Characteristics of Past Flood Behavior Reconstructed from Botanical Evidence in a Mountain Gorge River System

Takashi KIMURA¹, Sunao WATANABE¹, Suk-Woo KIM², Tomomi MARUTANI¹

¹ Dept. of Forest Science, Graduate School of Agriculture, Hokkaido University (Kita-ku, Sapporo, Hokkaido 060-8589, Japan)
² College of Forest and Environmental Sciences, Kangwon National University (Chunchon 200-701, Korea)

To reconstruct the history of high-magnitude floods in a mountain gorge channel, botanical evidence from two vertically isolated strath terraces assumed to be affected only by large, infrequent floods was investigated. The maximum water level was estimated from peak and bankfull discharges during major storm events of the past 20 years. Injury of shrubs significantly indicated that overflow on the downstream terrace occurred in 1993 storm event, but no flood event overflowed both terrace surfaces according to the estimation of peak and bankfull discharges. We also found field evidences that a landslide on the slope opposite the downstream terrace generated a landslide dam in 1993 storm event. Formation of the landslide dam probably caused local overflow onto the downstream terrace during the 1993 event. Therefore, it is essential to investigate not only the hydrologic characteristics, magnitude, and frequency of discharge, but also the spatial and temporal patterns of lateral sediment input to the channel to understand flood behavior in mountain gorge river systems.

1. Introduction

Flood history is fundamental information for understanding the characteristics of river hydrology and predicting flood and sediment disasters. However, flood history is often unknown in mountain gorge river systems where gauging data are scarce. To reconstruct flood history in such settings, botanical evidence has proven to be a reliable tool and has been used for several decades by geomorphologists [Sigafoos, 1964; Alestalo, 1971; Hupp, 1988; Gottesfeld, 1996; George and Nielsen, 2000].

Such evidence includes corrosion scars on trees left by flood-borne debris and stem tilting caused by the force of a flood. Tree scars and annual rings thus provide unique temporal information about flood history [Hupp, 1988]. Scar heights on injured trees can also indicate the flood stage [Hupp, 1988]. Despite the high availability of botanical evidence, vegetation-based reconstructions of flood history have mainly examined valley bottom vegetation that would be disturbed by ordinary flood events [George and Nielsen, 2000]. However, vegetation on the valley bottom and, occasionally, sediment deposits at a vegetated site are susceptible to removal by high discharge. Thus, botanical evidence of a large flood may not remain at the valley bottom. For purposes of flood and sediment disaster mitigation, records of large, infrequent flood events are crucial because of the potential of such events to cause disaster. Therefore, to reconstruct flood history, botanical evidence should be collected from areas isolated from valley bottoms that only experience large, infrequent floods [George and Nielsen, 2000].

This study examined botanical evidence represented by tree scars and forest structure on strath terraces that were vertically isolated from the valley bottom. To reconstruct the magnitude of flood overflow onto terrace surfaces, the highest water levels during major storm events were also estimated using a hydraulic equation.

2. STUDY AREA

The field site was Oyabu Creek, a headwater catchment of the Hitotsuse River located in the Kyushu Mountain Range, Japan (Fig. 1). Mean annual rainfall is approximately 3500 mm, with rainfall concentrated in the rainy season from June to October. Geologically, the Oyabu Creek catchment consists of weathered and crushed Mesozoic sandstone and shale phylite, underlain by the Nobeoka-shibisan tectonic line [Hashimoto, 1957]. Because the Oyabu catchment has experienced rapid uplift, channel incision into the bedrock has dominated [Moriwaki, 2001]. Currently,
strath terraces exist along the meandering channel course. The mean channel width, channel slope, and sinuosity are 13.2 m, 0.02 m m$^{-1}$, and 2.09, respectively. On the strath terraces, most of the canopy layer consists of *Pinus densiflora*, with clusters of shrubs such as *Rhododendron reticulatum*, *Pieris japonica*, and *Stewartia monadelpha* in the understory (Fig. 2C, D). Three major storm events were recorded in the Oyabu Creek area during the past 20 years. A typhoon in September 1993 (rainfall intensity exceeded 108.5 mm h$^{-1}$ with an antecedent rainfall of 428 mm for almost 3 days until the rainfall gauge was broken) triggered landslides and induced major channel bed aggradation along Oyabu Creek [Kasai et al., 2004], and storms in September 1997 (834 mm for 3 days) and September 2005 (1101 mm for 4 days) also induced landslides.

