RESEARCH ON METHODS FOR ANALYZING THE IMPACT OF FLOOD CONTROL FACILITIES ON EXTREME RAINFALL EVENTS

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ABSTRACT

In recent years, flood damage attributed to the influence of climate change has been occurring frequently in many parts of the world. Hokkaido Prefecture, Japan, was hit by four tropical storms in August 2016. The basin of the Chitose River, a tributary of the Ishikari River, is greatly affected by the Ishikari River's backwater for a length of 30 km. The tributaries are also affected by the backwater. Thus, the Chitose River has a high flood risk from heavy rainfall associated with climate change. This study estimates flood damage caused by extreme rainfall associated with climatic changes. The study was conducted in three stages. (1) Extract the rainfall data for large-scale flooding from the Database for Probabilistic Description for Future climate change (d4PDF) as input data of heavy rainfall (external force) associated with climate change. (2) Calculate the discharges of the main river and the tributaries by inputting the basin area and the mean rainfall for each sub-basin into a one-tank storage function model. (3) Estimate the inundation depth using a flood model that incorporates the operations of sluiceways and drainage pump stations, and the development or non-development of 6 retarding basins. The heavy rainfall data due to climate change is applied from the ensemble experiment results (d4PDF) calculated by the Earth Simulator supercomputer. The results of the study can be used to estimate what kind of risks the treatment facility group contains in a comprehensive manner, and to make a multifaceted evaluation for new flood control measures.

Keywords: Flood analysis, Flood control basins, Pumping stations, d4PDF, iRIC SRM

1. INTRODUCTION

The basin of the Chitose River, which is the basin addressed in this study (Ca=1,244km^2, L=108km), is characterized by the fact that much of the river flows through low-lying areas. The Chitose River is affected for an extended time by backwater from the Ishikari River. The backwater eventually affects tributaries of the Chitose River and navigable/drainage canals connected to those tributaries. The flood analysis model was verified by simulating a major flood (the greatest flood ever recorded) that took place on the Ishikari River in August 1981. The authors have been developing a flood analysis model for large river basins in low-lying areas. In this model, inland waters and river water are analyzed in an integrated manner, and consideration is given to overflow due to backwater from tributaries and navigable/drainage canals, the operation of sluiceways and drainage pump stations, and 6 flood control basins developed along the river. This is the first time in Japan for six or more flood control basins to be developed in a single river basin. This study aims at estimating the effectiveness of flood control facilities against extreme rainfalls. For this purpose, flood analysis was conducted by considering inland waters and river water in an integrated manner for the cases with and without flood control facilities including flood control basins, on the assumption that climate change will cause critical rainfall in the future.

2. METHODS

2.1 Analysis method outline

The flood analysis was conducted in three stages (Figure 1). In the first stage, data were extracted regarding heavy rainfall events that are likely to take place in the future due to climate change. The grid size of the data used for extraction was downscaled from 20km given by d4PDF to 5km (dynamical downscaling) by Yamada et al. Rainfall events in the Ishikari River Basin were extracted in descending order of 3-day cumulative rainfall. In the second stage, runoff analysis was conducted for each of the sub-basins of the upper mainstream of the Chitose River, its tributaries, and 10 drainage canals. In the third stage, the inflow rates obtained by the runoff analysis were fed into a 1-D unsteady flow calculation model. Then, a 2-D planar unsteady flow calculation model was used for estimating inundation heights on the assumption that overflow water runs toward floodplain areas when the river overflows its banks.

