A Morphometric Approach to Post-Glacial Channel Development in the Mountains of Central Japan

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Abstract: In Japanese mountains, erosive force markedly increased after the Pleistocene—Holocene transition because of increased heavy rainfall, resulting in channel incision along hillslope hollows and tributaries. This paper investigates the process of channel incision in the Matsumoto Region of central Japan based on morphometry. Attention is directed toward the effects of headward erosion and channel widening on channel expansion. Channel length and area occupied by channels were measured for more than eight hundred 500×500 m morphometric samples taken from eight watersheds. Analyses of channel length and channel area based on location-for-time substitutions have revealed that channels develop through two stages. At the early stage, the channel length—channel area relation is expressed by a power function. The function indicates that headward erosion contributes to about 80 percent of the channel-area increase whereas channel widening contributes to about 20 percent. At the late stage, channel length tends to be unchanged owing to the stabilization of channel heads, and channel widening solely accounts for the channel-area increase. The stabilization of channel heads occurs when channel length has reached about 80 percent of total valley length. The ratio of 80 percent most likely represents a limit of channel elongation determined by the geomorphological and hydrological threshold of erosion.

Key words: channels, headward erosion, channel widening, morphometry, Japan

Introduction

Formation of channels has been an object of study in the field of geomorphology. Numerous researchers have investigated channels or gullies on hillslopes from morphological and hydrological viewpoints (e.g., Horton 1945; Heede 1970; Tsukamoto 1973; Dunne 1980; Ebisemiju 1989; Montgomery and Dietrich 1989; Dietrich and Dunne 1993). Previous studies have indicated that channels on hillslopes are dynamic or unstable geomorphic elements, whose forms change rapidly with the alteration of extrinsic variables. For instance, channel incision is often enhanced owing to changes in base level, vegetation cover, and climate particularly rainfall (e.g., Graf 1982; Dietrich and Dunne 1993; Selby 1993).

In Japanese mountains, incised channels due to Pleistocene—Holocene climatic change occur along hillslope hollows and tributaries (e.g., Ono and Hirakawa 1975; Hatano 1979; Tamura 1987; Oguchi 1988a, 1992, 1994a, 1994b; Yanai

1989). The Japanese Islands are subject to heavy rains with the world's highest intensity (Matsumoto 1993), because they lie below the Polar frontal zone in early summer and typhoon tracks in late summer and autumn. By contrast, the frequency of such heavy rains was markedly reduced in the late Pleistocene because of the southward shift of frontal zones (Suzuki 1971; Sugai 1993). Thus, during the Pleistocene—Holocene transition, dominant hillslope processes changed from freeze-thaw actions to storm-induced slope failure and subsequent channel incision. The resulting channels can be identified by tracing marked convex breaks of slopes on aerial photographs (Hatano 1979; Oguchi 1988a, 1994a, 1994b). Therefore, Japanese mountains provide a good example to analyze channel development on steep hillslopes. Few studies on Japanese mountains, however, focused on the process of post-glacial channel expansion, although researchers pointed to the existence of incised channels, made their mapping, and related them to climatic changes (Hatano 1979; Tamura 1987; Oguchi

1988a, 1994a, 1994b).

Previous studies on channels and gullies have paid much attention to the processes of headward erosion and factors controlling the position of the heads (e.g., Horton 1945; Segner 1966; Graf 1977, 1982; Montgomery and Dietrich 1989; Dietrich and Dunne 1993). Some researchers have also examined erosion at the side walls of channels or gullies and the resultant increase in channel width (e.g. Tuckfield 1964; Blong 1970; Ebisemiju 1989; Tanaka 1990; Joshi and Kale 1995). Thus, we need to discuss channel development by considering both headward erosion and widening. The effects of the two processes, however, have not been fully understood, since previous studies tended to lack quantitative analyses of channel forms using a large data set.

This paper discusses the process of post-glacial channel incision in mountains of central Japan based on morphometric analyses. Attention is addressed to the effects of headward

erosion and channel widening on channel expansion. Mountain river basins in the Matsumoto Region were selected as a study site, since incised channels formed after the Pleistocene—Holocene climatic change are well developed (Oguchi 1988a, 1988b, 1992).

