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Application of Distributed Hydrological Modeling to Identify River Structures Vulnerable to Extreme Floods

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Abstract: Japan has experienced several unprecedented precipitations in last two years. These extremes have resulted in catastrophic floods in different parts of the country. In this study, flooding in, the Asuwa River in July 2004 due to torrential rains caused by baiu-front, the Miya River in October 2004 caused by typhoon 0423 and the Gokase River in September 2005 due to typhoon 0514 are modeled using physically-based distributed TOPMODEL with Muskingum-Cunge flow routing method. The Asuwa, the Miya and the Gokase river basins have two, four and five AMeDAS rainfall recording stations respectively. Those limited data are not sufficient to model floods caused by unprecedented downpours. Therefore radar derived rainfall intensities were used to determine spatial and temporal distributions of rainfall during the storm periods. The worst damage was reported in the Asuwa river basin due to localized intensified rainfall. The basin maximum hourly and five hour rainfalls were 95 mm and 317 mm. A continuous 48 hour downpour resulted in severe flooding in the Gokase River basin. The recorded maximum hourly and 2-day rainfalls were 80 mm and 1441 mm. In the Miya river basin, 57 mm of hourly and 220 mm of eight-hour maximum rainfall were recorded. Incidentally, the typhoon followed the Miya River meandering path resulting severe damages in downstream areas. Several river structures, mainly railway bridges were washed away by heavy river flows. The hydrological model was applied to simulate discharges at different locations of the three river basins. Simulated discharges at damaged bridge locations were used to calculate drag forces acted on bridge piers and hence to compute experienced maximum bending stresses of the collapsed bridge piers. Results are compared with their bearing capacities of the collapsed locations. The maximum rainfall regions of baiu-front, typhoon 0423 and 0514 were identified and those values exported to the other two river basins to simulate perceptual hydrological processes. It was found that peak runoff values resulting from typhoon 0514 are the largest in three basins. Similar kind of studies can be used to understand river structures in ungauged basins that are vulnerable to floods due to different types of storms.

Keywords: Floods, Distributed Hydrological Models, River Structures, Japan

1. INTRODUCTION

Several regions of Japan have experienced catastrophic storms due to baiu-fronts or typhoons during last couple of years. Those storms have resulted in record breaking intensified precipitations in short duration or longer durational large rainfalls. In 2004, heavy rainfall related natural disasters caused more than 230 casualties in Japan. Those heavy rainfalls were induced by 10 strong typhoons and intensified baiu-fronts. In early September, 2005 the typhoon Nabi (0514) hit Japan, causing 26 deaths and bringing a record breaking three-day precipitation in western Japan, which was approximately three times as much as its normal monthly rainfall of September. These unprecedented torrential rains have caused severe damages due to floods and land slides. Larger river flows resulted in bursts of riverbank and spilling the levees disturbing the livelihoods of the inhabitants of the regions.

A number of river structures mainly railway bridges have been washed away by these heavy river flows. Five bridges on the JR Etsumi Hoku Line in the Asuwa river basin, two railway bridges in the JR Takachiho line in the Gokase river basin and three railway bridges in JR Takayama line in the Miya river basin were washed away by the flood forces. Ishino *et al.*(2005) has studied bridge collapsing mechanism using a constant river discharge along the Asuwa River[1)]. Nawarathna *et al.*(2006) applied a physically based distributed hydrological model using radar derived rainfall intensities to simulate hydrological processes in the Asuwa river basin. Estimated discharge values were used to calculate bending stresses of the collapsed bridge sections[2)]. In this paper different bridge collapsing scenarios of both the Asuwa and the Gokase river basins are being discussed.

In Japan approximately 50% of the population lives in alluvial plains. Short and steep Japanese rivers are often subjected to short durational flash floods. During floods river water levels are higher alluvial plain. As a result, people will suffer from floods unless river banks are properly constructed. It is an uttermost important to investigate maximum possible river flows along the river for proper river management practices. In this study each of the three storms (baiu-front, typhoon 0423 and typhoon 0514) are applied to other two basins to study possible flood situations.

