Journal of Hydroscience and Hydraulic Engineering
Vol. 28, No.1 May, 2010, 43-53

STUDIES ON TOPOGRAPHIC AND METEOROLOGICAL CONTROLS ON FLASH FLOODS

By

Josui Matsuda

Pacific Consultants Co., Ltd., Shinjuku-ku, Tokyo, Japan

Takao Yamakoshi

Public Works Research Institute, Tsukuba, Japan

and

Keiji Tamura

Public Works Research Institute, Tsukuba, Japan

SYNOPSIS

Flash flood disasters caused by localized torrential rain have occurred frequently, in Japan. In this work, we analyzed the characteristics of river basin and river channel where flash floods actually occurred and show that flash flood-prone torrents can be selected through the simple combination of indices which are basin constant number and river channel constant number. In addition, the results of simple numerical runoff simulation using kinematic routing shown that localities of rainstorms and the shape of river systems, that is length/width ratio of drainage basin, can affect the height and keenness of peak discharge of flood hydrograph.

INTRODUCTION

A flash flood is a sudden rise in water level occurring in mountainous or semi-mountainous areas, where the streams are steep and often contain sediments or driftwood. A flash flood is characterized by the quickness the event changes into a disaster. Many flash flood events are considered to be phenomena that lie in the transition region between a flood and a hyperconcentrated flow (Fig.1). Therefore, we define a flash flood as a phenomenon which occurs in a region that ranges from a debris flow to a low-concentration sudden freshet.

Recently, many flash floods have been reported, but because of the difficulty in understanding the actual conditions of the event, knowledge about flash floods is insufficient. The reason is that a flash flood is a short-lasting phenomenon and often occurs locally. For flash flood events that do not have concurring inundation, there is often an ambiguity about the water level signs. Therefore, it is difficult to understand the conditions after occurrence. In addition, although flash floods cause damage to humans almost every year, such events are often reported simply as "a sudden rise in water" or "a sudden muddy stream" unless some newsworthy happenings incidentally occur.

Furthermore, because flash floods are treated as "floods" or "debris flows" in Japan, it is difficult to know the frequency of such events.

According to the previous findings, flash floods are considered to be caused by torrential rain or the failure of natural dams (Mizuyama (1)). But no clear explanation has been obtained about the mechanism of how flash floods occur. Therefore, at present it is difficult to predict flash floods, and so, countermeasures are not sufficient.

Our study focused on collecting and analyzing data on recent flash flood disasters and outlined the disaster characteristics to understand the occurrence characteristics and mechanism of flash floods. From the viewpoint of topographical characteristics (river basin characteristics and channel characteristics), we also learned that we could evaluate the types of river basins (areas or points) that are likely to cause flash floods. In our study, we also reviewed the runoff characteristics of small river basins in the mountains to identify runoff characteristics that tend to cause flash floods, we obtained some important knowledge, about such matters which are reported in this report.

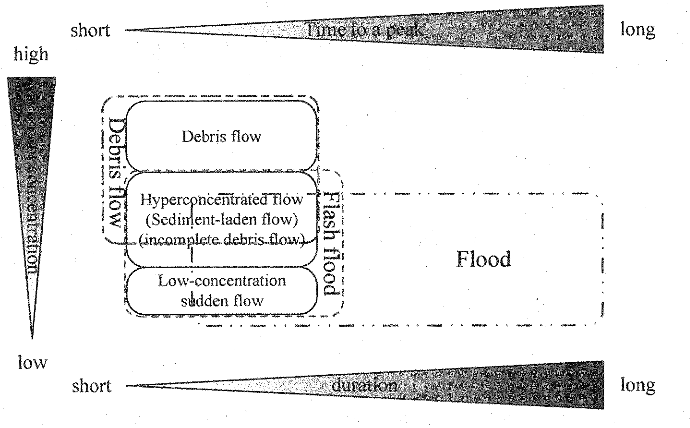

Fig. 1 Schematic diagram of the relationship between a flash flood, flood and debris flow

METHOD OF STUDY

In our study, we investigated recent disaster incidents that seem to make it relatively easy to understand the phenomena and sorted outline of flash flood disasters. Using these cases, we analyzed the topographical characteristics and runoff characteristics and evaluated, from the viewpoint of topographical characteristics, river basins where flash floods are likely to occur. Then we analyzed the runoff characteristics in small river basins in the mountains and discussed the runoff characteristics that are likely to cause flash floods based on the results of numerical experiments using the runoff model.