The Study Area

Regional setting

Eight river basins surrounding the Matsumoto Basin were surveyed (Figure 1). The river basins, which have alluvial fans in their lowest reaches, consist mostly of steep valley-side slopes, with minor fluvial terraces along trunk streams and major tributaries. The area of the basins ranges from 12 to 78 km², the altitude at the fan apex from 720 to 830 m, and the maximum altitude from 1,935 to 2,922 m. The relief ratio, basin relief divided by basin length (Schumm 1956), ranges from 0.10 to 0.29. The

Figure 1. Location map of study area, showing 8 river basins: (1) Chi, (2) Ashima, (3) Nakafusa, (4) Karasu, (5) Kurosawa, (6) Kusari, (7) Metoba, (8) Susuki. Contour interval is 500 m.

Figure 2. A channeled hillslope in the Kusari (No. 6) river basin.

C: channel (lower incised slope), U: Upper hollow (upper incised slope). Note that the area experienced recent logging. Channels developed previously, under the naturally forested condition.

basins are underlain by five major rock types: Paleozoic-Mesozoic sediments, Mesozoic granites, Neogene sedimentary and plutonic rocks, Quaternary volcanics, and Quaternary terrace gravels.

Most hillslopes are densely forested, except for recent landslide scars, the ridges of high mountains exposed to strong winds, and areas subjected to recent logging. The annual precipitation observed at a station near the study area (the Taisho-ike Pond Sta., 1,495 m in altitude) is about 2,500 mm (Japan Meteorological Agency 1959). Heavy rains generally fall in June, July, and September from storms associated with the Polar Front and typhoons. Storms often trigger hillslope failure, especially at the heads and walls of incised channels (Figure 2).

Types of hillslopes

From aerial-photo interpretation and tephrochronological field surveys, I already classified hillslope units in the river basins (Oguchi 1988a, 1988b, 1992). The hillslopes formed after the

Pleistocene—Holocene climatic change were classified into two: upper and lower incised slopes. The lower incised slope is a deep gully formed by the incision in consolidated bedrock. The upper incised slope is a hollow-shaped shallow depression that surrounds the lower incised slope (Figure 2). Shallow failures of the periglacial deposits that accumulated during the Last Glacial age have accounted for the formation of the upper incised slopes (Oguchi 1989, 1992). The lower incised slopes can readily be identified by tracing the edge of well-defined banks on aerial photos, whereas the borders of the upper incised slopes are less distinct (Figure 2). This fact indicates that the lower incised slopes are comparable to "channels" defined by Dietrich and Dunne (1993), who note that channels are separated from surrounding hillslopes by well-defined banks. In addition, perennial flow often occurs in the bottoms of the lower incised slopes, whereas the bottoms of the upper incised slopes are generally dry. Therefore, the lower incised slopes are considered as

Figure 3. Distribution of incised channels and fluvial surfaces (river terraces and valley bottoms) in the Nakafusa (No. 3) river basin. (Simplified after Oguchi, 1988a)

channels in this paper. The mapping of the channels has revealed that their network extends to whole parts of the river basins (Figure 3). Although erosion on the upper incised slopes may modify the position of channel edges, the depth of the erosion is much more limited than that of channel incision (Figure 2). Furthermore, at a given part of hillslopes, periglacial deposits that had accumulated before the Late Glacial were generally eroded before channel incision, because the deposits were more erodible than bedrock (Oguchi 1989, 1992). These facts suggest that erosion on the upper incised slopes has played only a minor role in determining the position of channel edges. Therefore, erosion on the upper incised slopes was not taken into account in examining channel development.

Methods

A morphometric method was developed to evaluate the effects of headward erosion and channel widening on post-glacial channelization. Geomorphological and hydrological processes operating in channels have been monitored to construct models of channel development (e.g., Tuckfield 1964; Malde and Scott 1977; Schouten and Rang 1984; Onda, 1994). However, long-term channel development as discussed here cannot be monitored. Therefore, the process of channelization was inferred based on an indicator of relative time. Channel length (L), width (W), and area occupied by channels (A) in a terrain generally increases with the passage of time. Thus, terrains with different values of L , W , and A are regarded as representing the different stages of channel de-

velopment. This concept of "location-for-time substitutions" (Paine 1985) permits us to discuss the changes in channel forms with time based on morphometric parameters and their functional relations.