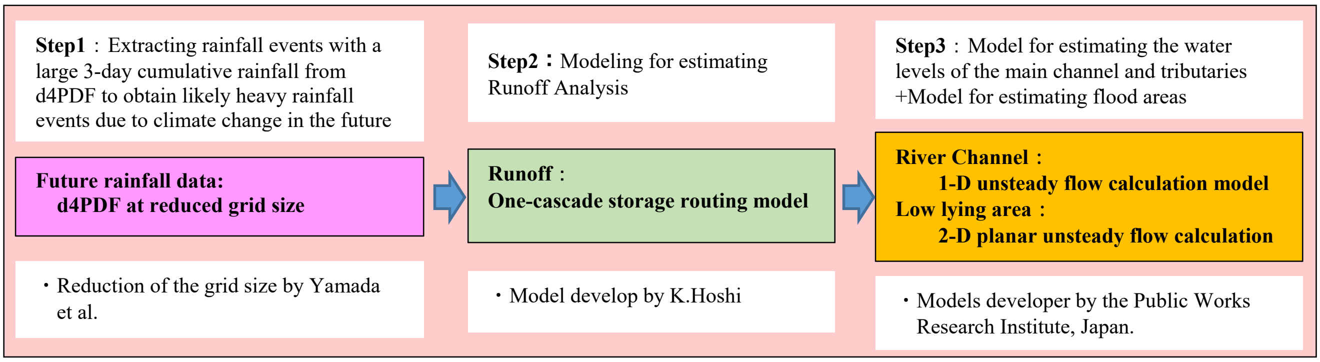

Figure 1. Schematic of the flood analysis model

2.2 Details of the Analysis Models, and Formulas

The details of application of these three models are shown in Figure 2. In the first model, runoff analysis is conducted for the area of basin shown in green in Figure 2. Runoff of the Chitose River and its tributaries is calculated by using a one-cascade storage routing model. In the second, flood routing in the Chitose River is analyzed by calculating the 1-D unsteady flow for the area shown in blue in Figure 2. Flood routing was analyzed for six major tributaries (the Old Yubari, Wattsu, Shimamatsu, Izari, Kenufuchi, and Shukubai), other tributaries, and navigable/drainage canals. In this model, the backwater effects of the Chitose River are assumed to be transmitted to these tributaries and canals. In the third model, flood analysis is conducted by calculating 2-D planar unsteady flow for the area shown in salmon pink in Figure 2. This flood analysis model takes into account inundation due to overflow from the Chitose River, its tributaries, and navigable/drainage canals. The model also takes into account major drainage pump stations with a drainage capacity of at least $10m^3/s$, and road embankments in the floodplain.

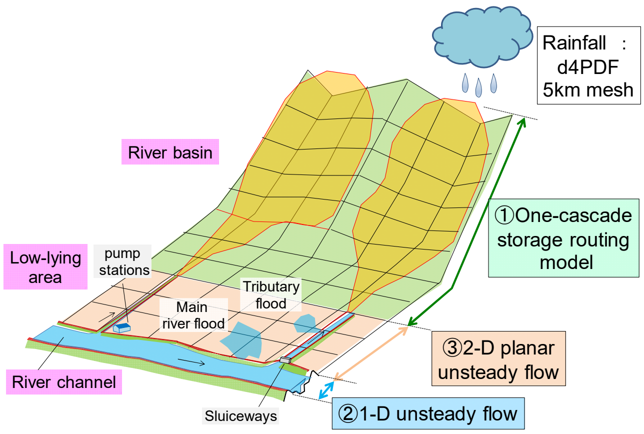

Figure 2. Flood model integrating inundation due to interior runoff and river flooding

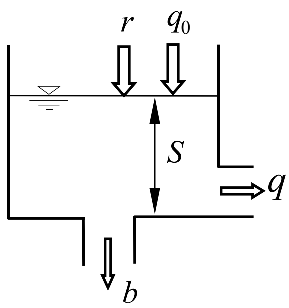

Figure 3. One-cascade storage routing model

2.2.1 Runoff Anlysis

Runoff analysis was conducted by using a one-cascade storage routing model that takes into account the loss mechanisms shown in Equation (1) (Figure 3). This model was developed by Hoshi of the Research Institute, Foundation of Hokkaido River Disaster Prevention Research Center (now the River Center of Hokkaido). The model, which is used as a solver called the Storage Routing Model (SRM), was incorporated into iRIC simulation software by Nakatsugawa, Usutani, et al. in order to make it easier for many researchers to use when analyzing river flow, sediment transport and riverbed variation. The model parameters k_{11}, k_{12}, k_{13} and λ shown in Equations (1), are defined as optimum parameters. These optimum parameters were calculated by Hoshi, et al. by analyzing 72 floods in the Ishikari River System.

