Temporal and spatial distributions of flood water storage volume of the main river and tributaries in the Ishikari River basin

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Abstract. In recent years, Japan experienced frequent and intense heavy rainfalls, resulting in serious flood disasters in many areas. It is also necessary to control floods in tributaries and basins of these tributaries in addition to flood control of the main river. This will be accomplished by understanding flood formation process in the basins of tributaries as well as the main river. Integrated flood flow analysis for the main river and tributaries was conducted by the use of observed temporal changes in the water surface profiles of the 2016 flood in the Ishikari River, Hokkaido, Japan. Temporal and spatial water storage volume distributions in the Chitose River and Ishikari River basins give a new graphical representative method to visualize that when, where, how much volume of rainfall are stored in each basin, and make it possible to verify effects of flood control measures.

1 Introduction

In recent years, Japan experienced frequent and intense heavy rainfalls, resulting in serious flood disasters. To have an integrated flood control plan of the entire basin including the main river and tributaries is important for reducing effectively flood disasters. For this purpose, it is essential to estimate the flood flow dynamics in the main river and tributaries. There are two analysis methods for such studies: hydrological rainfall-runoff analysis and hydraulic flood flow analysis.

The former is a method for mainly representing the runoff mechanism of rainfall and estimating the discharge. The storage function method (Kimura 1961; Hoshi et al.1982), tank models (Sugawara 1972; Gotoh et al. 2019), and distributed models (Tachikawa et al. 2004) considering rainfall distribution and topographical and geological characteristics are used to estimate runoff discharge.

On the latter method, Fukuoka (2004) proposed 2D flood flow analysis method to obtain flow velocity distributions and flood flow discharge hydrographs at any point in rives. Fukuoka (2017) also estimated the temporal and spatial distributions of water storage volume in the upstream basin, dams, rivers, and inundation area in the September 2015 flooding of the Kinu River basin and visualized water storage volumes in the basin. Mikami et al. (2021) evaluated effects of the discharge hydrographs of the primary and secondary tributaries on the flood discharge of the main river in the upper Tone River basin by 2D flood flow analysis.

In this study, analysis of flood flow of the 2016 typhoon was conducted to obtain the water surface profiles over

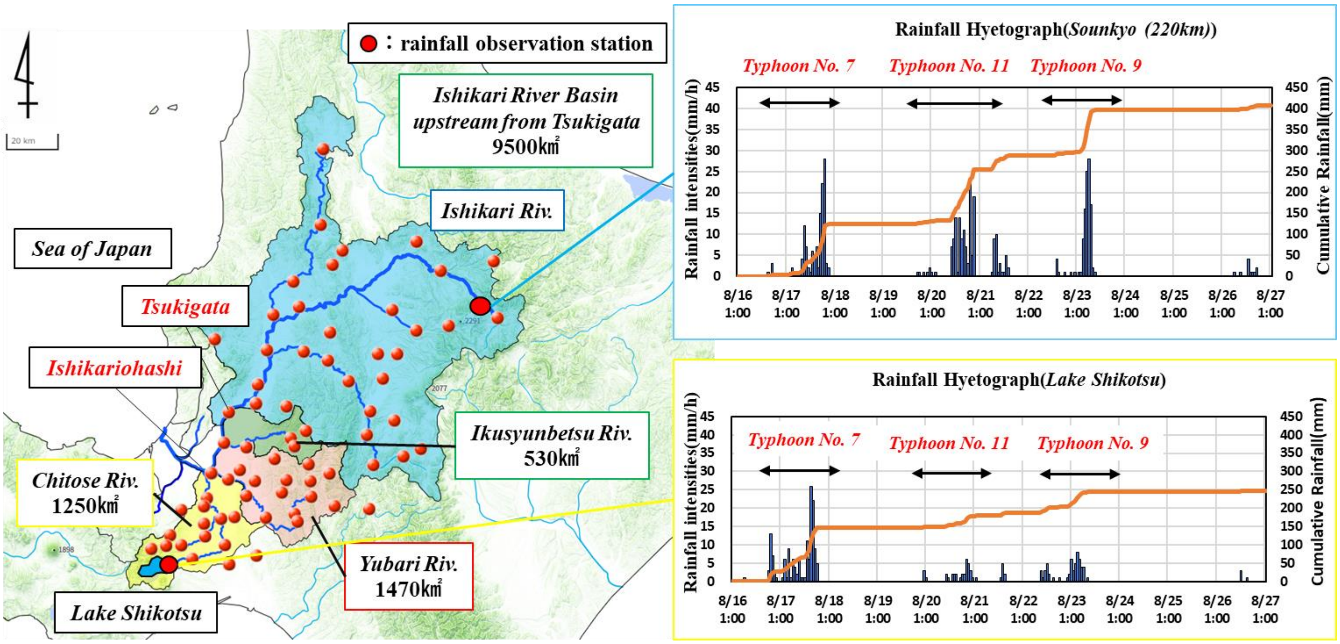

Figure 1: Basin map of the Ishikari River and the Chitose River

and the rainfall hyetographs at the main stations in the upper Ishikari River basin and the Chitose River basin.