The following two functions were found to be useful in examining the effects of headward erosion and channel widening on channel expansion,

$$L=f(A) \quad (1)$$

and

$$W=g(A) \quad (2)$$

For a given time, the relation among the area occupied by channels in a terrain (A), the total length of channel axes (L), and mean channel width (W) is expressed as

$$LW=A \quad (3)$$

Channels expand owing to both headward erosion (erosion in a headward direction) and widening (erosion in a direction perpendicular to channel axes). Thus, Equation (3) after channel expansion can be written as

$$(L+\Delta L)(W+\Delta W)=A+\Delta A \quad (4)$$

where ΔA , ΔL , and ΔW are increases in channel area, length, and mean width, respectively. Subtracting both sides of Equation (3) from those of Equation (4), we have

$$L\Delta W+W\Delta L+\Delta L\Delta W=\Delta A \quad (5)$$

The three terms at the left side of Equation (5) represent different components of channel-area increase, i.e., $L\Delta W$ is the areal increase caused by widening of existed channels, $W\Delta L$ is that by headward erosion of existed channels, and $\Delta L\Delta W$ is that by widening and elongation of newly developed channels. During a short time (Δt), the third component is negligible, and thus Equation (5) can be simplified as

$$L\Delta W+W\Delta L=\Delta A \quad (6)$$

Dividing both sides of Equation (6) by ΔA , we have

$$L \frac{\Delta W}{\Delta A} + W \frac{\Delta L}{\Delta A} = 1 \quad (7)$$

where $L(\Delta W/\Delta A)$ represents the contribution

of widening during a unit increase of channel area, and $W(\Delta L/\Delta A)$ represents the contribution of headward erosion. If $\Delta t \rightarrow 0$, then ΔL , ΔW , and $\Delta A \rightarrow 0$, and thus Equation (7) is rewritten as

$$L \frac{dW}{dA} + W \frac{dL}{dA} = 1 \quad (8)$$

The substitution of Equations (1) and (2) into Equation (8) yields,

$$f(A)g'(A)+g(A)f'(A)=1 \quad (9)$$

Equation (9) shows that both the two terms on the left side of Equation (8) are functions of A that increases with the passage of time. Consequently, changes in the values of the two terms with A represent changes in the effects of headward erosion and widening with time. From Equations (1), (2), and (3), we have,

$$f(A)=\frac{A}{g(A)} \quad (10)$$

or

$$g(A)=\frac{A}{f(A)} \quad (11)$$

These equations show that, if either Equation (1) or (2) is known, the other equation can be derived from the known one. Consequently, only Equation (1) or (2) is necessary to analyze channel development based on Equation (9). If channel distribution is mapped, the measurement of channel length is much easier than that of average channel width, meaning that Equation (1) is obtained more readily than Equation (2). Thus, Equation (1) was first determined by morphometric measurements.

The first term on the left side of Equation (9), which represents the effect of channel widening on channel-area increment, is rewritten as $h(A)$. The substitution of Equation (11) into $h(A)$ yields

$$\begin{aligned} h(A) &= f(A)g'(A) = f(A) \left[\frac{A}{f(A)} \right]' \\ &= f(A) \left\{ \frac{f(A) - Af'(A)}{[f(A)]^2} \right\} \end{aligned}$$

$$= 1 - \frac{Af'(A)}{f(A)} \quad (12)$$

Similarly, the substitution of Equation (11) into the second term on the left side of Equation (9) gives the function $i(A)$ that expresses the effect of headward erosion

$$i(A) = g(A)f'(A) = \left[\frac{A}{f(A)} \right] f'(A) = A \frac{f'(A)}{f(A)} \quad (13)$$

Equations (12) and (13) show that the sum of $h(A)$ and $i(A)$ is unity, which satisfies Equation (9). The effects of headward erosion and widening on channel expansion were quantified using Equations (1), (12), and (13).