$$\begin{cases} S = k_{11}q^{p_1} + k_{12}\frac{d}{dt}(q^{p_2}) \\ \frac{dS}{dt} = r - q - b + q_o \\ q_o = q_B \exp(-\lambda t) \quad ,b = k_{13}q \end{cases} , \quad \begin{cases} k_{11} = c_{11}A^{0.24} \\ k_{12} = c_{12}k_{11}^2(\bar{r})^{-0.2648} \\ k_{13} = c_{13} - 1 \end{cases} , \quad \begin{cases} c_{11} = 11.193 \\ c_{12} = 0.144 \\ c_{13} = 1.848 \end{cases} \qquad (1)$$

In the equations above:

S: storage height (mm), t: time (h), r: observed rainfall (mm/h), q: calculated height of runoff (mm/h), b: loss of height (mm/h), q_o: height of base runoff (mm/h), q_B: initial height of runoff (mm/h), λ: attenuation coefficient, A: basin area (km^2), $\bar{r}$: mean rainfall intensity (mm/h), k_{11} & k_{12}: storage coefficients, k_{13}: loss coefficient, p_1 & p_2: storage index (p_1=0.6, p_2=0.4648), c_{11}, c_{12} and c_{13}: model parameters

2.2.2 Flood routing

For flood routing and flood analysis, the authors used a planar two-dimensional flood analysis system developed by Computer Science Co., Ltd. Flood routing in the Chitose River was analyzed by calculating 1-D unsteady flow as shown in Equation (2).

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \quad , \qquad \frac{1}{g}\frac{\partial u}{\partial t}+\frac{\partial}{\partial x}\left(\frac{u^2}{g}+h\cos\theta\right)=I_o-I_f \tag{2}$$

In Equation [4] above:
A: river cross-sectional area (m^2), Q: flow rate (m^3/s), q: lateral inflow rate per unit width (m^2/s), t: time (sec), g: gravitational acceleration (m/s^2), x: distance along the flow path (m), u: flow velocity (m/s), h: water height (m), $I_o = \sin\theta$: channel gradient, θ: angle of channel slope, I_f: friction slope, n: Manning's roughness coefficient, R: hydraulic radius (m), I=$A\sin\theta$, $I_f = n^2u^2/R^{4/3}$

2.2.3 Flood analysis

Flood analysis was conducted by using Equation (3) for calculating 2-D planar unsteady flow. The topographic data used for analysis was based on digital national land information with a grid cell size of 250 m. The ground elevations along levees were corrected on the basis of Fundamental Geospatial Data with a grid cell size of 5 m and on the basis of cross-sectional survey data because the flood volume is underestimated when the ground elevations in digital national land information are higher than the actual elevations. To analyze water in the river channel and the flood plain in an integrated manner, the volume of overflow water was calculated by using Homma's overflow formula when the simulated water level of unsteady flow in the Chitose River, which was calculated every 200 m along the river, was higher than the levee height. The calculated volume of overflow water was added to the water volume in the floodplain.

$$\frac{\partial H}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0$$
$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}(uM)+\frac{\partial}{\partial x}(vM)=-gh\frac{\partial H}{\partial x}-\frac{1}{\rho}\tau_{bx} \quad , \quad \frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(uN)+\frac{\partial}{\partial x}(vN)=-gh\frac{\partial H}{\partial y}-\frac{1}{\rho}\tau_{by} \tag{3}$$

In Equation (4) above:
H: water level (m), h: water height (m), M: flux in the x-direction (m^2/s), N: flux in the y-direction (m^2/s), u: flow velocity in the x-direction (m/s), v: flow velocity in the y-direction (m/s), ρ: density of water (kg/m^3), τ_{bx} & τ_{by}: shear force in the x- and y- directions (N/m^2), g: gravitational acceleration (m/s^2)