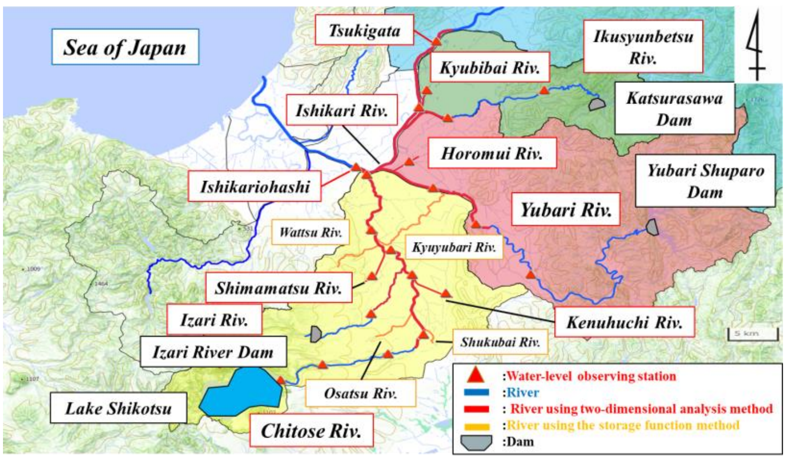

Figure 2: Basin map of the lower Ishikari River.

time for the main river and tributaries in the lower Ishikari River basin shown in Figure 1 and Figure 2. The discharges from most of secondary tributaries are estimated by using the storage function method by Hoshi et.al (1982). We first examined propagation characteristics of the three flood flows of 2016 typhoon and the effects of the discharge hydrographs in the Chitose River basin on the Ishikari River. Then, the temporal and spatial water storage volume distributions in each tributary and entire basin are discussed.

2 Characteristics of river basin and rainfall

The Ishikari River has the second largest basin in Japan and consist of a large number of tributaries. The Ikusyunbetsu River, Yubari River, and Chitose River are primary tributaries and confluent in the lower Ishikari River reach between Ishikariohashi (25 km) and Iwamizawaohashi (45 km).

There are 83 rainfall observation stations in the lower Ishikari River basin as shown in Figure 1. The hyetographs at the main stations in the upper Ishikari River basin and

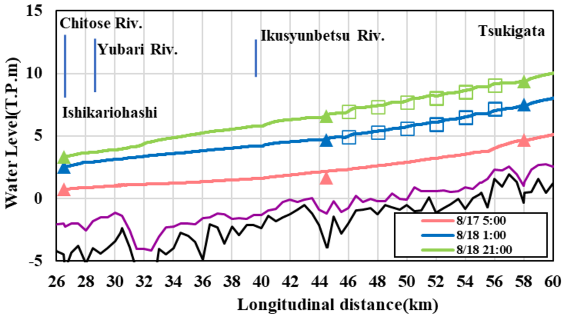

Figure 3: Flood surface profile of the Ishikari River in Typhoon No. 7.

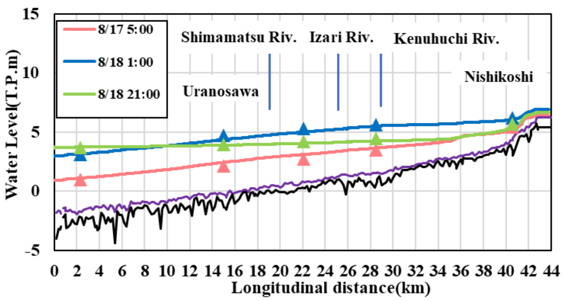

Figure 4: Flood surface profile of the Chitose River in Typhoon No. 7.

the Chitose River basin are also shown in Figure. 1. Typhoons No. 7, 11, and 9 hit Hokkaido during August 17-23, 2016, and brought extensive disasters in the Ishikari River basin. The three typhoons took different paths, resulting in different rainfall distributions. Typhoon No. 7 brought the rain exceeding 20 mm/h in the Chitose River basin and Typhoons No. 11 and 9 did the peak rain about 25 mm/h in the upper basin of the Ishikari River basin.