OUTLINE OF FLASH FLOOD DISASTERS

Figure 2 shows the location flash flood disasters which have occurred recently (disaster cases reported to be flash flood events that occurred in the past 10 years with those in the past 3 years as the main data), and these disasters are overviewed as follows.

Note that Fig. 2 includes cases which are appropriate to treat as small-scale floods (such as cases occurring in the Kushida River) and cases appropriate to treat as debris flows (such as cases occurring in the Yunotsubo River and Sunya River).

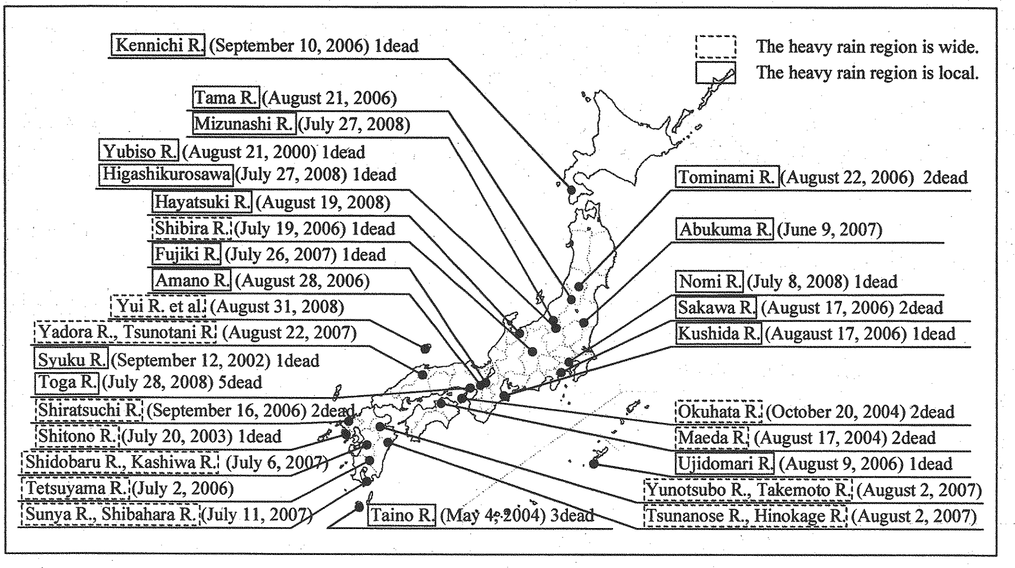

Fig. 2 The position of the flash flood disaster in recent years

Causes of flash floods

Disaster cases reported as flash flood events are classified by causes as in Table 1.

Causes of flash floods are largely divided into two categories: direct runoff phenomena such as heavy rain in the source area, and runoff phenomena that accompany storage of water such as river channel blockage and failure (Matsuda et al. (2)). Many of these disasters are considered to be direct runoff phenomena such as rainfall in the source area, and are characterized by flash flood damage caused by a sudden rise in the water level as a result of short-lasting torrential rain.

Among them, there are many cases that are seen as runoff phenomena accompanied by water storage such as river blockage and failure (in the Shiratsuti River and Shibahara River). Also, flash flood disasters occurred as a result of failure of storage facilities, such as reservoirs, due to heavy rains (such as cases occurring in the Okuhata River and Tetsuyama River) in addition to river blockage and failure resulting from riverbank collapse. Cases where flooding occurred due to a problem with the flow section such as river blockage at the narrow part of the channel (such as cases occurring in the Yunotsubo River or Takemoto River) may be reported as flash flood events. Such cases often occur in alluvial fans. In fact, these incidents occur as follows: blockage at narrow flow paths such as at bridges causes river water to flow over roads that flank the original flow channel; and such an overflow suddenly appears as a flooding flow hitting a place far from the river channel.