2.3 Future Rainfall Events Associated with Climate Change (d4PDF)

For the purpose of estimating the risk of inundation associated with climate change, this study utilized the data set containing 5,400 cases, which was created by Yamada et al. by reducing the grid size to 5km from the 20km used in d4PDF. From these massive data on the ensemble experiment results, 10 rainfall events with the large 3-day cumulative, basin-averaged rainfall in the Ishikari River Basin were extracted (Table 1.). Ishikari and Chitose River flood control plan is determined by the 3-day cumulative rainfall. The largest 3-day cumulative rainfall was 454mm, 1.61 times the past largest 3-day cumulative rainfall of 282mm, recorded during a major flood in August 1981. A significantly high risk of flood damage was predicted. In estimating future rainfall in the Chitose River Basin, the basin-averaged rainfall was calculated by using the relationship between the observed rainfall in the Chitose River Basin and the observed rainfall in the Ishikari River Basin (Figure 4.).

Table 1. Estimated future extreme rainfall events and their magnitudes in comparison to the past 10 largest rainfall events (Ishikari River Basin).

Ranking	Cases forecast on the basis of D4PDF	Annual maximum rainfall in Ishikari basin (mm/72h)	Multiplying factor in comparison to the rainfall in Aug. 1981
1	HFB_MP_m112_2062	454	1.61
2	HFB_MI_m108_2094	454	1.61
3	HFB_GF_m110_2052	386	1.37
4	HFB_GF_m104_2072	373	1.32
5	HFB_MR_m102_2062	356	1.26
6	HFB_HA_m102_2065	345	1.22
7	HFB_CC_m114_2085	331	1.17
8	HFB_MI_m103_2103	325	1.15
9	HFB_MI_m106_2059	315	1.12
10	HFB_MP_m101_2067	311	1.10

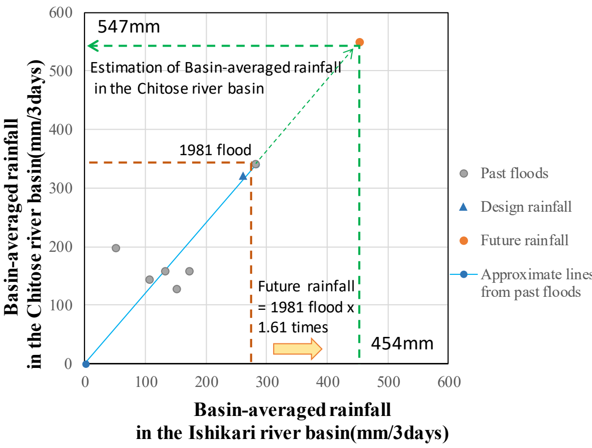

Figure 4. Estimation of future extreme rainfall events in the Chitose River Basin

3. ANALYSYS RESULTS

Figures 5 and 6 show the estimated heights of inundation associated with climate change. Figure 5 shows the estimation results under the condition that no flood control facilities (i.e., drainage pump stations or flood control basins) are in place. In Figure 6, the estimation results are based on the condition that drainage pump stations and 6 flood control basins are in place. The river channel conditions are the same in both cases, because it is assumed that the river channel has been improved according to a river development plan.

