls were estimated by multiplying the correction coefficients by the MIROC data for every return period. These bias-corrected data were used to assess the impact of climate change on drainage systems to obtain predictive values for the future design rainfall.

Table 2. Probabilistic 3-day rainfalls and correction coefficients, obtained by using Present rainfall data (1981–2000) (Précipitations probabilistes de 3 jours et coefficients de correction, déterminés à partir des données pluviométriques présentes (1981-2000))

Return period (year)	A	B	A/B
	Observed (mm/3 days)	Predicted (mm/3 days)	Correction coefficient
2	141.0	101.1	1.40
3	163.6	112.9	1.45
4	178.1	120.5	1.48
5	188.8	126.1	1.50
8	210.4	137.5	1.53
10	220.4	142.7	1.54
15	238.2	152.1	1.57
20	250.7	158.7	1.58

The same correction coefficient values in each return period were used to correct the rainfall data for the Near Future (2046–2065) and End of the 21st Century (2081–2100).

4. DEVELOPMENT OF A DRAINAGE ANALYSIS MODEL

An analytical model consisting of a kinematic runoff model, which was applied to the uplands (uninundated areas), and a diffusive tank model (Hayase and Kadoya, 1993), which was applied to the inundated area, was developed to evaluate the impact of climate change on drainage systems in the study basin. It was applied concurrently to the Shibayama and Kiba Lagoon networks.

Various kinds of data; for example, a drainage plan of this area, survey maps of rivers and canals, topographic maps (1/25,000 and 1/2,500), and land-use digital maps for GIS (Geographic Information System) analysis, were collected to create a data set for an areal model. Information on the shapes and bottom elevations of drainage canals for which there were no data was obtained by our own surveys using an RTK GPS system (System 1200, Leica Geosystems). The analytical model is described below.

4.1 Application of the kinematic runoff model to uninundated areas

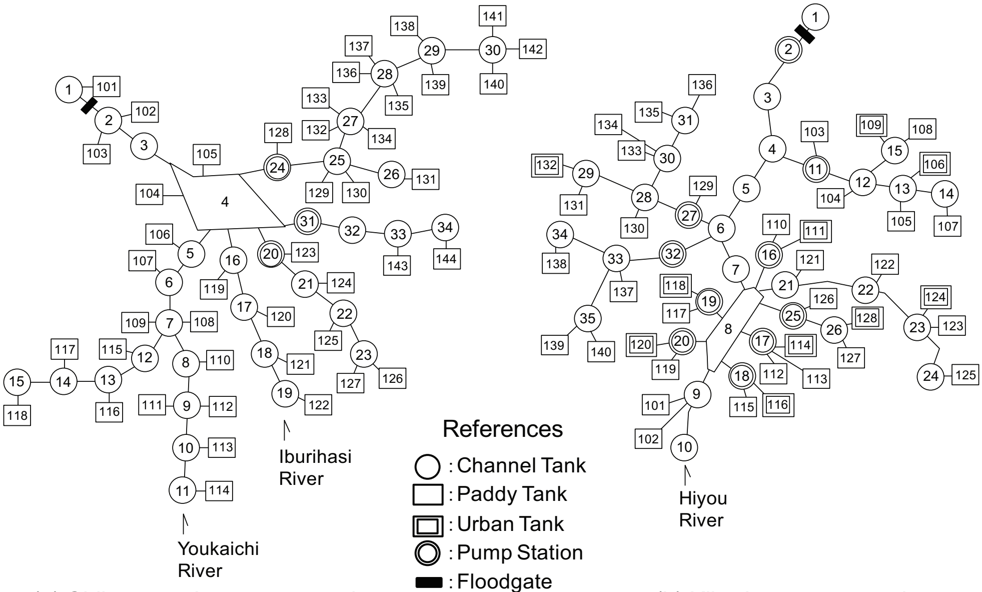
Most land use in the uninundated area was depicted as forest, with some areas of housing and paddy fields. The river lines and the basin were divided into small basin blocks along branch lines by using topographic maps. The area and slope angle of each block were calculated by using the GIS, and the elevation data were selected from the data in the DEM (digital elevation model) with 50-m pixel resolution.