Table 1 Causes of recent flash flood disasters

Causes	Pattern of disaster
1. Direct runoff phenomena such as heavy rain in the source area.	• Sudden rise in water level as a result of short-lasting torrential rain. • Sudden rise in water level by subsequent flow of debris flow.
2. Runoff phenomena that accompany storage of water such as river channel blockage and failure.	• Sudden rise in water level by water storage such as river blockage and failure resulting from riverbank collapse. • Sudden rise in water level by failure of storage facilities such as reservoirs.

Rainfall that caused flash floods

In regard to the distribution of rainfall areas in river basins affected by reported events, there are two major categories: heavy rain characterized by a wide area with strong rainfall and a large amount of total rainfall in the entire river basin, and heavy rain with intense but localized rainfall fields (Fig. 2).

The former is caused by a widely stretching set of rainfall fields such as frontal heavy rain, and the pattern of this disaster is typical of a heavy rainfall disaster, and often occurs with flood disasters or sediment disasters.

The latter is caused by a local rainfall field with a high rainfall intensity during a short period of time in the rainfall field, but a small total rainfall in the river basin. This type of event often causes a disaster at a place where there is no or a little rainfall. Therefore, river channel users or construction workers find it difficult to predict the danger of a sudden water increase and often become the primary victims. The pattern of such a disaster is a typical flash flood disaster.

River basins where flash floods occur

Flash floods usually occur in steep mountainous areas where there are river basins, but such events also occur at a small frequency in hilly river basins with a moderate level of urbanization (such as the Ujidomari River or Nomi River). The drainage pattern for such events is mainly dendritic, which is considered common for ordinary rivers, followed by trellis. In many cases the main flow joins with a tributary at almost a right angle, and many river basins are dendritic or trellised strips in shape.

ANALYSIS AND EVALUTION OF TOPOGRAPHICAL CHARACTERISTICS

Findings on the topographical characteristics and runoff characteristics

It is generally understood that the planar profile or longitudinal profile of a river basin greatly restricts the shape of its hydrograph. As shown in Fig. 3, for rivers of a "centripetal" river system (E) in which the river basin is almost round in shape and where large tributaries converge into the main flow intensively along a short stretch of the main channel, the waveform of the hydrograph is sharp and the runoff period is short. Findings indicate that, in cases where rivers flow in a long and thin profile of catchment the hydrograph is soft but the runoff period is long (Suzuki (3), Kikkawa (4)).

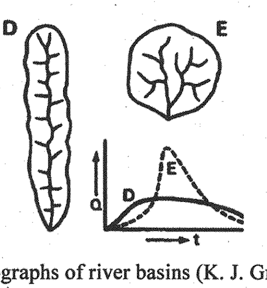

Fig. 3 Planar profiles and hydrographs of river basins (K. J. Gregory and D. E. Walling (5))

Analysis and evaluation of the topographical characteristics (river basin characteristics and channel characteristics)

To analyze the topographical characteristics (river basin characteristics and channel characteristics) prone to flash floods, it is necessary to use indices that allow the reflection of runoff characteristics. Now we attempt to give figures to the topographic characteristics (river basin characteristics and channel characteristics) using indices that allow us to apply a runoff model.

We can apply the kinematic wave method (equivalent roughness method) to sudden runoff phenomena such as flash floods. This method hydrologically tracks the runoff processes using the motion equation and continuity equation by treating a river basin as a combination of slopes and channels. The Manning formula and the characteristic curve method are often used with the motion and the solution method, respectively. The kinematic wave method uses river basin constant numbers and channel constant numbers to express the topographical characteristics. The river basin constant number is determined by means of the river basin equivalent roughness and average slope gradient in the river basin, while the channel constant number by channel width, channel roughness and riverbed slope.

a) Basic equation

The Manning formula is applied to the river basin constant number (*Ks*, *Ps*) and the channel constant number (*Kr*, *Pr*) as used in the characteristic curve method. A simplified equation uses the channel constant number (*Kr*).