2. BACKGROUND

2.1 Study Area

Three Japanese river basins (**Fig. 1**) namely the Asuwa River in Fukui prefecture, the Gokase River in Miyazaki prefecture and the Miya River in Gifu prefecture were selected for the study. Watershed physical properties are shown in **Table 1**.

Table 1: Watershed physical characteristics of the study basins

Name of the River	Wartershed Area (km^2)	Maximum Slope	Mean Slope	Maximum Elevation	Mean Elevation	Mean Topographic Index	% of Forest
Asuwa	354	1.47	0.48	1447.0	433.9	6.42	90.8
Gokase	1048	2.80	0.47	1699.0	639.8	6.48	76.6
Miya	1155	2.36	0.45	3012.0	959.7	6.60	89.0

The topographies of three watersheds are dominated by steep, heavily forested mountains. Average values of slopes and topographic index are approximately equal. Drainage area of the Asuwa river basin up to Tenjinbashi gauging station (**Fig. 1 a**) is about 354 km^2. And it has the smallest drainage area among the three study basins. Therefore hydrological respond to intensified local heavy rainfalls per unit catchment area is large. Other two basins may require comparatively longer durational storms to cause heavy floods. Minimum flood plain elevation of the Asuwa, Gokase and Miya river basins are 19 m, 6 m and 220 m respectively. Paddy field covers 5.1, 4.5 and 5.7 percentages of the Asuwa, Gokase and Miya river basins. Scrub forest and farm land covers 11.3 and 5.4 percentage of the Gokase river basin. That is the main difference in land cover types among these three watersheds. There are no dam reservoirs in both the Asuwa and the Gokase river basins. The Miya river basin has a series of small capacity dams in addition to the large Shimokotori dam (3.5 MCM capacity).

2.2 Storm characteristics

On July 18^{th},2004 torrential rains induced by baiu-front in Fukui prefecture caused devastating damages due to floods and mudslides mainly in the Asuwa River basin. The observed peak discharge ($2320m^3/s$) at the Tenjinbashi was almost twice larger than the previously recorded peak discharge[2)]. Six hour and daily accumulated rainfall on 18^{th} at Kidouchi measuring station was 314 mm and 338 mm respectively.