Discharges in rivers were calculated by using the kinematic runoff model, and the results of these calculations were used in the inundation area modeling as flow boundary conditions.

4.2 Application of the diffusive tank model to inundated areas

A diffusive runoff model was constructed by using channel and paddy tanks. Flows between the channel tanks were expressed by non-uniform flow, and the paddy tanks were connected to the channel tanks by weirs. These tanks were divided by using GIS on the basis of topographical information. Figure 2 shows the block diagram of the diffusive runoff model for this area.

Channel tanks were created by dividing rivers and drainage canals into several parts with 500 - 1500m length range. Lagoons were treated as channel tanks with large surface areas. Tank no. 4 in Figure 2(a) corresponds to Shibayama Lagoon and tank no. 8 in Figure 2(b) is equivalent to Kiba Lagoon. The shape and elevation of the tanks were obtained from survey maps and from collected sounding and measured data.



(a) Shibayama Lagoon network (b) Kiba Lagoon network

Fig. 2. Block diagram of the diffusive tank model (Schéma fonctionnel du modèle de ruissellement diffusif)

Paddies were extracted from the GIS land-use digital map and separated into blocks and treated as paddy tanks. In addition, in the Kiba Lagoon network, urban tanks were created to consider the influence of rapid runoff from urban areas into the target channels. The elevation data of these tanks were read visually with an accuracy of 10 cm from topographic maps (1/2,500), and the areas of paddies were calculated by using GIS. Thirty-four channel tanks and 44 paddy tanks were created in the Shibayama Lagoon network, and 35 channel tanks and 40 paddy tanks (including 10 urban tanks) were generated in the Kiba Lagoon network. Moreover, drainage pumps and floodgates were set in each network. In the model, they were automatically switched to ON/OFF or OPEN/CLOSED in accordance with each operational rule, as a system of controlling water levels.

The tanks were numbered sequentially from downstream to upstream. Discharge data calculated in the uplands were inputted to tanks no. 11 and 19 in the Shibayama Lagoon network and tank no. 10 tank in the Kiba Lagoon network as boundary conditions for discharge.

4.3 Flood routing and verification of the models

A heavy rainfall event of about 300 mm in total from 16 to 19 July 2006 was utilized to verify the model. Figure 3 shows the hazardous situation caused by the heavy rainfall event near Shibayama Lagoon. The model was adjusted in accordance with the observed discharges in the rivers and the water levels at the lagoons. The observed hydrographs were compared with the calculated ones for the flood routing analyses of the Shibayama Lagoon network (Fig. 4). The hydrograph in Figure 4(a) indicates discharge in the Iburihashi River at an observation point with inflow from an uninundated area (tank no. 17 in Fig. 2(a)), and the hydrograph in Figure 4(b) shows the water level in Shibayama Lagoon (tank no. 4 in Fig. 2(a)). Both of the calculated results were consistent with the hydrographic observations.

Fig. 3. The flood disaster caused around Shibayama Lagoon by heavy rainfall from 16 to 19 July 2006 (photos courtesy of Hokkoku newspaper, 18 July 2006) (Les inondations catastrophiques provoquées par les fortes pluies du 16 au 19 juillet 2006 autour du lagon de Shibayama (photos reproduites avec l’aimable autorisation du quotidien Hokkoku, 18 juillet 2006))