River basin constant number : $$Ks = \left(\frac{N}{\sqrt{I}}\right)^{Ps} \quad ; \quad Ps = 0.6 \qquad (1)$$

Channel constant number : $$Kr = b^{0.4}\left(\frac{n}{\sqrt{i}}\right)^{Pr} \quad ; \quad Pr = 0.6 \qquad (2)$$

Where N: river basin equivalent roughness ($s/m^{1/3}$), I: average slope gradient in the river basin, b: average channel width at the evaluation point (m), n: roughness coefficient of the channel ($s/m^{1/3}$), and i: channel gradient (bed slope).

The standard values shown in Table 2 are used for the river basin equivalent roughness, which vary depending on the land use and area ratio in the river basin. The average slope gradient in the river basin is determined by the thalweg method from the National Basic Map (1:5,000 to 1:10,000) or topographical maps (1:25,000). For the channel width, the widths at the evaluation points are used. For the channel roughness coefficients, since roughness coefficients are established for some evaluation points such as water level and flow observation points, those values are used. In the case where it is not known whether coefficients are established or not, the standard values (Japan River Association (6)) reasonably determined from each channel condition are used.

Table 2 River basin equivalent roughness coefficients by the land use (Japan River Association (6))

Land use	Standard value
fields of rice	2.0
mountain forest	0.7
hilly area, dry field, golf course, etc.	0.3
built-up area	0.03

b) Analysis and evaluation of the topographical characteristics

River basin constant numbers (*Ks*) and channel constant numbers *(Kr)* applied to the selected disaster cases are listed in Table 3. In this table, cases treated as sediment disasters are indicated by a "●" mark.

Since many of such disasters occur in rivers in mountainous or semi-mountainous areas, the river basin equivalent roughness (*N*) and the average slope gradient in the river basin (*I*) often have a value of about 0.7 and 0.5 respectively, while the river basin constant number (*Ks*) often takes a value around 1.

The dominant channel width where the disasters occurred is between 5 and 20m. Where the channel constant number (*Kr*) is not more than 1, rivers are often characterized by their narrow width, small channel roughness, or steep bed slope. For the evaluation points where the channel constant number (*Kr*) is smaller than the river basin constant number (*Ks*), the events which are often treated as sediment disasters are characterized by apparent relocation of sediments or disturbance of channel or the occurrence of channel disasters. On the other hand, where the channel constant number (*Kr*) is larger than the river basin constant number (*Ks*), the incidents there are treated as cases of sudden water increase since they did not move sediment significantly. When we look at cases that occurred in the middle and lower reaches of rivers, such as the Sakawa River or Kushida River, the channel constant number (*Kr*) is larger than the other cases since the channel is wide and the bed slope is steep at the disaster location.

In other words, *Ks*/*Kr* is often larger than one for cases that were treated as sediment disasters at the evaluation points, while Ks/Kr is smaller than one for those cases not treated as sediment disasters.

The data of Table 3 are depicted as in Fig. 4. It is assumed that the point where *Ks*/*Kr* equals 1 is the dividing line between the group with a big movement of sediment and the group with a small movement of sediment. A in Table 5 is a group with a large movement of sediment and contains the phenomena closer to debris flow. B is a group with a small movement of sediment characterized by a rapid and sudden increase in water. Of the subgroups of B, B1 contains those in steep mountainous areas, while B2 contains those in hilly river basins with urbanization already covering the river source area. C is a group of events that may be described as small-scale flood for their slower rise in water level and smaller sediment movement compared with B. But the closer to the left side the cases are plotted, the greater the speed of water level rise.

It should be noted that the cases plotted closer to the left are in the region of disasters that occur in a short time and that those closer to the right are in the region of disasters that occur in a certain continuous length of time. One may find here that the cases considered to be the phenomena closer to debris flow (such as cases in the Yunotsubo River) or small-scale flood (such as cases in the Kushida River) tend to be plotted farther away from the dividing line.

For Fig. 5 where the cases are plotted by the bed slope and channel width, note that there is no clear separatability of groups when only those indices are used; Group A and B are overlapped, and B1 and B2 cannot be separated from each other, not to mention the fact that it is impossible to identify any tendency about the rising speed of water level.