3 Analysis method

3.1 Flood flow analysis in the main river and primary tributaries

The objective rivers of this study are coloured in red in Figure 2. The upstream boundary condition for the analysis was given by observed water level. The 2D flood flow analysis was conducted to coincide with the observed water surface profiles and then, flow velocity distributions were calculated at each cross-section. The discharge hydrograph was obtained from calculated velocity distributions and channel area during flood.

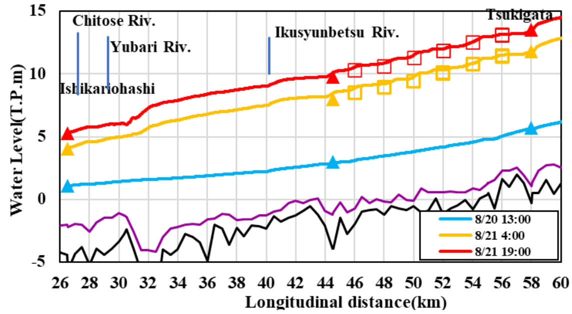

Figure 5: Flood surface profile of the Ishikari River in Typhoon No. 11.

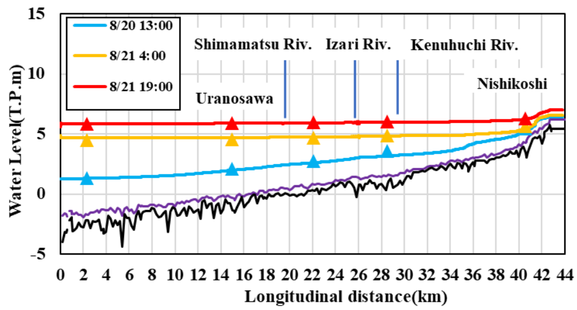

Figure 6: Flood surface profile of the Chitose River in Typhoon No. 11.

3.2 Calculation method of runoff discharge in secondary tributaries

Flood flows of the secondary tributaries coloured by red in Figure 2 were analysed in the same way as the flood calculation of the main and primary rivers. However, for the secondary tributaries coloured by orange in Figure 2, water levels were not available. Therefore, runoff volumes from such tributaries were estimated by the storage function method (Hoshi et al.1982).

4 Analysis results

Figure 3 shows the temporal variations of the water surface profiles of the Ishikari River floods due to Typhoon No. 7. Figure 4 also shows the temporal variations of the water surface profiles of the Chitose River. The peak discharge of Ishikari River occurs at 21:00 August 18. On the other hand, the Chitose River reaches its peak at 1:00 August 18. Backwaters from the Ishikari River to the Chitose River are comparatively small at the peak time.

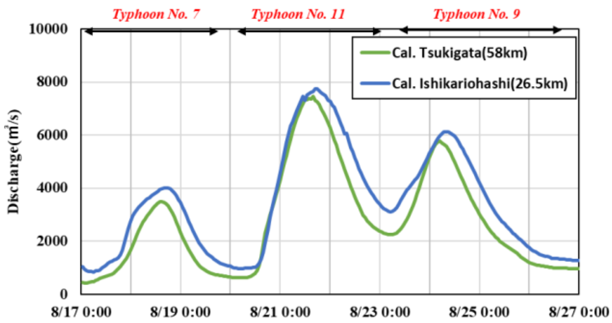

Figure 7: Discharge hydrograph of the Ishikari River.

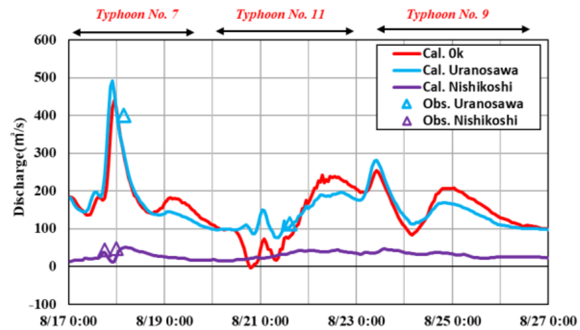

Figure 8: Discharge hydrograph of the Chitose River.

Typhoon No. 11 brought more rainfall in the upper reach of the Ishikari River than Typhoon No. 7. Figure 5 shows that the peak water level of the Ishikari River of Typhoon 11 is higher than that of Typhoon No. 7. Figure-6 shows that the water level of the Chitose River is also rising due to the influence of the backwater of the Ishikari River. In particular, at 19:00 August 21, the backwater reaches up to 40 km.