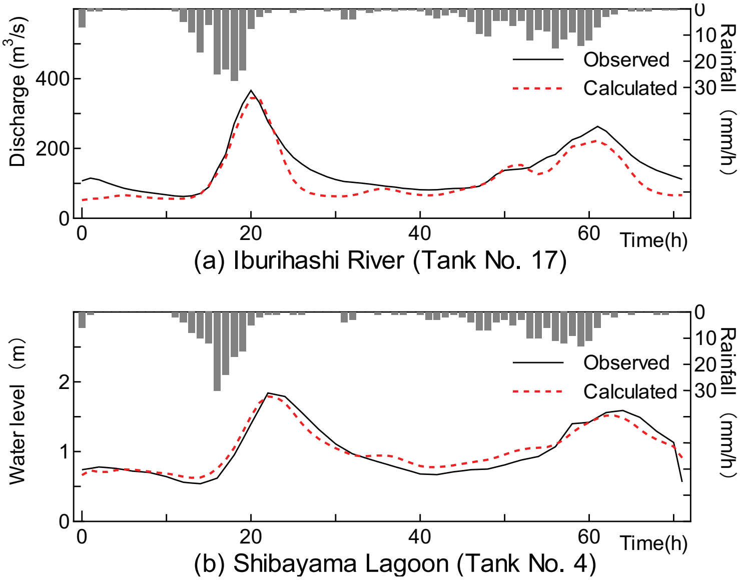


Fig. 4. Comparison of calculated hydrographs and observed ones (Comparaison des hydrogrammes calculés et observés)

Additionally, the model was used to estimate changes in the water levels at paddy tanks. The distribution of peak water levels for the whole analysis is shown in Figure 5. The results showed that at that time there was inundation damage to the paddies adjacent to the lagoons or in low-lying areas.

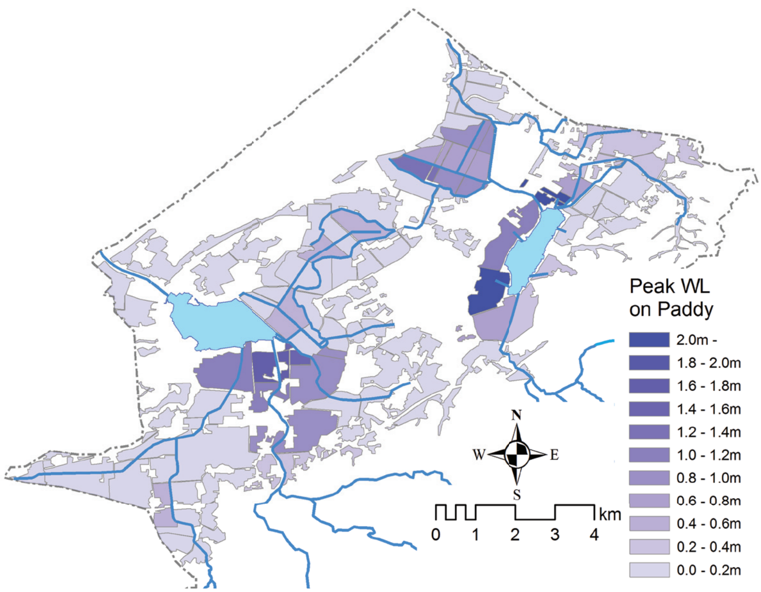


Fig. 5. Distribution of peak water levels calculated at each paddy tank. WL: water level (Distribution des niveaux d’eau maximaux calculés pour chaque réservoir rizicole)

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Changes and drifts in observed rainfall from past to present

The observed rainfall data in each divided period were analyzed (Table 3). The results showed that the frequency of heavy rainfall events did not increase with time in this area. However, comparison of the hourly data in the observed heavy rainfall events showed that the average maximum 6-, 12-, 24-, and 48-h rainfalls increased by about 4% to 9% from period I to period III.

