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Study on the Fluvial Geomorphological Meanings of Valley Plain in the River and Estimation of the Extreme River Discharge

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ABSTRACT

In every region of the world, the number of large-scale natural disasters is increasing year by year. According to a World Resources Institute (WRI) report, in 15 years, the economic impact of such disasters will be approximately five times what it is now.

In 2007, the European Union (EU) issued Directive 2007/60/EC on the assessment and management of flood risks. In the directive, the probabilities of high-frequency to low-frequency or extreme floods are expressed in terms of annual exceedance probabilities (1/2 to 1/10,000). Risk management is being implemented for floods of varying magnitude. Recently in Japan, efforts have begun to officially announce areas at risk of flooding under the assumption of an extreme rainfall event with an annual exceedance probability of 1/1000 as the maximum probable external force.

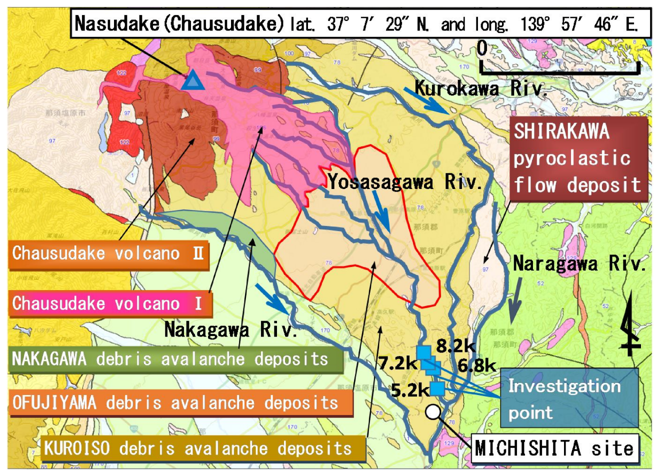
Current practice around the world is to use annual exceedance probability to assign the magnitude of low-frequency floods. In this study, however, we attempt to estimate the maximum flood discharge (extreme discharge) of actual floods that have occurred within the recent epoch (that is, within approximately the last 10,000 years) based on geomorphological and geological traces of rivers that flow through erosional valley-floor (valley plain). We believe this to be an alternative method for estimating maximum probable external force.

KEY WORDS: valley plain , terrass, Yosasagawa Riv., extremal discharge,

INTRODUCTION

The goal of this study was to estimate the discharge of largescale historical floods on the basis of geomorphological and geological traces.

Fluvial geomorphology is formed through the sediment deposition and erosive action of water flowing through river channels. Efforts to reconstruct ancient flooding events on the basis of traces of deposition action began in the field of paleohydrology in the mid-twentieth century; successful reconstruction of flood history has been achieved through using the stratigraphy and radiocarbon dating of slackwater deposits (Baker et al., 1987). Although radiocarbon dating yields relatively reliable estimates of sediment age, it is time consuming and complicated; furthermore, in contrast to the precision of the age estimates, because the geomorphology, hydraulic grade line (bed slope), and roughness coefficient at the time of sediment deposition must be estimated, the precision of flow rate calculation models is low.



Geological features	Depositional age
Chausudake volcano Ⅰ	Since 16 thousand years ago
Chausudake volcano Ⅱ	Since 150 thousand years ago
OFUJIYAMA debris avalanche deposits	40～25 thousand years ago
NAKAGAWA debris avalanche deposits	170 thousand years ago
KUROISO debris avalanche deposits	500 to 400 thousand years ago
SHIRAKAWA pyroclastic flow deposit	1.4 to 1.0 million years ago
※Aira-Tn(AT)	29 to 26 thousand years ago

Fig. 1 Geology of Yosasagawa Riv. basin

Meanwhile, no method currently exists to directly estimate historical flood discharges on the basis of traces of erosive action. That said, it may be possible to use regime theory, whose empirical equations have long been used to determine stable channel cross-sectional geometry, to estimate the discharge forming a given channel from the channel cross-sectional geometry(Knighton, 1998). There are, however, a number of problems with this approach, including the fact that the equations constituting regime theory were developed empirically on the basis of specific rivers and not on general conditions, and the fact that it is not possible to determine whether present-day channel cross-sections were formed by a single or multiple floods. To overcome these problems, in