Morphometric Data

Geomorphometric data were collected from the river basins above the fan apex. To derive Equation (1) from statistical analyses of a large data set, data were sampled from 500×500 m square cells. The cells are the same as those used by Oguchi (1988b, 1996a, 1996b) to investigate factors affecting post-glacial hillslope incision and the effect of hillslope failure on drainage density. The data for the cells were found to be appropriate to analyze hillslope erosion in the finely dissected basins. The total number of cells in the basins was 1,659, from which those suitable for analyses were selected based on the following criteria. The main point

of this study was channels on hillslopes, and thus the data for 528 cells that include fluvial terraces and/or wide valley bottoms were not collected. Some cells are smaller than 500×500 m since they are located on basin divides. From total channel length in such a smaller cell (L_s ; m), channel length in a 500×500 m cell (L ; m) can be estimated using the following equation

$$L = 2.5 \times 10^5 \frac{L_s}{AC} \quad (14)$$

where AC is the area of a smaller cell (m^2). Similarly, channel area in a 500×500 m cell (A ; m) can be estimated from that in a smaller cell (A_s ; m)

$$A = 2.5 \times 10^5 \frac{A_s}{AC} \quad (15)$$

These estimations are less trustworthy if AC is much smaller than $2.5 \times 10^5 m^2$. Thus, the estimations were made for cells that have an area more than half of $2.5 \times 10^5 m^2$. Consequently, 864 cells were selected for analyses. For each cell, I measured the area occupied by channels and the total length of channel axes (Figure 4). The measurement was performed on 1:25,000 geomorphological maps with a digitizer. Channel length and area in the smaller cells were converted into those in 500×500 m cells using Equations (14) and (15).

Channels generally develop along hillslope depressions and tributaries, indicating that

Figure 4. Definition sketch of channel axes and hollow axes.

(a) Contour lines of small catchment, (b) definition of channels, channel axes, and hollow axes.

Figure 5. Distribution of channel area (A), channel length (L), and valley length (LV) for 500×500 m morphometric samples in the Nakafusa (No. 3) river basin.

* shows cells including river terraces and/or wide valley bottoms. Cells with an area less than a half of 500 m×500 m are not shown.

channel length and area in a cell probably vary depending not only on time, but also on the frequency of ridges and valleys determined before channel development. As an indicator of the frequency, the total length of valleys that include both channels and hollows above channel heads was measured for each cell. First, the unchanneled hollows were identified from all v-shaped contour lines shown in 1:25,000 topographic maps of the Geographical Survey Institute of Japan. Next, the total length of hollow axes was measured for each cell (Figure 4). If the size of a cell was less than $2.5 \times 10^5 \text{ m}^2$, the measured length was converted into that in a $500 \times 500 \text{ m}$ cell. The valley length (LV ; m) in a $500 \times 500 \text{ m}$ cell was computed as

$$LV = LH + L \quad (16)$$

where LH is the hollow length in a $500 \times 500 \text{ m}$ cell. The identified hollow axes combined with channel axes are the same as the "t-type drainage nets" in the reports of Inoue and Oguchi (1995) and Oguchi (1996b). Thus, LV is comparable to the density of t-type drainages. Figure 5 shows the distribution of channel area (A), channel length (L), and valley length (LV) in the Nakafusa (No. 3) river basin.

Data Analysis

Channel length—channel area relation for all sample cells

The relation between measured channel length and channel area was investigated to derive Equation (1). Figure 6 is a plot of L versus A for the 864 cells, showing a positive correlation. The plot reveals that L converges toward zero when $A \rightarrow 0$, indicating that the graph of the L — A relation goes through the origin. This is apparent because channel area should be zero if channel length is zero. Therefore, two equations through the origin were fitted to the data,

$$L = kA \quad (17)$$

and

$$L = mA^n \quad (18)$$

where k , m , and n are constants. The fitting of

the equations to the 864 data by the least-square method yields

$$L = 0.0252A \quad r = 0.854 \quad (17a)$$

and

$$L = 0.311A^{0.781} \quad r = 0.952 \quad (18a)$$

Both the equations have a good correlation with more than 99.99 percent confidence. Especially, the correlation expressed by Equation (18a) is highly significant.