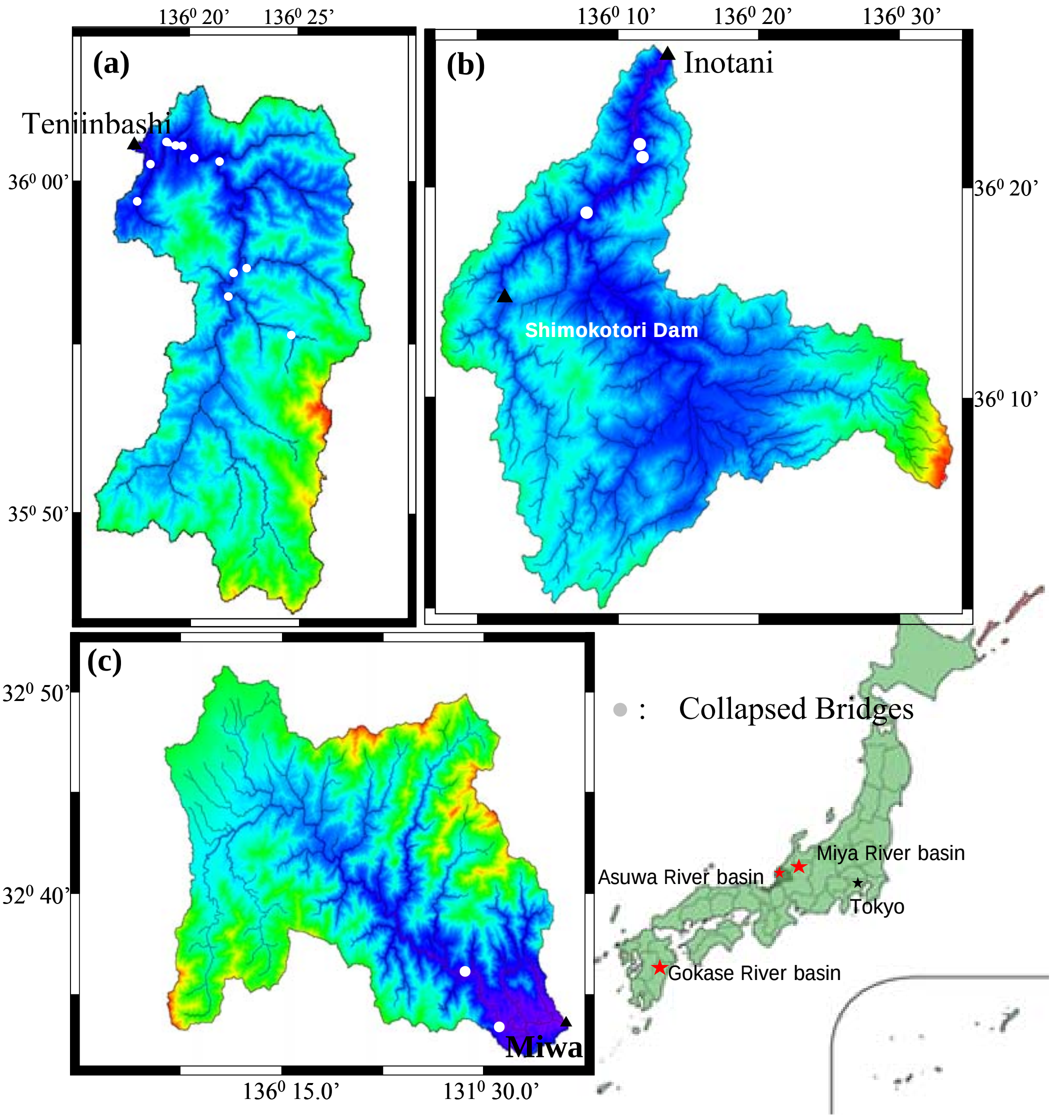

Fig. 1 Study river basins; a) Asuwa, b) Miya, C) Gokase

Record breaking 10 typhoons struck Japan in 2004. The last typhoon of the year, TOKAGE (0423), left severe damages in many regions in Japan; more than 90 people were killed making it the deadliest storm to hit Japan in 25 years. The typhoon hit Japan's main island of Honshu on 20th October 2004. Tokage caused mudslides and flash floods while the strong winds uprooted trees. Some 480 mm of rain fell in some part of Kyushu Island in 24 hours. The storm left over one million homes without power and forced around 20,000 people to evacuate.

Typhoon Nabi (0514) which hit Japan in first week of September, 2005 exposed her to danger for many hours. The maximum hourly rainfall was not so great, but more than 500 mm of three day continuous rainfall caused severe damages. This typhoon caused incidences of 30 landslides. On account of that, 19 people were killed in Kagoshima, Miyazaki and Yamaguchi Prefecture. The Gokase river basin in Kyushu Island experienced recorded downpours and as a result severe flooding caused severe damages to river structures and hampering livelihood of thousands of people.

Basin averaged cumulative radar derived rainfall with storm duration is shown in **Fig. 2.** These three graphs clearly differentiate the spatially averaged storm characteristics in the study basins. **Fig. 3** depicts the radar derived maximum rainfall within the basin against storm duration. Both typhoon 0514 and rain induced by baiu-front produced nearly equal amount of maximum cumulative rainfall in first five hours. Hourly maximum rainfall is about 95.0 mm in the Asuwa river basin. Five hour time averaged maximum rainfall is about 63.4, 71.2 and 33.6 mm/hr in the Asuwa, Gokase and Miya river basins respectively.