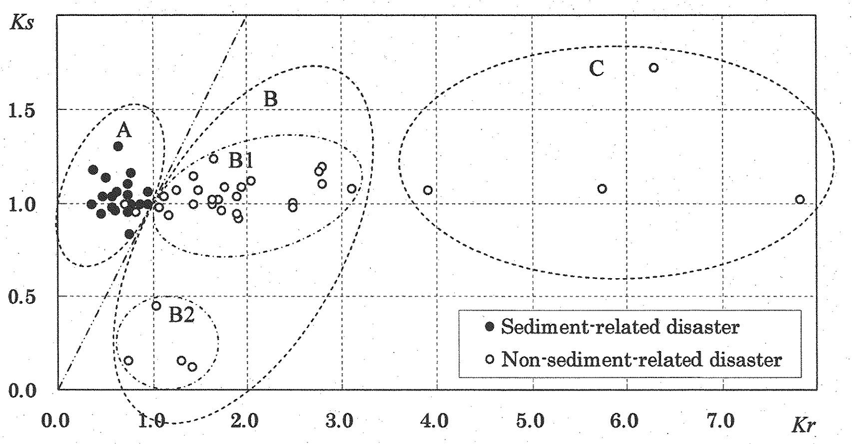

Fig. 4 River basin constant numbers (*Ks*) and channel constant numbers (*Kr*) in the disaster cases

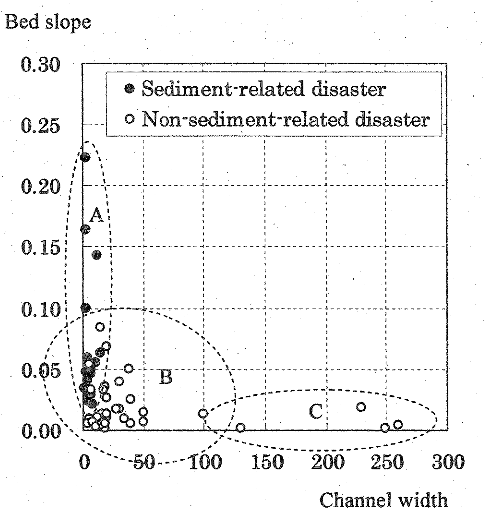

Fig. 5 Bed slope and channel width in the disaster cases

Table 3 River basin constant numbers and channel constant numbers in the disaster cases