Photo 1 Cutbank of the 1998 flood

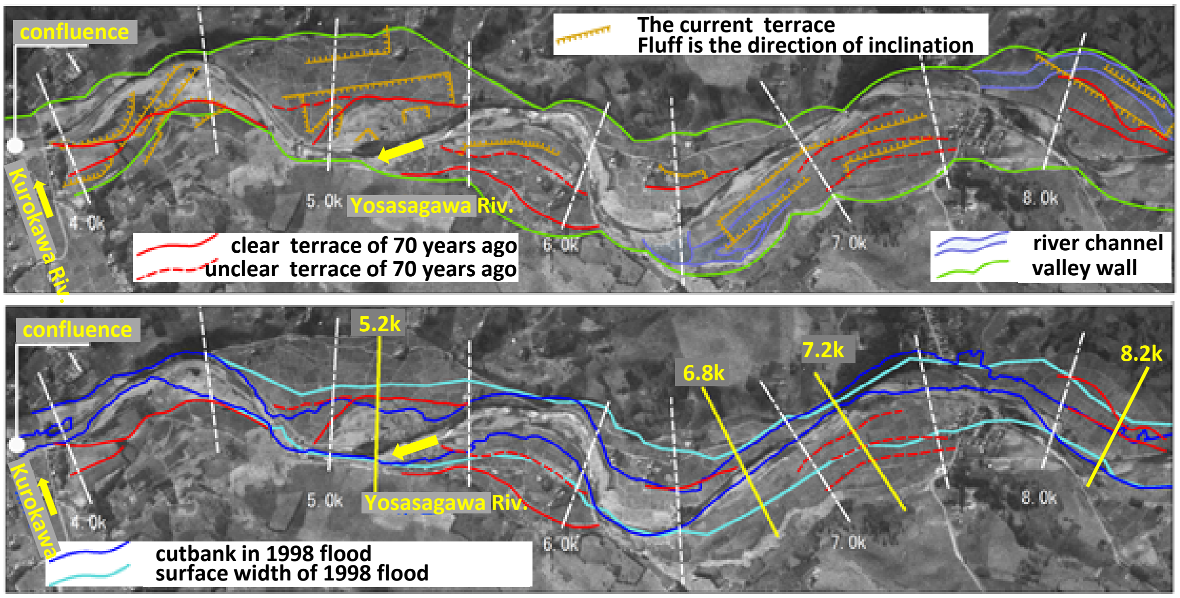


Fig. 3 Erosion width of the 1998 flood、Step position by the 70-year-old aerial photograph interpretation

the present study we used the Fukuoka equation (a mechanical relationship equation) for dimensionless stable channel cross-sectional geometry derived through dimensional analysis as the relationship equation(Fukuoka, 2012). In addition, we focused on rivers running through erosional valley-floor(valley plain) as sites where eroded channel cross-sections formed by single historical floods might still exist today.

During normal or small to medium flows, rivers that flow through eroded river valley floors meander along the valley bottom while limited by the valley walls. However, an investigation of the 1998 flood of the Yosasagawa (a river that flows through Nasumachi, Tochigi Prefecture) confirmed that during large-scale discharge events, rivers cut the inner banks of bends along meandering river channels in a straight line and leave behind stream banks that lie in a straight line along the axis of valley bottom (Photograph 1). We used the width of this erosion as the channel width in the stable channel cross-sectional geometry for the Fukuoka equation. In addition, we identified the high terraces oriented in the direction perpendicular to the long axis of the valley floor as erosion traces formed through erosive action of a large-scale historical flood. Using the Fukuoka equation, we attempted to estimate the extreme discharge based on this erosion width. Based on this analysis, we estimated the extreme discharge of the Yosasagawa to be approximately double that of the 1998 flood.

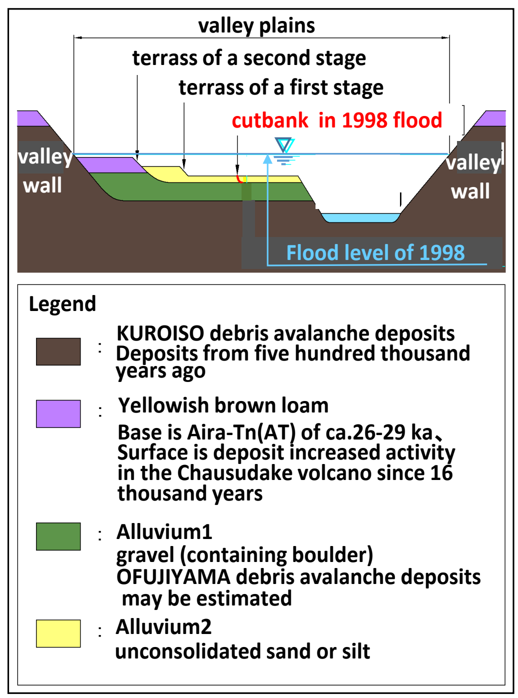


Fig. 2 Yosasagawa Riv. Geologic sketchy profile

Photo 2 terrace of valley plain in Yosasagawa Riv.