Table 3. Occurrences of heavy rainfall events and average maximum rainfalls in each period (Récurrence des événements à forte pluviométrie et hauteur de pluie moyenne pour chaque durée)

Period	No. of heavy rainfall events	1-h max. (mm)	3-h max. (mm)	6-h max. (mm)	12-hmax. (mm)	24-h max. (mm)	48-h max. (mm)	72-h max. (mm)
I	69	20.6	38.7	52.6	70.0	91.8	118.9	128.7
II	78	19.7	39.3	55.5	75.1	97.2	122.6	136.2
III	50	20.0	39.1	56.9	76.1	99.2	123.4	133.3

In addition, the distribution of the maximum amount of 6-h rainfall changed with time, such that its peak moved to the large side (Fig. 6). Therefore, recently, the intensity of heavy rainfall has increased and more heavy rain is falling over shorter periods of time. In the future, rainfall intensity could change even more.

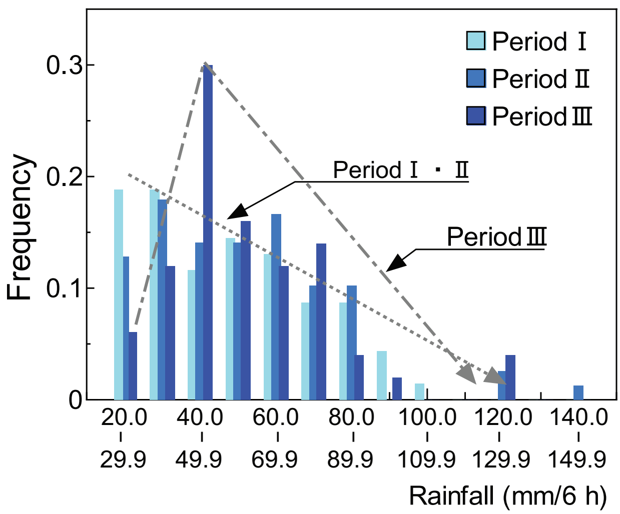


Fig. 6. Frequencies of 6-h maxima in heavy rainfall events (Fréquences des maxima pour 6 h pendant des événements à forte pluviométrie)

5.2 Changes and drifts in rainfall patterns in the future

Analysis of the data predicted by MIROC indicated that the frequency distribution of heavy rainfall will change with time, and the average monthly rainfall will especially increase in summer (Fig. 7). Therefore, the amount of heavy rainfall could increase in the future and could influence the drainage system in this basin.

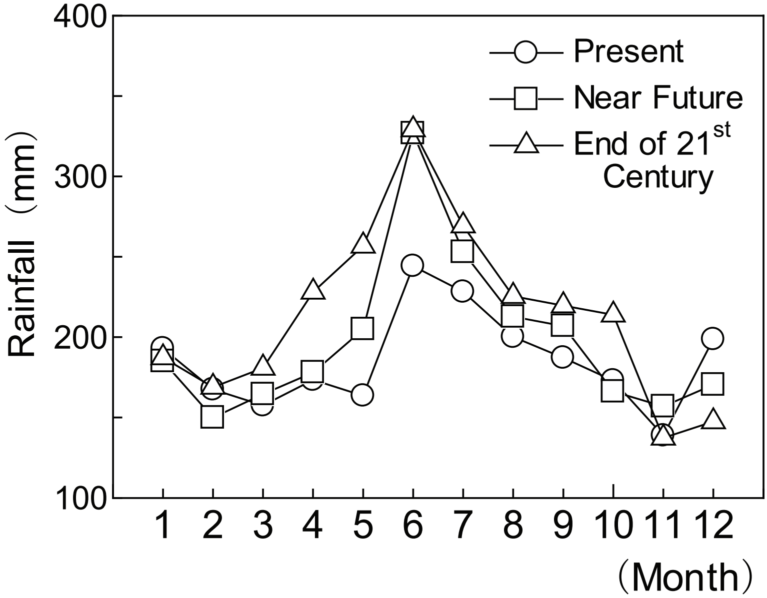


Fig. 7. Average monthly rainfall in each period, as predicted from MIROC data (Précipitations mensuelles moyennes pour chaque période, établies d'après les données du MIROC)

In addition, correction for bias between the observed and calculated rainfalls showed that the probabilistic 3-day rainfall would increase in the future (Fig. 8). In 3-day rainfall events with a 10-year return period (i.e. a 90% non-exceedance probability) it peaked in the Near Future at about 270 mm/3-days (about 50 mm greater than in the Present). It is therefore anticipated that the frequency of heavy rainfall that exceeds the capacities of drainage facilities will increase in the future.