River name	Basin		Channel (disasters occurred)			*Ks*	*Kr*	*Ks/Kr*	Disaster situation at the evaluation point
	Average slope gradient in the river basin	River basin equivalent roughness	Channel gradient (bed slope)	Channel width (m)	Roughness coefficient of the channel				
Yubiso R.	0.51	0.70	0.027	20	0.05	0.99	1.63	0.61	○
(Entire basin)	0.47	0.70	0.039	30	0.05	1.01	1.71	0.59	○
Syuku R.	0.17	0.37	0.005	18	0.03	0.94	1.90	0.49	○
Sitono R.	0.29	0.70	0.222	3	0.045	1.17	0.38	3.08	●
Taino R.	0.47	0.70	0.050	38	0.045	1.01	1.64	0.62	○
Maeda R.	0.41	0.70	0.020	7.5	0.035	1.05	0.96	1.09	●
Okuhata R.	0.35	0.75	0.032	6	0.035	1.16	0.77	1.50	●
Tetsuyama R.	0.17	0.50	0.034	1	0.06	1.13	0.51	2.22	●
Shibira R.	0.40	0.66	0.100	3	0.06	1.03	0.57	1.80	●
Sakawa R.	0.20	0.60	0.013	100	0.03	1.19	2.80	0.42	○
(Entire basin)	0.20	0.50	0.004	260	0.03	1.07	5.75	0.19	○
Tama R.	0.50	0.70	0.014	50	0.04	1.00	2.49	0.40	○
(Entire basin)	0.39	0.70	0.007	50	0.04	1.07	3.12	0.34	○
Tominami R.	0.40	0.70	0.014	16.5	0.035	1.06	1.49	0.71	○
(Entire basin)	0.38	0.70	0.010	20	0.035	1.08	1.77	0.61	○
Kushida R.	0.24	1.20	0.001	130	0.03	1.72	6.29	0.27	○
(Entire basin)	0.24	0.50	0.001	250	0.03	1.01	7.84	0.13	○
Kennichi R.	0.50	0.70	0.054	5	0.045	0.99	0.71	1.39	○
(Entire basin)	0.30	0.70	0.006	40	0.035	1.16	2.78	0.42	○
Shiratsuchi R.	0.26	0.50	0.164	3	0.035	0.99	0.36	2.76	●
Ujidomari R.	0.05	0.01	0.033	7	0.03	0.15	0.74	0.21	○
(Entire basin)	0.05	0.01	0.010	12	0.03	0.15	1.31	0.12	○
Abukuma R.	0.24	0.70	0.013	20	0.035	1.23	1.65	0.75	○
Kashiwa R.	0.52	0.70	0.055	10	0.04	0.98	1.10	0.89	●
(Entire basin)	0.52	0.70	0.026	20	0.04	0.98	1.44	0.69	○
Shidobaru R.	0.60	0.70	0.059	3.5	0.03	0.94	0.47	2.00	●
Thuru R.	0.40	0.70	0.035	18	0.04	1.06	1.26	0.84	○
Sunya R.	0.93	0.70	0.143	12	0.045	0.83	0.75	1.10	●
Shibahara R.	0.54	0.70	0.041	3.5	0.035	0.97	0.58	1.68	●
Fujiki R.	0.01	0.03	0.009	5	0.035	0.44	1.04	0.43	○
Hinokage R.	0.54	0.70	0.009	35	0.04	0.97	2.49	0.39	○
Thunanose R.	0.51	0.70	0.063	14	0.04	0.99	0.95	1.04	●
(Entire basin)	0.45	0.70	0.017	30	0.04	1.03	1.90	0.54	○
Yunotsubo R.	0.21	0.70	0.050	7	0.03	1.29	0.65	1.98	●
Takemoto R.	0.45	0.70	0.047	3	0.03	1.03	0.47	2.17	●
Yadora R.	0.57	0.70	0.033	4.5	0.03	0.96	0.62	1.55	●
(Entire basin)	0.51	0.65	0.029	6.5	0.03	0.95	0.75	1.26	●
Tsunotani R.	0.42	0.70	0.031	4.5	0.03	1.05	0.63	1.66	●
Yui R. (Entire basin)	0.51	0.70	0.024	4	0.04	0.99	0.77	1.28	●
Nagu R. (Entire basin)	0.36	0.70	0.028	4	0.04	1.10	0.74	1.49	●
Yabi R. (Entire basin)	0.27	0.60	0.002	18	0.035	1.09	2.81	0.39	○
Nakamura R. (Entire basin)	0.38	0.65	0.005	4	0.035	1.03	1.12	0.92	○
Tsuma R. (Entire basin)	0.38	0.70	0.004	14	0.035	1.08	1.96	0.55	○
Omosu R. (Entire basin)	0.34	0.70	0.005	18	0.035	1.12	2.06	0.54	○
Kumi R. (Entire basin)	0.32	0.70	0.006	8	0.035	1.14	1.43	0.80	○
Sokose R. (Entire basin)	0.43	0.70	0.046	6	0.04	1.04	0.75	1.39	●
Nomi R.	0.03	0.01	0.003	11	0.02	0.12	1.42	0.08	○
Higashikurosawa	0.59	0.70	0.083	15	0.035	0.95	0.83	1.14	○
(Entire basin)	0.55	0.70	0.068	20	0.04	0.97	1.07	0.90	○
Mizunashi R.	0.66	0.70	0.025	40	0.04	1.92	0.91	0.48	○
(Middlestream basin)	0.58	0.70	0.017	28	0.035	1.73	0.95	0.55	○
Toga R.	0.20	0.40	0.050	17.5	0.035	1.00	1.03	0.97	○
Hayatsuki R.	0.40	0.70	0.018	230	0.035	1.06	3.92	0.27	○

Disaster situation at the evaluation point : ● : Sediment-related disaster, ○Non-sediment-related disaster

Discussion on the Runoff Characteristics in Small River Basins in the Mountains

Many such disaster are regarded as the direct runoff phenomena characterized by heavy rains over a short time at the source areas. For many of those cases, the river basin has a dendritic or has a slightly trellised elongated shape, and the source area, which was the heavy rainfall field, has a steep topography characterized by plenty of exposed rocks .Therefore it is considered to be highly prone to runoff.