INVESTIGATION METHOD

Selection of target section of the river

In this study, we focused on terraced landforms formed through the action of rivers flowing along erosional valley-floor. In the context of fluvial geomorphology, the main causes of terrace formation generally include crustal movement (uplift and subsidence), changes in sea level (fall), and erosive action during large-scale flooding events. Terraces formed via the first two mechanisms are known as fluvial terrace scarps. Because we limited our investigation to terraces formed through the erosive action of large-scale flood events, the terraces have essentially been unaffected by crustal movement and sea level change in the recent epoch. The largest flood event in recorded history occurred recently (1998), leaving a wide variety of flood-related records. For this reason, we chose the Yosasagawa, which flows through Nasumachi, Tochigi Prefecture, as our study target.

The Yosasagawa flows in a southeasterly direction from Mt. Nasu (elevation 1,915 m), which is an active volcano. In the target section of the river, the watershed catchment area is 127 km^2, the main channel length is 34 km, and the average grade is 1/32. The target section was a 5 to 9 km stretch of the lower reach of the Yosasagawa marked by prominent erosive features and a clear erosional valley-floor (Fig. 1).

In this study, although we assumed the terraces along the valley floor to be erosion traces formed during a flooding event, we will first discuss the possibility that they are faults or were formed by the falling sea level. The Sekiya fault, Kenkatsura fault, and the Nasuyumoto-Hokuto fault are known to exist near the upper reaches of the Yosasagawa in the vicinity of the Mt. Nasu volcanic zone. However, no active faults have been reported downstream of the study area along the Yosasagawa or in the Nakagawa river basin, which is the main river. On the basis of the existence and absence of active faults, in this study, we assumed the impact of crustal movement to be insignificant.

As can be seen in the schematic diagram of valley floor terraces in Fig. 2, the terraces consist of brownish-yellow loam or unconsolidated sand to silt (N value smaller than 4 by a standard penetration test). The first terrace is estimated to have been formed 26,000 years ago or later on the basis of a trench excavation of historic site (Fig. 1); the second terrace is believed to have been formed in the recent epoch (Holocene). The sea level began falling 120,000 years ago during the last glacial period but has been rising since 18,000 years ago. In other words, any terraces formed due to sea level drop would have formed between 120,000 and 18,000 years ago. Given that the target section of the Yosasagawa is located approximately at 80 km inland from the coastline, we assumed that the influence of sea level drop was insignificant.

Investigation method

The goal of this study was to explore the significance of lateral erosion traces left during the 1998 flood (peak discharge of 1,740 m3/s) and the significance of the terrace landforms cut into the valley floor was confirmed during our field survey. In our investigation, we (i) surveyed the present day microtopography, interpreted historical aerial photographs, and analyzed measurements taken at the time of the disaster with the goal of understanding geomorphological characteristics of the study site, and (ii) examined existing geological maps and geological survey results to understand the geological characteristics. In addition, we evaluated the composition of the surface soil using a boring stick and analyzed the various hydrologic factors at the time of peak flood discharge. We conducted our investigation while comprehensively considering all of the above.

RESULTS

Geomorphological characteristics

Photograph 2 shows terrace landforms observed along the valley floor. Terrace height ranges from 0.3 to 1.2 m. At first glance, it appears that these landforms may have been formed during farmland consolidation. In order to confirm that these terraces existed prior to farmland consolidation, we interpreted aerial photos taken by the US armed forces in 1947 (the oldest aerial photographs that still exist), which predate substantial artificial improvement of the landscape, superimposed with the terrace locations. As can be seen in Fig. 3, although there are minor discrepancies in a few locations, for the most part, the historical terrace locations match up with the present terrace locations. This and that the terraces, although varying in height, lie in series in the same direction as the river indicate that the terraces existed prior to farmland consolidation.

It is worth special mention that the lateral erosion caused by the 1998 flood widened the channel width three- to fivefold. Figure 3 indicates the locations of erosion traces on the left and right banks of the widened channel. We defined the width of the cutbank to be the erosion width.