The trends and extents of change in predictive rainfall depend on the type of GCM used, the CO_2 emission scenario, and the conditions used in the calculation. However, both the observed and the predicted rainfall data confirm that there will be changes in rainfall due to global warming.

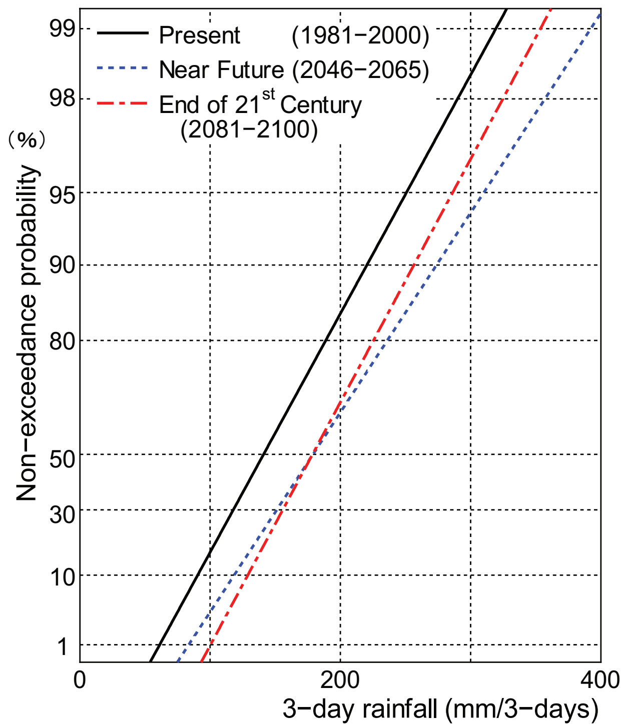


Fig. 8. Drift change in the probabilistic 3-day rainfall (Évolutions dans les précipitations probabilistes de 3 jours)

5.3 Impact of climate change on the drainage system

In many cases, agricultural drainage plans use a rainfall pattern with a 10-year return period as a standard for assessing the capacities of drainage facilities. Therefore, the impact of climate change on drainage facilities was estimated by comparing the flood regime data after the bias-corrected rainfall data had been input into the drainage system model for the Present (220 mm/3-days) and Near Future (270 mm/3-days). At the same time, the amounts of 3-day rainfall with a 10-year return period were distributed into statistically correlated hourly data (for 72 h) by using a short-duration-rainfall simulation generator. The internal structures of heavy rainfall in the Present and the Near Future were each generated for 300 patterns. All of them were input to the model, and the hourly results of each flood regime were obtained for 72 hours.

In this basin, Shibayama Lagoon is important in terms of flood prevention, and the highest water level (HWL) there was established at 1.67 m. As one of the results of the influence evaluation of climate change there, the frequencies of peak water levels in the Present and the Near Future were calculated by using the model (Fig. 9). In the Near Future, the maximum peak water level was predicted to rise, and the risk of exceeding the HWL was predicted to rise by nearly 10% compared with that in the Present.