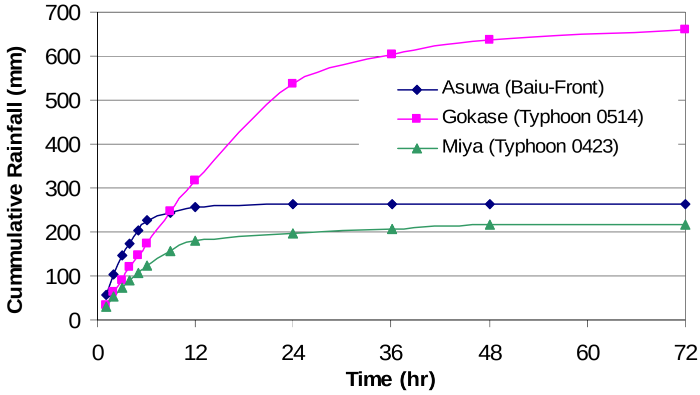

Fig. 2 Basin averaged radar derived rainfall characteristics

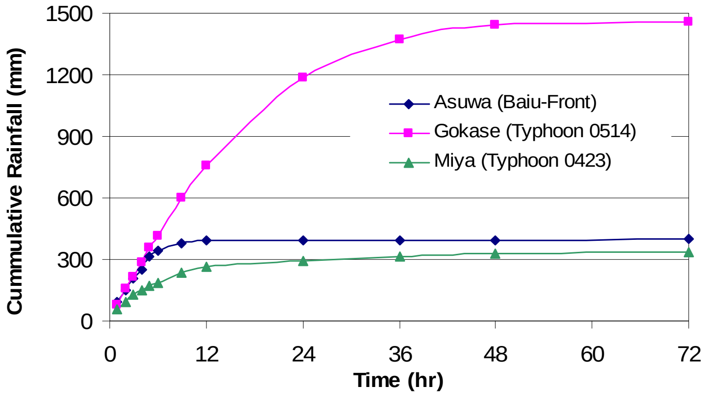

Fig. 3 Maximum localized radar derived rainfall characteristics with storm duration

3. HYDROLOGICAL SIMULATION

Modeling of hydrological processes is obscure task due to its complex governing processes and loss of information in downscaling. TOPMODEL is a small-catchment scale rainfall runoff model based on spatially distributed soil topographic index[3)]. The BTOPMC[4)] model developed in Yamanashi University, Japan adopted a block wise concept to the TOPMODEL together with Muskingum-Cunge flow routing method. Nawarathna et. al, extended the model by introducing distributed parameters and applied it to a part of the Mekong river basin[5)].

3.1 Model structure

Sub-Basin wise, TOPMODEL and Muskingum-Cunge flow routine method[2)] was used to simulate hydrological processes of the study basins. This model was modified as follows to accommodate base flow contribution and saturations deficit.

$$q_b(i,t) = T_0 e^{-SD(i,t)/m} \tan\beta = a_i * R = a_i * e^{-\left(\frac{\overline{SD}}{\overline{m}} + \frac{\overline{m\gamma}}{\overline{m}}\right)} \qquad (1)$$

$$SD_i = \overline{SD}\left(\frac{m_i}{\overline{m}}\right) - m_i\left(\gamma_i - \frac{\overline{m\gamma}}{\overline{m}}\right) \qquad (2)$$

Where Topographic Index, $\gamma_i = \ln\frac{a_i}{T_{0,i}\tan\beta_i}$ and $\overline{m\gamma} = \frac{1}{A}\sum_i m_i \ln\frac{a_i}{T_{0,i}\tan\beta_i}$

The watersheds are divided into number of imaginary sub-basins and local saturation deficit which controls the depth to the local saturation zone is calculated with respect to the sub-basin average saturation deficit. The local saturation deficit also depends on local soil-topographic index relative and its sub-basin average value. Both overland flow and base flow depend on local saturation deficit. Overland flow from each grid and subsurface flow calculated at sub-basin outlets are routed to the down stream along the drainage network which was determined from 50 m resolution digital elevation model using Muskingum-Cunge flow routing method.

3.2 Parameterization

Four model parameters namely, lateral transmissivity under saturated conditions T_0, decay factor m, maximum root zone storage, and flood plain Manning's coefficient, are assigned as functions of land use. The Ministry of Land Infrastructure and Transport publishes the land cover details of Japan in regular intervals. The data published in 1997 was used to detect the land use distribution of the study basins. Because of the difficulties in finding high resolution reliable soil property databases which can correlate T_0 and m of each grid, it is assumed that soil properties are largely correlated to land use. This assumption is likely to be valid for a basin that has not significant human interference on its natural environment.