3. METHODS

3.1. Reconstruction of flood history from botanical evidence on strath terraces

A preliminary field survey found that strath terraces were continuously distributed on the inside of the meander bend along the 1.5-km study reach (Fig 1). The terraces were primarily composed not only of fluvial deposits, but also of bedrock blocks, indicating that they were created by long-term channel incision into bedrock. Two typical terraces that had vegetation and that seemed to have suffered large, infrequent flooding were selected (Terrace 1 and Terrace 4 in Fig. 1). Survey plots 15 × 30 m (Terrace 1) and 20 × 40 m (Terrace 4) in size were placed on each terrace along the streamflow direction. Because Terrace 1 consisted of two terrace surfaces of obviously different height, the survey plot was laid across both surfaces (3.0 m and 4.2 m, shown as higher and lower terrace in Fig. 1).

To detect flood evidence, vegetation structure, position, species, and diameter at breast height (DBH) of all trees were recorded in each plot. Tilt degree and direction were also measured using a clinometer. For injured trees, the heights of scar tops on tree trunks (hereafter, scar height) were also measured. To identify the age and injury years using dendrochronological methods, cross-sectional disks from 17 shrub tree individuals and increment cores from 10 canopy tree individuals were extracted within and around the plots. All increment core and disk samples were sanded, and their annual rings and scars were counted under a stereomicroscope. To avoid errors in the tree ring count caused by missing or false rings, a list method of cross-dating [Yamaguchi, 1991] was also applied.

Fig. 1 Map of the study site reach in Oyabu Creek, headwater streams of Hitotsuse River Catchment. Spatial distribution of strath terraces that were obtained by a preliminary field survey along the study reach were illustrated on the magnified reach map.
3.2. Estimation of peak and bankfull discharges during major storm events

To determine the peak discharge during each storm event, we applied an empirical relationship, including high flow data, determined in a previous study of Oyabu Creek [Kasai et al. 2004]. The daily water discharge for day \( t \), \( Q_t \) (m\(^3\) s\(^{-1}\)), was derived from an index of daily stream flows \( F_t \) as follows:

\[
Q_t = 38.64 F_t + 1.02 \quad (n = 344, R^2 = 0.88) \quad (1)
\]

\( F_t \) (m) was derived from rainfall data as follows:

\[
F_t = R_t + 0.5 R_{t-1} \quad (2)
\]

where daily rainfall data for day \( t \), \( R_t \) (m), were measured at the office of the Siiba Research Forest, located approximately 6 km from the study site. The empirical equation was generated based on discharge recorded at the downstream end of the study reach, where major tributaries (the Kouchino-tani and Shikino-tani) flow into the main stream; thus the estimated discharge should have been larger than the actual discharge at each terrace.

\[
F_t = R_t + 0.5 R_{t-1}
\]

Table 1 Summary of stand structure measured in the two terraces

<table>
<thead>
<tr>
<th>Species</th>
<th>Terrace 1</th>
<th>Terrace 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Density</td>
<td>Injury ratio(^{a})</td>
</tr>
<tr>
<td></td>
<td>no ha(^{-1})</td>
<td>%</td>
</tr>
<tr>
<td>Canopy layer(^{a})</td>
<td>222</td>
<td>0.0</td>
</tr>
<tr>
<td>Understory Rhododendron reticulatum</td>
<td>911</td>
<td>4.9</td>
</tr>
<tr>
<td>Pieris japonica</td>
<td>1400</td>
<td>4.8</td>
</tr>
<tr>
<td>Other species</td>
<td>844</td>
<td>10.5</td>
</tr>
</tbody>
</table>

\(^{a}\)Canopy layer mainly consisted of Pinus densiflora (over 50% of tree number) with Abies firma, Tsuga sieboldii and Quercus crispula in both two stands.