In small river basins in the mountains where rivers flow in slender-shaped river basins with localized occurrence of short-lasting torrential rains because of the steep basin gradient or channel gradient, the hydrograph tends to be sharp. Such features become more apparent when the flow stretch of water as kinematic waves is long and the speed of the flow that follows the flood is larger because of a large amount of water supply from upriver compared with the flow speed of the front part of the flood. Thus, a flash flood is more likely to occur when short-lasting heavy rain falls in a small river basins in mountainous areas.

As discussed above, although the categorization in Fig. 4 may be able to evaluate river basins (areas or points) prone to flash floods from the viewpoint of topographical characteristics, we think it is necessary to analyze the data from the viewpoint of rainfall characteristics such as occurrence frequency or spatial distribution of localized torrential rain in order to identify river basins where flash flood events are likely to occur.

As a reference, we postulated a small river basin in a mountainous area, using the conditions indicated in Table 4 and Fig. 6, and conducted runoff calculation for those assumed river basins by changing the rainfall distribution, river basin gradient or channel gradient. The results are shown in Fig. 7.

Table 4 Analysis cases

Case	Basin	Slope gradient in the river basin	Main stream gradient	Tributary stream gradient	Rain area
Case1-1	A	I	A	1/40	Upstream basin
Case1-2	A	I	A	1/40	Downstream basin
Case1-3	A	II	B	1/80	Upstream basin
Case1-4	A	II	B	1/80	Downstream basin
Case1-5	A	I	A	1/40	Entire basin
Case1-6	A	II	B	1/80	Entire basin