Despite the good correlation, neither Equation (17a) nor Equation (18a) adequately describes the observed L — A relation. To illustrate a general trend of the L — A plot in Figure 6, the 864 cells were categorized by A in $1.0 \times 10^4 \text{ m}^2$ intervals or bins, and the mean of L for each bin was plotted against the modal value of A for the bin (Figure 7). The graphs of Equations (17a) and (18a) were also drawn in Figure 7, revealing that observed channel lengths for large A ($> \text{ca. } 1.1 \times 10^5 \text{ m}^2$) are systematically smaller than those predicted by Equations (17a) and (18a).

To derive an equation that fits better to the observed data, I divided the data into two according to the values of A . Figure 7 shows that Equation (18a) fits well to the data with small A , indicating that a power function adequately describes the L — A relation. By contrast, L tends to be constant for large A . Consequently, different equations were applied to the data with large and small A

For $A < A^*$

$$L = mA^n \quad (18)$$

For $A \geq A^*$

$$L = p \quad (19)$$

where A^* is a critical channel area (around $1.1 \times 10^5 \text{ m}^2$) whereafter channel length no longer increases with increasing channel area, and p is a constant. For the continuity of the L — A relation at A^* , the following equation needs to be held

$$mA^{*n} = p \quad (20)$$

Equation (20) was employed to determine the value of A^* . First, tentative values of A^* were set between $8.0 \times 10^4 \text{ m}^2$ and $1.5 \times 10^5 \text{ m}^2$ at 2.5

Figure 6. Plot of channel area (A) versus channel length (L) for 864 morphometric samples.

Figure 7. Plot of mean channel length (L) versus modal channel area (A) for groups categorized by channel area [open squares], and equations fitted to the L — A relation [thin dashed line: Equation (17a), thin solid line: Equation (18a), and bold solid line: Equation (18b) combined with Equation (19a)].

The combination of Equation (18b) and Equation (19a) fits best to the trend of the L — A relation.

$\times 10^3 \text{ m}^2$ intervals. For each A^* , the least-square method was applied to the data with $A < A^*$, to determine the constants m and n of Equation (18). The constant p of Equation (19) was also determined as a mean of L for the data with $A \geq A^*$. The calculated values of m , n , and p as well as the value of A^* were inserted into the following equation

$$j(A^*) = mA^{*n} - p \quad (21)$$

Among the tentative values of A^* , $1.125 \times 10^5 \text{ m}^2$ made $j(A^*)$ closest to zero, showing that the

value provided the best solution to Equation (20). When A^* is $1.125 \times 10^5 \text{ m}^2$, Equations (18) and (19) are written as:

For $A < 1.125 \times 10^5 \text{ m}^2$

$$L = 0.234A^{0.808} \quad r = 0.953 \quad (18b)$$

For $A \geq 1.125 \times 10^5 \text{ m}^2$

$$L = 2.81 \times 10^3 \quad (19a)$$

Figure 7 confirms that Equations (18b) and (19a) fit well to the trend of the observed L — A relation.

Channel length—channel area relation for selected cells with similar valley length

As noted, total channel length in a terrain depends not only on time but also on the frequency of ridges and valleys determined before channel incision. This supposition is affirmed from the positive correlation between valley length (LV) and channel length (L) for the 864 cells (Figure 8; $r=0.779$). In addition, channel area (A) and valley length are positively correlated (Figure 9; $r=0.688$). These correlations are significant with >99.99 percent confidence. Therefore, one can say that both the length and

the area of channels tend to be large where valley length was originally large. This may affect the channel length—channel area relation in Figure 6, i.e., the increase of channel length with increasing channel area can result from the increase in original valley length. If the effect of valley length is strong, Equations (18b) and (19a) are inappropriate to analyze the mode of channel development with time.

To minimize the effect of valley length and focus on the effect of time, the channel length—channel area relation was reexamined for cells with similar valley length around the average. As illustrated in Figure 10, the frequency distri-

Figure 8. Relation between valley length (LV) and channel length (L) for 864 sample cells, showing a positive correlation ($r=0.779$).

Figure 9. Relation between valley length (LV) and channel area (A) for 864 sample cells, showing a positive correlation ($r=0.688$).