Although erosion width varies considerably by location, by comparing the terrace locations in the 1947 aerial photograph with present-day terrace locations, we can ascertain that erosion has occurred on the inner banks of the meandering river channel. We believe that these represent erosion traces that were formed by water flows shortcutting meandering segments of the river channel during a large-scale flood event.

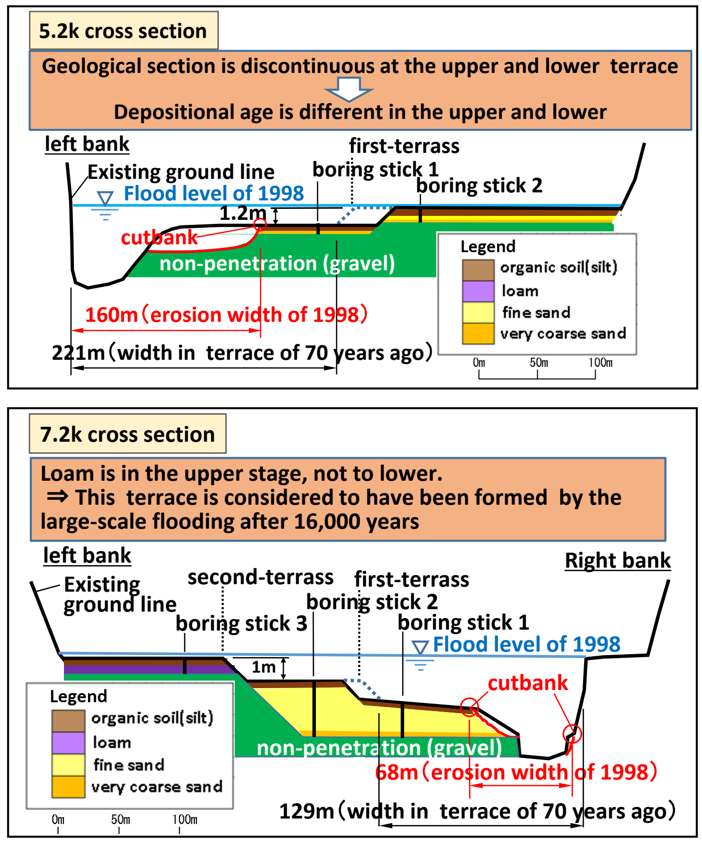


Fig. 4 cross section of valley plain in Yosasagawa Riv.(10:1 format)

Geological characteristics

In order to clarify the terrace formation process, we confirmed the geological continuity of the land interrupted by terraces by collecting surface soil samples to a depth of 1 to 2 m (down to the impenetrable pebble layer) using a boring stick.

We measured and surveyed terraces along four transverse transects at representative locations where the valley floor widens (5.2 k, 6.8 k, 7.2 k, and 8.2 k) (Figs. 1 and 3). The results of this survey, shown in Fig. 4, reveal the following:

(1) We observed one or two terraces along each transect. Terrace heights ranged between 0.3 and 1.2 m. The terraces consisted of two types: those that are 0.5 m or less in height and are difficult to discern in the field, and distinct terraces that are on the order of 1 m in height.
(2) For terraces that are on the order of 1 m in height, we were unable to confirm the continuity of soil quality above and below the terrace (first terrace on the right bank at 5.2 k and second terrace on the left bank at 7.2 k).
(3) The upper surface of the second terrace on the left bank at 7.2 k was found to consist of brownish-yellow loam. Although we did not determine the age of this brownish-yellow loam, we are certain that it was deposited before the most recent magma eruption of Mt. Nasu, which occurred 600 years before present. Thus, we can conclude that the second terrace was formed through the erosive action of a large-scale flood sometime after the deposition of the loam.

DISCUSSION

Significance of the erosion width at points where lateral erosion traces were left by the 1998 flood

The valley walls of the Yosasagawa that flows along the erosional valley-floor were formed 400,000 to 500,000 years ago by compacted KUROISO debris avalanche deposits. Because the kuroisoiwa is highly resistant to erosion, even if flow occurs toward the outer river bank, erosion width does not readily increase. In contrast, when flow occurs toward the inner river bank, the loose Holocene sediment is readily eroded, causing large-scale river bank recession and increased erosion width.

In the 1998 flood, erosion width was large in some locations (5.2 k and 8.2 k) and smaller in others (6.8 k and 7.2 k). We believe that erosion width is determined by channel sinuosity, channel cross-sectional geometry, water depth, and flow velocity.