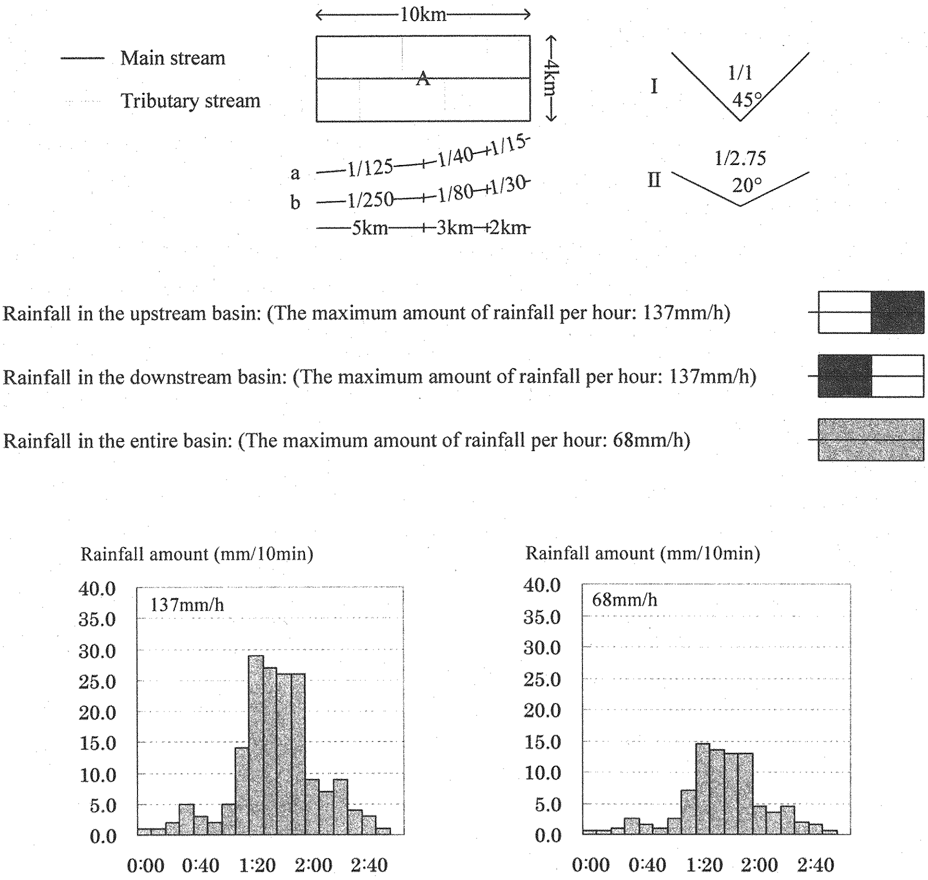

Fig. 6 Topographical conditions (river basin conditions and channel conditions) and rainfall conditions

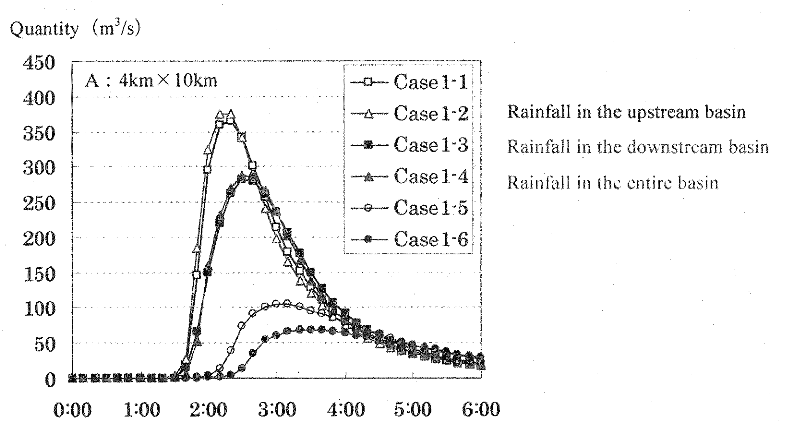

Fig. 7 Example of the runoff analysis results for the hypothetical river basin

CONCLUSION

In this work, we reviewed the flash flood disaster cases and found that we can evaluate river basins (areas or points) where flash floods are likely to occur from the viewpoint of topographical characteristics. The results showed that flash flood-prone torrents could be selected through the simple combination of indices which are basin constant number and river channel constant number. In addition, the results of simple numerical runoff simulation using kinematic routing showed that localities of rainstorms and the shape of river systems, that is length/width ratio of drainage basin, could affect the height and keenness of peak discharge of flood hydrograph.

Recently, in line with the increase in the number of localized torrential rainfall in Japan, a problem has arisen in areas where people who play or work in river channels, because they were killed by flash flood. The likelihood of flash flood is considered to depend primarily on that of localized torrential rainfall. This study reveals that the eccentric distribution of rainfall, topographic features of river basin and channel morphology could be factors in causing flood disasters.

Acknowledgement

The authors would like to acknowledge the Committee on Hydroscience and Hydraulic Engineering of the Japan Society of Civil Engineers for their recommendations in writing this paper.

REFERENCES

1. Mizuyama, T. : Study on the Occurrence of Flash Flood and the Flow Mechanism, 1997 (in Japanese).
2. Matsuda, J., Yamakoshi, T., Tamura, K., Oda, A., Hasegawa, Y. : Disaster Phenomena Expressed as Flash Flood, 2008 Japan Society of Erosion Control Engineering Study Presentation Compendium, pp.200-201, 2008(in Japanese).
3. Suzuki, R. : Introduction to How to Read Topographic Maps for Construction Engineers Part 3 - Terraces, Hills and Mountains, Kokin Shoin, pp.716-725, 2000(in Japanese).
4. Kikkawa, H. : River Engineering, Asakura Shoten, pp.3-5, 1980(in Japanese).
5. K.J. Gregory, D. E. Walling, : Drainage Basin Form and Process – A geomorphological approach-, 1973.
6. Japan River Association, : River Erosion Control Technical Standard with Commentaries, Ministry of Land, Infrastructure, Transport and Tourism (Draft) and its Description and Research Book, 1997(in Japanese).

(Received Jul 15, 2009 ; revised Jan 27, 2010)