\(^{b}\)Injury ratio is defined as the ratio of the number of injured trees to the total number of individuals at each survey plot.
point (see Fig. 1 for location). The peak discharge at the terraces was then estimated taking the ratio of the drainage area into account as follows:

\[ Q_t' = 0.60 Q_t \]  

(3)

To examine whether the study terraces experienced inundation, bankfull discharge \( Q_b \) \( (\text{m}^3 \text{s}^{-1}) \) during each event was estimated from Manning’s equation, expressed as:

\[ Q_b = A S^{0.67} R^{0.50} n^{-1} \]  

(4)

where \( A \) is the cross-sectional area of the channel bounded by terraces \( (\text{m}^2) \), \( S \) is the channel slope \( (\text{m} \text{m}^{-1}) \), \( R \) is the hydraulic radius \( (\text{m}) \). To determine Manning’s roughness coefficient \( n \), we applied Jarrett’s [1984] equation derived from steep mountain streams, given as:

\[ n = 0.32 S^{0.38} R^{-0.16} \]  

(5)

The cross-sectional profiles of the channel, including both terraces and the channel slope, were obtained from field observation data collected during the past 15 years. Measurement along the study reach has been conducted since July 1995. Cross-sectional profiles surveyed in July 1995 were used to estimate bankfull discharge in September 1993. Bankfull discharges were also estimated for the storm events in September 1997 and September 2005. In order to take account changes in channel geomorphology induced by the storm events, cross-sectional profiles measured at May 1997 and October 1997, and those measured at August 2004 and July 2005 were used for 1997 event and 2005 event, respectively.

4. RESULTS

4.1. Stand structure and disturbance history of terrace forests

The stand structures measured in the two survey plots are summarized in Table 1. In both terraces, the canopy layer was dominated by \( P. \) densiflora established 40–80 years ago. Understory vegetation on both terraces primarily consisted of shrubs such as \( R. \) reticulatum and \( P. \) japonica. For each species, the injury ratio on Terrace 4 was 1.7–3.0 times higher than that on Terrace 1. The tilt directions of these two species appeared to be biased against the downstream direction on Terrace 4, and the tendency was unclear on Terrace 1 (Fig. 3). However, the degree of tilt varied widely in the two species and did not differ much between the two terraces (Table 1).

Scars and tree rings of shrubs suggested that most trees were injured in 1993 or established after that year on Terrace 4. In contrast, the injury and establishment years of shrubs were different from each other on Terrace 1 (Table 2). Although no substantial difference was found between the two terraces in terms of the ranges of scar heights (from 0.2 to 1.1 m on both terraces), the scar heights of

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Disturbance years and ages of shrub species ((R. ) reticulatum ) and ( P. ) japonica) sampled in the two terraces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>No.</td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
</tr>
<tr>
<td>Terrace 1</td>
<td>Rhododendron reticulatum</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pieris japonica</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrace 4</td>
<td>Rhododendron reticulatum</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pieris japonica</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3

Inclination direction of the two shrub species \((R. \) reticulatum \) and \( P. \) japonica\) on the two terraces.

Terrace 1
- Downstream direction: SW
- Number of trees: 103

Terrace 4
- Downstream direction: S
- Number of trees: 186
trees injured in 1993 showed a small range of values (from 0.4 to 0.6 m) on Terrace 4 (Table 2). Thus, a large proportion of the shrubs on Terrace 4 may have been simultaneously wounded by coarse, flood-borne materials when the water level reached the terrace surface during the 1993 storm event.