The discharge hydrographs of the Ishikari River are shown in Figure 7. The calculated discharge hydrograph and the observed discharge at two stations of the Chitose River are compared in Figure 8. Typhoon No. 7 brought heavy rainfalls in the Chitose River basin, and the peak of flood flows of the Chitose River occurred about 1 hour before of the Ishikari River. In particular, the peak at 1:00 a.m. August 18 was 491 m^3/s at Uranosawa.

In the second and third typhoons, the Chitose River are strongly influenced by the backwater of the Ishikari River. At 19:00 August 21, the peak discharge time of the Ishikari River, the discharge at 0km of the Chitose River is nearly zero. As the water level of the Ishikari River drops, the discharge from the Chitose River to the Ishikari River increases, reaching 240 m^3/s at 7:00 August 22.

5 Graphical representations of the distribution of temporal and spatial water storage volume in the basin

Let us discuss the method how to obtain the temporal and spatial water storage distributions of the entire basin and each tributary basin. Temporal and spatial water storage volumes are estimated by the 2D flood flow analysis determined to coincide with the observed temporal and spatial distributions of the water level of each river. The discharge hydrographs at each cross-section are determined from the velocity distributions and water level change obtained from the analysis. Then, the temporal and spatial river water storage volume, S_{river}, is calculated from Equation (1).

$$dS_{river}/dt = Q_{in}(x) - Q_{out}(x + \Delta x) \qquad (1)$$

$Q_{in}(x)$ (m^3/s) is the discharge at the upstream section x. $Q_{out}(x + \Delta x)$ (m^3/s) is the discharge at the downstream section x+Δx.

Then, the water storage volume of the river basin can be obtained by Equation (2), storage volume equation, which is based on the rainfall volume in the basin, storage volumes by dams, retarding basins, etc., and river channel storage volume calculated by Equation (1).

$$dS_{river}/dt + dS_{river}/dt + dS_{river}/dt = \frac{1}{3.6} A \cdot R - Q_{out} \qquad (2)$$

A(km^2) is the basin area, R(mm/h) is the rainfall in the basin, S_{dam}(m^3) is the volume of water storage in dams, retarding basins and lakes, S_{basin} (m^3) is the volume of water stored in the basin, and Q_{out} (m^3) is the river discharge outgoing from the downstream end of the basin.

Calculated distributions of temporal and spatial water storage volume demonstrate when, where, how much rain waters are in the basin. Figure 9 shows the graphical representation of distribution of water storage volume in the Chitose River basin for three typhoons. Typhoon No. 7

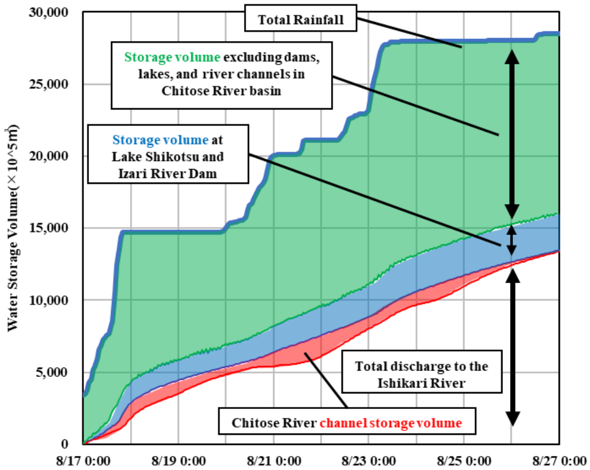

Figure 9: Graphical representation of temporal and spatial water storage volume distributions in the Chitose River basin.

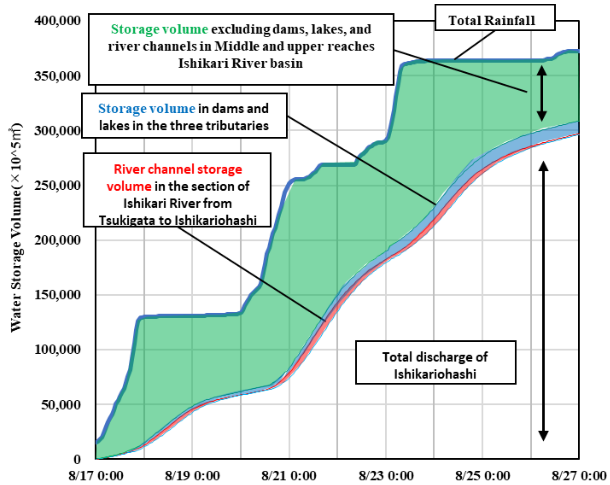

Figure 10: Graphical representation of temporal and spatial water storage volume distributions in the Ishikari River basin.