3.3 Hydrological simulation results

The model was applied to simulate temporal and spatial distributions of hydrological processes and discharges of the basins. The Asuwa River spilled the river banks before reaching Tenjinbashi and also observed discharges are controlled by the hydraulic structure near the gauging station. These controls can not be accurately taken into account by the hydrological model. Therefore, calibration was carried out considering higher observed peak discharge than the recorded **(Fig. 4)**. Recorded inflow to the Kamishiiba dam (211 km^2) was used to calibrate a watershed model for the Mimi River basin which is an adjacent basin of the Gokase River basin (**Fig. 5**). Physical characteristics of both Gokase and Mimi watersheds are quite similar and they are located in same climatic region. Calibrated watershed model parameters were exported to the Gokase watershed model due to lack of observed discharges for calibration. Simulated hydrograph of the Gokase river basin at Miwa gauging station is depicted in **Fig. 6.** Miya watershed model was calibrated using recorded inflow to Shimokotori dam (162 km^2). Simulated hydrograph of Shimokotori dam location and Miya river basin's most down stream location at Inotani are shown in **Fig. 7 and Fig. 8.**

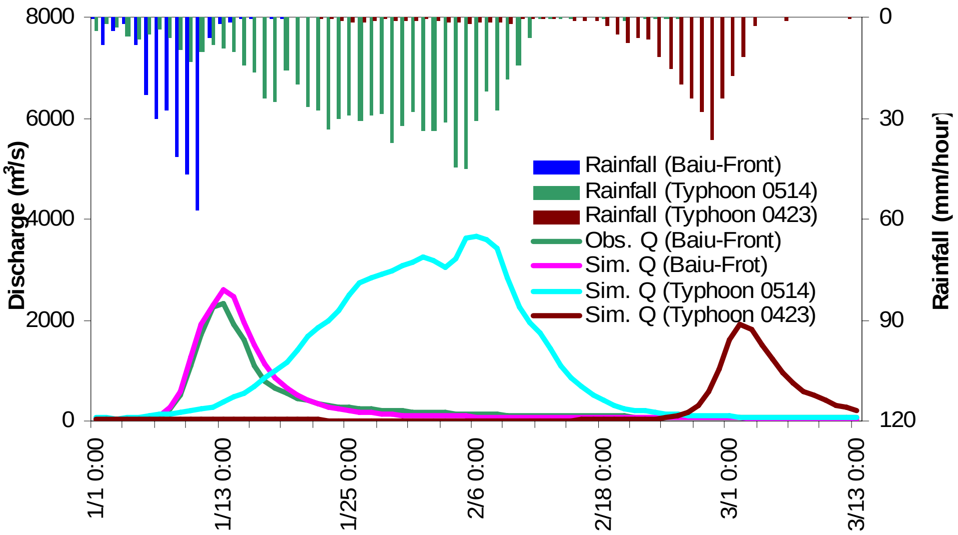

Fig. 4 Simulate Hydrograph at Tenjinbashi of the Asuwa River

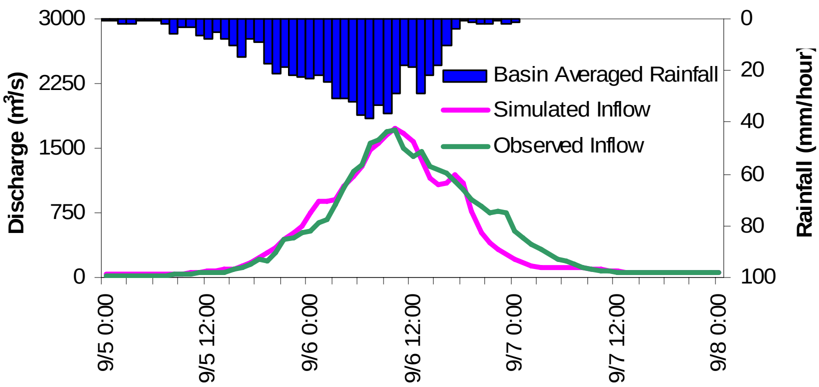

Fig. 5 Simulate Hydrograph at Kamishiiba Dam catchment of the Mimi River

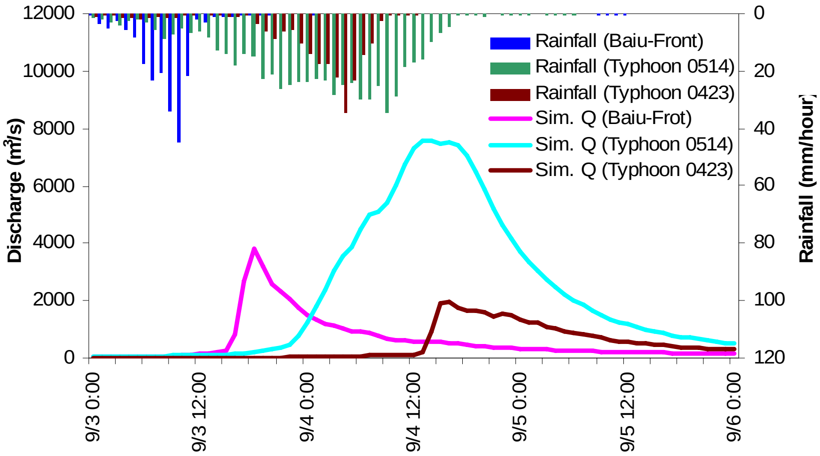

Fig. 6 Simulate Hydrograph at Miwa of the Gokase River