4.2. Possibility of overflow during storm events

Peak discharges of the three events ranged from 15 to 20 m$^3$ s$^{-1}$ (Table 3), at least 20 times higher than base flow at the study reach (0.61 m$^3$ s$^{-1}$). Bankfull discharges varied during the storm events, reflecting temporal and spatial changes in the cross-sectional profile (Fig. 4). Among the three events, estimated bankfull discharges were lowest in 1997 and highest in 2005 at both terraces (Table 3). Because the channel bank morphology of the two terraces appeared to be stable (Fig. 4), the channel bed adjustment process substantially affected changes in bankfull discharges during the period. Nevertheless, bankfull discharges were estimated to be 1.9–6.2 times higher than peak discharges. Thus, overflowing onto the terraces may be improbable in any rain event.

4.3. Additional field evidence from Terrace 4

Some other field evidence of the 1993 event remained on Terrace 4. A large landslide scar was located on the side of the creek opposite the terrace (Fig. 5). This landslide was approximately 6340 m$^2$ in area and connected with the channel. Thus, the channel must have directly moved large amounts of sediment generated by the landslide. Finer particles possibly yielded by the landslide were still deposited on the terrace surface and slope facing the landslide scar. Moreover, hemlock (*Tsuga sieboldii*) tree rings indicated tree injury in 1993 (Fig. 5). These evidences suggest that the landslide occurred in 1993, yielding sediment that buried the side terrace slope on the opposite side of the channel. According to these evidences, height of this landslide dam reached 3.0–3.4 m above the channel bed that is almost equal to the terrace height.

5. DISCUSSION AND CONCLUSIONS

This study reconstructed the history of large, infrequent floods using botanical evidence from two vertically isolated strath terraces, and estimated the maximum water levels from peak and bankfull discharges during major storm events over the past 20 years. On the downstream terrace (Terrace 4), scars and the tilt of shrubs suggested that the creek overflowed onto the terrace in the 1993 storm event, whereas no significant evidence of overflow was found on the upstream terrace (Terrace 1) (Table 2 and Fig. 3).

The maximum water level, estimated from scar heights of injured trees on the downstream terrace, was approximately 4.0 m above the channel during the 1993 storm event. In contrast, peak discharges in the major events were not sufficient to cause overflow onto the terraces (Table 3). Estimations of flood discharge in mountain streams from hydraulic equations such as Manning's equation can include serious errors. Errors mainly are attributed to underestimation of channel roughness coefficient due to complexity of channel morphology such as obstructions, vegetation and irregular banks [Jarrett, 1987]. Jarrett's [1984] equation, using in this study, developed by in situ measurements on 21 mountain streams with boulder or cobble bed material and is

### Table 3 Estimation of peak and bankfull discharge at the three heavy rainfall events

<table>
<thead>
<tr>
<th>Event</th>
<th>Peak discharge, m$^3$/s</th>
<th>Bankfull discharge*, m$^3$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Terrace 1</td>
<td>Terrace 4</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>September 1993</td>
<td>16.66</td>
<td>35.93 - 63.71</td>
</tr>
<tr>
<td>September 1997</td>
<td>15.02</td>
<td>28.54 - 64.25</td>
</tr>
<tr>
<td>September 2005</td>
<td>19.75</td>
<td>44.61 - 71.24</td>
</tr>
</tbody>
</table>

* Ranges of bankfull discharge were produced by differences in sampled three cross sections at each terrace and changes in each cross section before and after the events.

Fig. 4 Net changes in channel and terrace cross section at the two terraces between July 1995 and July 2009.
often applied to predict channel roughness coefficient for high-gradient (slopes from 0.002 to 0.05 m m⁻¹) streams [e.g. Phillips, 2002]. Thus, the equation can be applied in this study reach (averaged slopes: 0.02 m m⁻¹). In order to take into account of geomorphic changes due to channel fill or scour, we estimated the channel roughness coefficients with profile data before and after storm events. The estimated bankfull discharges were 1.9-6.2 higher than the peak discharges (Table 3). Although they would be considered minimum because we did not include additional energy losses by other factors (e.g. bank vegetation), the error may not be high as much as it compensate the differential between the peak discharge and the estimated bankfull discharge at each storm event.