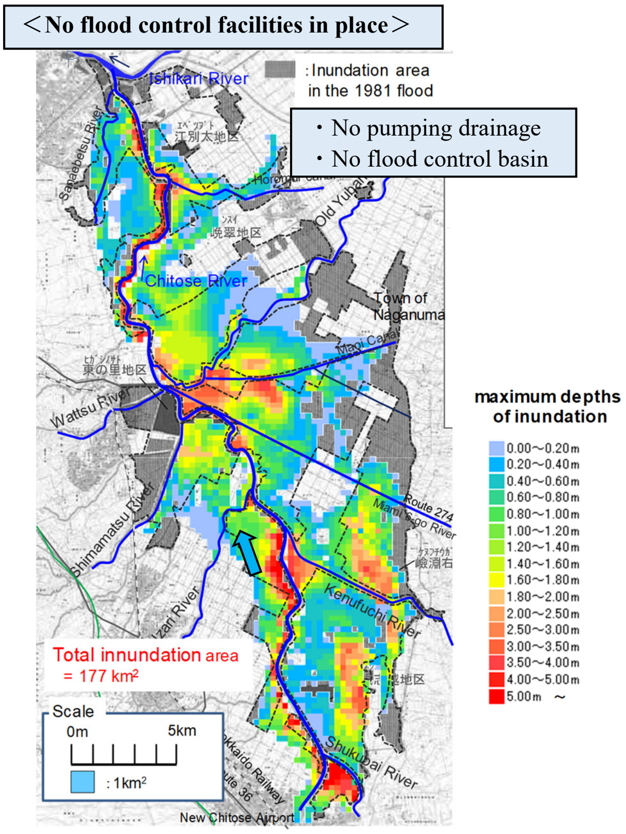

Figure 5. Simulation results for maximum depths of inundation(w/o flood control facilities)

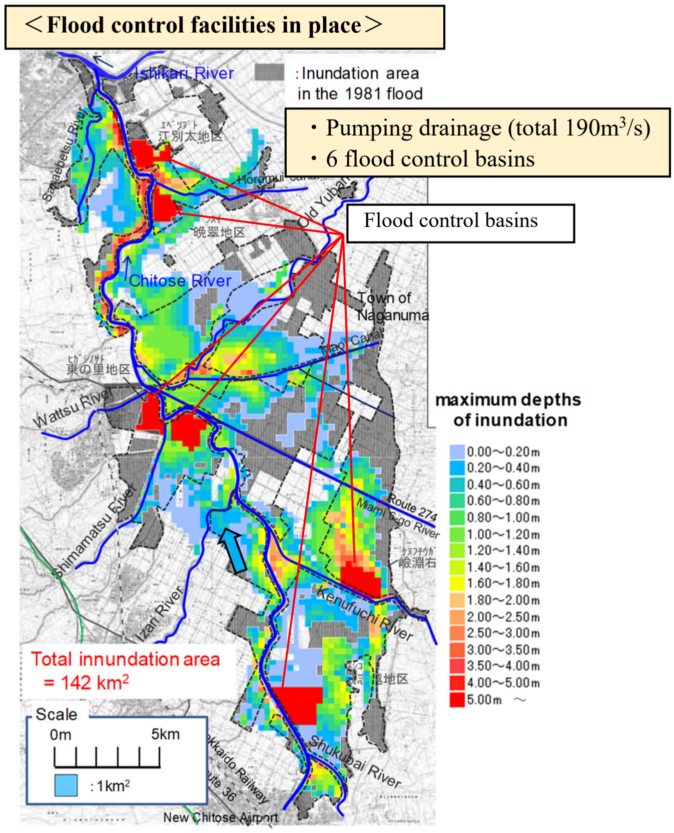

Figure 6. Simulation results for maximum depths of inundation(w/ flood control facilities)

4. CONCLUSIONS

- The inundation area without flood control facilities is increased to 177km^2 (Figure 5.). Because urban areas and national highways will be affected by inundation, high risks to human life and economy are expected.
- An area equivalent to 142km^2 will be inundated when 6 flood control basins and other flood control facilities are in place (Figure 6.) Excluding the total inundated area in the flood control basins, the area affected by inundation is 35km^2 smaller in Figure 6 than in Figure 5. The total area with inundation heights of 0.5m or greater decreased by 25km^2 in Figure 6. Because a water depth of 0.5m makes it difficult for people to walk, it can be concluded that flood control facilities help to mitigate flood disaster.
- This analysis model is useful for evaluating the effectiveness of flood control facilities against the risks associated with climate change as well as for examining disaster prevention countermeasures for the future.

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REFERENCES

T.Oki. and M. Nakatsugawa (2017). A study on flood analysis method in which inland waters and external waters are integrated for rivers in low-lying areas, Proceeding of 2017 IAHR World Congress, pp.1714-1723.

T. Hoshino. and T. J. Yamada (2018). Analysis of annual maximum precipitation over first-class river basins in Japan using a large-ensemble dataset(d4PDF), Journal of Japan Society of Civil Engineers, Vol.74, No.4, I_187-I_192, 2018.