The recognition of the maximum possible flooding remains a major challenge for hydro-meteorologists. Floods arise as a consequence of heavy rainfall falling upon a rapid response drainage basins or long durational rainfall falling on medium to large river basins. Whilst the basin physical characteristics govern the specific timing, location and depth of flooding, the amount and the spatial and temporal distribution of rainfall are prime factors in determining whether flooding is likely to occur at all.

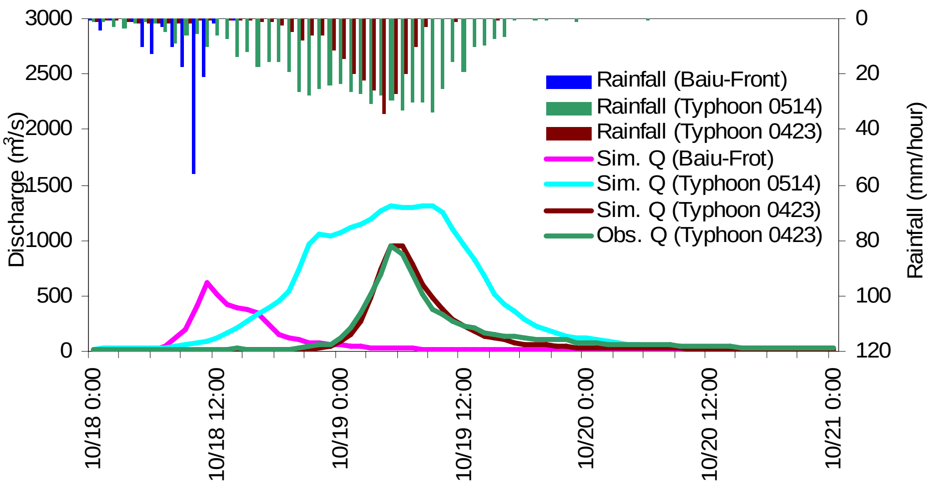

Fig. 7 Simulated Hydrograph of the Shimokotori Dam

The maximum rainfall areas of baiu-front, typhoon 0423 and 0514 were identified and exported to the other two river basins to simulate perceptual hydrological processes. Simulated hydrographs at Tenjinbashi, Miwa, Shimokotori dam and the

Miya river basin are shown in **Fig. 4, 6, 7** and **8**. It was found that peak runoff values resulting from typhoon 0514 are the largest in all basins. However, the possibility of experiencing similar long durational storm in the Asuwa and Miya River basins is in question. Nevertheless similar kinds of watershed models are good tools to investigate hydrological responds to storms of different nature.

Generalized procedures are needed for dealing with influence of different types of uncertainties (ex: model and data uncertainty) in hydrological forecast. Initial soil moisture condition or deficit (SMD) greatly controls the starting point flood hydrograph. In this study SMD of study basins kept similar for comparison.