The strath terraces along Oyabu Creek were created by progressive channel incision in response to rapid uplift [Moriwaki, 2001]. Almost all terraces are over 3 m above the contemporary channel, suggesting that flow rarely overflows the terraces to disturb their vegetation. The inconsistency in botanical evidence between the two terraces also suggests that overflow associated with peak discharge alone did not occur during the study period. We additionally detected evidence of landslide occurrence in 1993 on the slope opposite the downstream terrace, and the yielded sediment appeared to have completely buried the channel (Fig. 5). Height of this landslide dam reached 3.0-3.4 m above the channel bed that is almost equal to the height of terrace surface, and 0.6-1.0 m below the estimated maximum water level in 1993 storm event. Although increased water level due to the landslide dam was failed to estimate because of uncertainty of flow profile at time of the overflow, formation of the landslide dam probably caused the overflow onto the downstream terrace and the water level reached 4.0 m above the channel. However, more accurate estimation of landslide volume and dam longevity induced by the 1993 storm event is required to elucidate the overflow process, including landslide dam formation and subsequent failure.

On the other hand, the botanical evidences also showed other factors that caused injury of trees and shrubs (Table 1, 2). Another possible reason for injury of shrubs is stripping bark and fraying with antlers by deers [Gill, 1992]. In the Oyabu catchment, sika deer (Cervus nippon) density has begun to increase between 1976 and 1984 [Murata et al., 2009], and rates of bark stripping increased since 1983 [Sakuragi et al., 1999]. Because the injury years of shrubs on the two terraces ranged from 1986 to 2005 (Table 2), those injuries are likely to attribute to bark stripping by sika deer. Nevertheless, Inoue and Koizumi [1996] reported that bark stripping was markedly biased toward species such as Clethra barbinervis, Parabenzoin trilobum, Euonymus oxyphyllus, Ilex crenata and Ilex pedunculosa. Thus, damages to the two species that we sampled (R. reticulatum and P. japonica) might not be frequent neither intensive in the study site.

In a previous study of Oyabu Creek, Kasai et al. [2004] reported that the channel adjustment process was characterized by progressive degradation following a major aggradation in 1993 caused by landslides. They also found the vegetation structure on strath terraces provided longer-term evidence (i.e., based on tree injury and establishment years) that this process occurs in approximately 20-year “cycles.” Our results suggest that landslide dam formation during the 1993 event caused local overflow (Table 2 and Fig. 3). Thus, the abrupt channel bed aggradation induced by the 1993 storm event [Kasai et al., 2004] probably represented heterogeneous sediment storage rather than uniform sedimentation, reflecting spatial distribution of landslide occurrence (Fig. 5). Such heterogeneity in
channel bed aggradation should be considered in flood history reconstruction based on botanical evidence from vertically isolated sites.

Because steep, narrow valley floors commonly feature closely coupled relationships between hillslopes and the channel [Harvey, 2002], temporary or permanent stream blockages by mass movements such as landslide dams are common phenomena in such settings [Korup, 2002]. Flooding due to landslide dam may also occur frequently in mountain gorge channels. Therefore, it is essential to investigate not only the hydrologic characteristics, magnitude, and frequency of discharge, but also spatial and temporal patterns of lateral sediment input to the channel to understand flood behavior in mountain gorge river systems. Botanical evidence vertically isolated from the valley bottom allows reconstruction of large, infrequent flood behavior.

ACKNOWLEDGMENTS: We thank Osamu Shimizu and Masanori Nunokawa for their support and interpretation of geomorphic processes in the field. We also thank the staff from the Siiba Research Forest of Kyushu University who provided rainfall data as well as hospitality during the fieldwork. We are also grateful to Satoshi Okamoto and Keisuke Sakurai for their support in the field survey and in processing the data. This work was supported in part by Global COE Program (Establishment of Center for Integrated Field Environmental Science), MEXT, Japan.

REFERENCES