If we use erosion width as the channel width for stable channel cross-sectional geometry in the Fukuoka equation, as can be seen in Fig. 5, then data points for locations with large erosion widths (5.2 k and 8.2 k) fall close to the mean curve of the Fukuoka equation; in contrast, data points for locations with small erosion widths (6.8 k and 7.2 k) diverge substantially from the Fukuoka equation. These results suggest that erosion width for cross-sections with large erosion widths represent the appropriate channel width for determining stable channel cross-sections.

Significance of terraces cut into the valley floor

In this study, we found that terraces on the order of 1 m in height occurred transverse to the direction of the valley floor. Given that the locations of these terraces confirmed in aerial photographs taken by the US armed forces in 1947, which predate any substantial artificial improvement of the landscape, were slightly shifted toward the valley wall compared to erosion traces of the 1998 flood (Fig. 3), we believe that terraces in locations such as 5.2 k and 8.2 k compatible with the previously mentioned Fukuoka equation that are also in locations where there is only one terrace may represent erosion traces formed by extreme discharge as part of the process of valley floor formation.

Fig. 5 shows a plot of the Fukuoka equation based on the relationship between the dimensionless channel width and dimensionless discharge for 5.2 k and 8.2 k. Using this curve, we then seek the dimensionless discharge associated with the dimensionless width of the first terrace. The resulting discharge is calculated to be in the range Qp = 3,600 to 3,900 m3/s, which is approximately double the discharge of the 1998 flood.

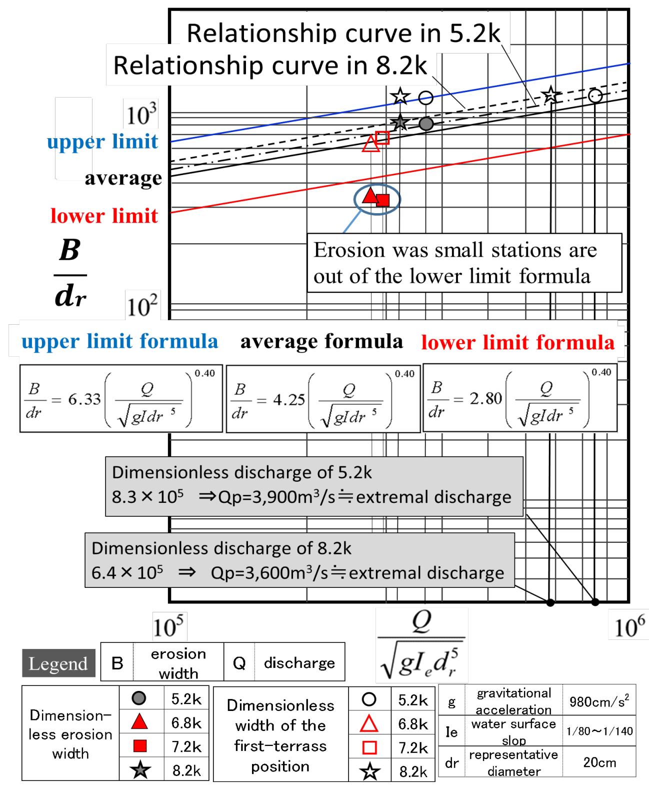


Fig. 5 Correlation of dimensionless erosion width to dimensionless

CONCLUSIONS

(1) This study demonstrates the possibility of utilizing historic geological maps and aerial photographs and conducting detailed microtopographic and geological surveys of the field site using simple instruments such as boring stick to clarify the historical development of river landforms and to estimate extreme discharge.
(2) We confirmed the location of terraces formed along an erosional valley-floor believed to have been minimally impacted by crustal movement and sea level change by using aerial photographs taken by the US armed forces in 1947, which predate any substantial artificial improvement of the landscape, and surveyed the soil quality and composition using a boring stick. High terraces on the order of 1 m in height that also exhibit discontinuity in the soil profile may have been formed by erosive action during a large-scale flooding event.
(3) We believe that the development of flow on the inner bank-side of meandering channels varies depending on the interactions between channel sinuosity, channel cross-sectional geometry, water depth, and flow velocity and, further, that this flow impacts the magnitude of erosion width.
(4) By thinking about the hydrologic characteristics of the Yosasagawa that flows along the valley floor separately in terms of single cross-

sectional flow and compound cross-sectional flow, for each location, we were able to estimate the extreme discharge that formed the valley floor. Based on this analysis, we estimated the extreme discharge to be approximately twice that of the 1998 flood.

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