brought a large amount of rainfall in the basin, and the flood flow in the Ishikari River was affected by inflow from the Chitose River flood. The storage volume in the Chitose River increased significantly due to the rising water level of the Ishikari River. This is evident by the water storage volume distributions described in the red area of Figure 9. This shows that the flood of the Chitose River is markedly controlled by the water level of the Ishikari River. Figure 10 also shows the integrated water storage volume distributions in the Ishikari River basin for three typhoons.

The amount of water storage volume in the basin, S_{basin}, is estimated from the difference between the total rainfall volume and the summation of water volume stored into the dams, lakes, and rivers and water volume outgoing from the basin. Therefore, it is a future issue to examine how, where, when, how much, S_{basin} waters are stored and to investigate the mechanism of water movement in S_{basin}.

By analysing the main river and tributaries as a whole, it is possible to obtain the water storage volume distributions not only in each basin consisting of these tributaries, but also in the entire basin including the main river.

Figure 11 presents the graphical representation of storage water volume distributions in each basin and the entire basin. This makes it easy to understand not only hydrological and hydraulic characteristics of each basins. It is an essential subject to find how the flood control in tributaries reduces severe floodings in the entire basin. Creating this map before and after the implementation of flood control measures in the basin makes it possible to verify effect of measures to be adopted.

6 Conclusion

The flood flow analysis was conducted in the lower Ishikari River basin for three typhoons in 2016. Based on the analysis results, we investigated the flood formation process of the Chitose River and its effects on the flood flow of the Ishikari River. The temporal and spatial water storage volume distributions in the Ishikari River basin and the Chitose River basin were analysed. The graphical representation of storage water volume distributions presents a new way to visualize when, where, how much volume of rainfall exist in the basin.

Graphical representation of storage water volume distributions before and after the implementation of flood control measures provides important means for making a choice of the proper flood control in the river basin.

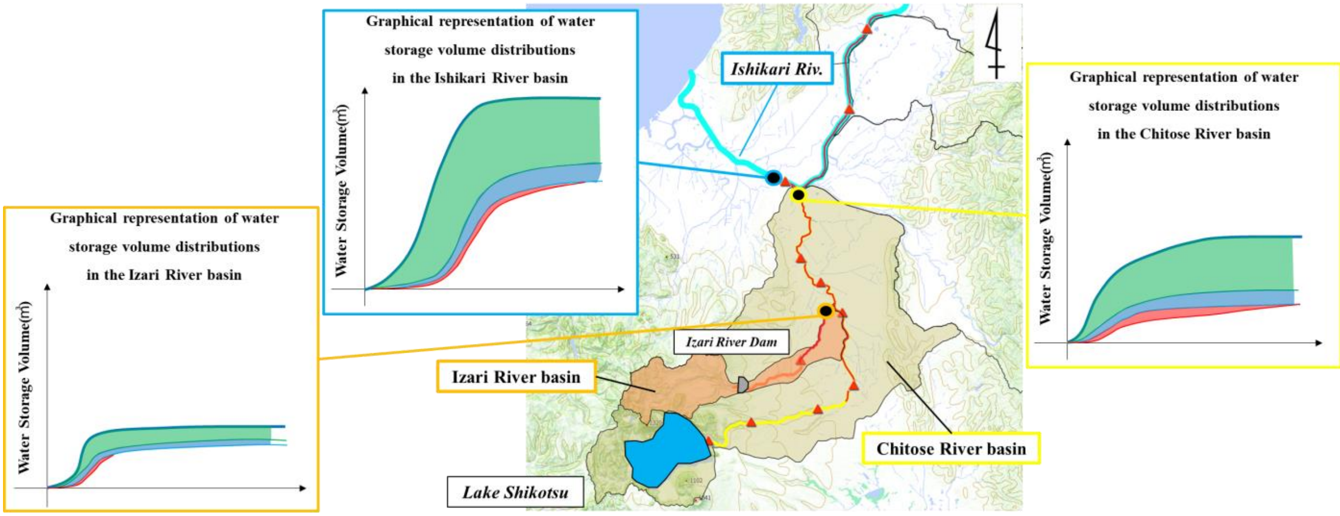

Figure 11: Graphical representations of temporal and spatial water storage volume distributions in each basin on the basin map.

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