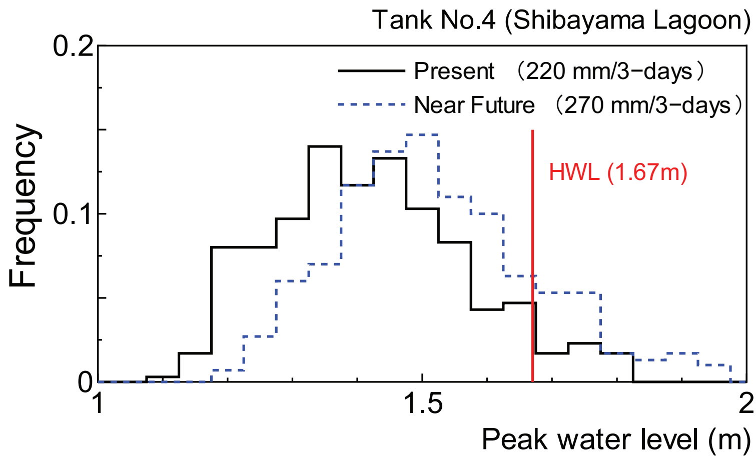


Fig. 9. Frequencies of peak water levels at Shibayama Lagoon (Fréquences des niveaux d'eau maximaux au lagon de Shibayama)

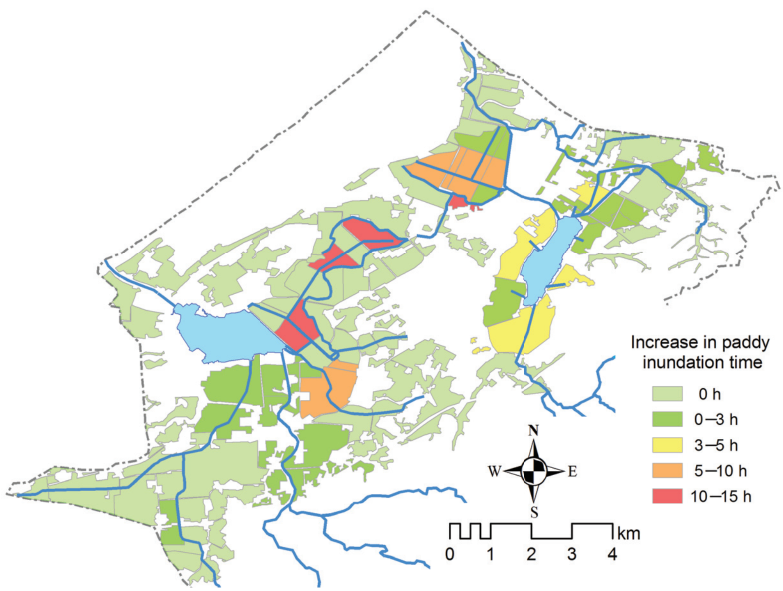


Fig. 10. Increases between the Present and the Near Future in duration of inundation of paddy blocks to depths of more than 30 cm (Augmentations entre le présent et le futur proche de la durée d'inondation des rizières sur des profondeurs supérieures à 30 cm)

In addition, the average duration of inundation to a depth of more than 30 cm was estimated for each paddy, and the difference between the Present and the Near Future was calculated. Figure 10 shows the distribution of the increase in inundation time in each paddy tank. The duration of inundation to more than 30 cm depth was estimated to increase in the Near Future, and in some locations it was predicted to increase by more than 10 h. This implies that the flood damage to paddies due to heavy rainfall will become more serious, especially in low-lying areas. Measures such as the revision of drainage planning and of the design standards for drainage pump capacities, as well as the strengthening of pumping capacities, may be necessary.

REFERENCES

Hayase, Y. and Kadoya, M. 1993. Diffusive tank model for flood analysis and its fundamental characteristics—Runoff analysis by the diffusive tank model in low-laying drainage basin(I)—, JSIDRE. 165: 75–84. (in Japanese with English abstract)

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J. and Taylor, K.E. 2007. The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bull. Amer. Meteor. Soc. 88: 1383–1394.

Minakawa, H. and Masumoto, T. 2010. Change of intensity and occurrence distribution of heavy rainfall events in observed and GCM-based generated data around Kanazawa. Appl. Hydrol. 22: 1–10. (in Japanese with English abstract)

Okada, M., Iizumi, T., Nishimori, M. and Yokozawa, M. 2009. Mesh Climate Change Data of Japan Ver. 2 for Climate Change Impact Assessments Under IPCC SERS A1B and A2, J. Agric. Meteorol. 65(1): 97–109.