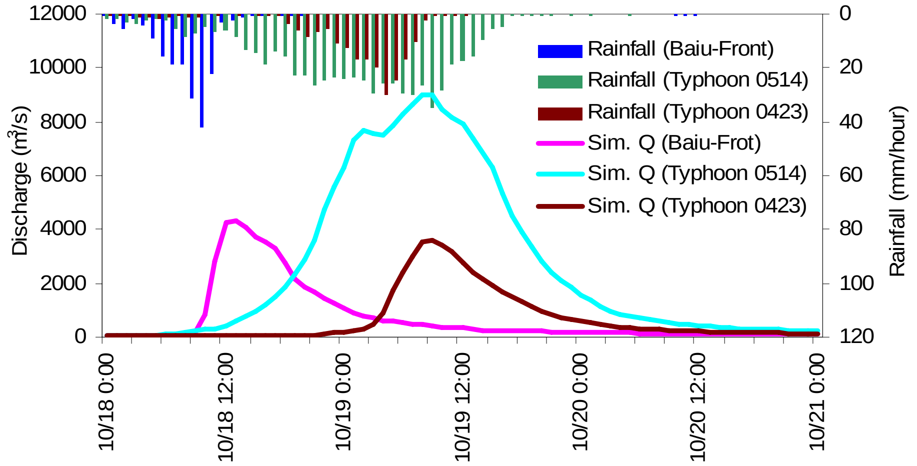

Fig. 8 Simulated Hydrograph of the Miya river basin at Inotani

4. ANALYSES OF COLLAPSE BRIDGES

Heavy floods have fully or partly washed away eight, four and three bridges in the Asuwa, Gokase and Miya River basins. Bending stresses of the collapsed railway bridge (RB) sections were calculated and compared with the bearing capacities of the construction materials as explained in Nawarathna et al.(2006). **Fig. 9** and **10** depicts collapsed RB# 3 of the Asuwa river basin and RB# 2 of Gokase river basin. The results of the collapsed bridge piers in the Asuwa River and the Gokase River are shown in the **Table 2** and **Table 3**. Heavy river flows had submerged the railway bridges before their piers were collapsed in the Asuwa River. However high flows exceeded river levee heights in upstream and over flowed to the flood plains. Therefore it is reasonable to say the maximum possible bearing stresses of river structures were experienced during 2004 flood. It is necessary to study the stress situation of the river structures in the Miya river basin for a storm similar to typhoon 0514.

Fig. 9 Collapsed RB 3 of the Asuwa River

Fig. 10 Collapsed RB 2 of the Gokase River

Table 2 Comparison of bending stresses with bearing capacities of the collapsed bridge pier sections of the Asuwa River

RB #	Drainage area (km^2)	River Width (m)	River Bed Slope	Height between Deck and foundation (m)	Maximum Flood water height (m)	Peak River Flow (m^3/s)	Maximum Flow Velocity (m/s)	σ (N/mm^2)	σ_{ca} (N/mm^2)
1	351	108	1/200	11.5	12.5	2650	2.9	0.19	0.18～2.6
3	332	75	1/87	11.6	12.5	2425	4.8	0.45	0.18～2.6
5	318	74	1/370	12.3	13.5	2368	3.8	2.82	0.18～2.6
7	288	58	1/270	12.4	14	2323	4.6	4.60	0.31～3.3

Table 3 Comparison of bending stresses with bearing capacities of the collapsed bridge pier sections of the Gokase River

RB #	Drainage area (km^2)	River Width (m)	River Bed Slope	Height between Deck and foundation (m)	Maximum Flood water height (m)	Peak River Flow (m^3/s)	Maximum Flow Velocity (m/s)	σ (N/mm^2)	σ_{ca} (N/mm^2)
1	980	130	1/270	9.5	10	7320	5.6	1.40	0.18～2.6
2	875	85	1/94	14.2	15	7100	5.6	2.04	0.18～2.6
3	780	95	1/350	19.1	14	6050	4.5	0.51	0.18～2.6

5. CONCLUSION REMARKS

Sub-basin wise TOPMODEL and Muskingum Cunge flow routing method with distributed parameterization using land use were used to simulate hydrological processes of the Asuwa, Gokase and the Miya River basins for the flood disasters in July 2004 due to baiu-front and typhoon 0423 and 0514. Bending stresses of the damaged railway bridge pier sections were compared with the bearing capacity of the construction materials at the time of collapse. The hydrological model can be used to study the bridge collapsing scenarios due to high flows at any location of the basin due to different types of storms. This methodology can be used to understand the vulnerability of river structures in ungauged river watershed.

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