Figure 10. Frequency distribution of valley length (LV) for 864 cells.

bution of valley length for the 864 cells is approximately a normal one, although it skews slightly to the left. Their average (χ) and standard deviation (σ) are 2.74×10^3 m and 6.92×10^2 m, respectively. Among the 864 cells, 334 cells have similar valley length between $\chi \pm 0.5\sigma$. The data for these cells were adopted to investigate channel development with the passage of time.

A plot of channel length (L) versus channel area (A) for the 334 cells (Figure 11) is similar to the plot for all the cells (Figure 6) in that L tends to increase with A , L converges into zero when $A \rightarrow 0$, and the rate of increase in L with increasing A decreases with A . Thus, Equation (1) for the 334 cells was determined by the same procedure as applied to the 864 cells. The fitting of Equations (17) and (18) to the 334 data yields

$$L = 0.0245A \quad r = 0.718 \quad (17b)$$

and

$$L = 0.605A^{0.719} \quad r = 0.916 \quad (18c)$$

The trend of the L — A relation in Figure 11 was shown by a plot of mean L against modal A categorized by 1.0×10^4 m² bins (Figure 12). The observed channel lengths for large A ($> \text{around } 1.0 \times 10^5$ m²) are systematically smaller than those predicted from Equations (17b) and (18c), and L tends to be constant for the large A (Figure 12). Thus, Equation (19) was fitted to the data with the large A , whereas Equations

(18) was fitted to the data with smaller A . The value of A^* , which separates the large A from the small A , was determined to be 9.75×10^4 m² by the same method as applied to the 864 data. Equations (18) and (19) for the 334 data were determined as:

For $A < 9.75 \times 10^4$ m²

$$L = 0.261 A^{0.798} \quad r = 0.923 \quad (18d)$$

For $A \geq 9.75 \times 10^4$ m²

$$L = 2.47 \times 10^3 \quad (19b)$$

These equations fit well to the trend of the observed L — A relation (Figure 12). The value of A^* and the constants of Equations (18d) and (19b) are different from those for the 864 data, suggesting that the L — A relation for the 864 data was affected by original valley length. Consequently, the processes of channel development with time were discussed using Equations (18d) and (19b), derived from the cells with similar valley length.

Discussion

The effects of headward erosion and widening on channel development were quantified based on the inferred morphometric relations. As noted, Equation (12) represents the component of channel-area increment due to widening, whereas Equation (13) represents the component due to headward erosion. If $f(A)$, the channel length—channel area relation, is given

Figure 11. Plot of channel area (A) versus channel length (L) for 334 selected cells with similar valley density.

Figure 12. Mean channel length (L) versus modal channel area (A) for groups of 334 selected cells categorized by channel area [open squares], and equations fitted to the L — A relation [thin dashed line: Equation (17b), thin solid line: Equation (18c), and bold solid line: Equation (18d) combined with Equation (19b)].

The combination of Equation (18d) and Equation (19b) fits best to the trend of the L — A relation.

by the power function of Equation (18), we have

$$A \frac{f'(A)}{f(A)} = A \frac{nmA^{n-1}}{mA^n} = n \quad (22)$$

The substitution of Equation (22) into Equations (12) and (13) yields

$$h(A) = 1 - n \quad (23)$$

and

$$i(A) = n \quad (24)$$

Equations (23) and (24) have revealed that the components of headward erosion and widening can be evaluated only from the exponent n of Equation (18). Equations (23) and (24) also suggest that change in A with the passage of time does not affect the two components as long as Equation (18) holds true. The value of n for Equation (18d) is 0.798 if $A < 9.75 \times 10^4 \text{ m}^2$, indicating that headward erosion is responsible for about 80 percent of channel-area increase, whereas widening is responsible for about 20

Figure 13. Relation between channel area (A) and ratio of channel length to valley length (L/LV) for 334 cells.

L/LV increases consistently with A for smaller A ($< \text{about } 9.75 \times 10^4 \text{ m}^2$), whereas it tends to be constant (ca. 0.8) for larger A .

percent.

The effects of headward erosion and widening can also be quantified for larger channel area. Equation (19) holds if $A \geq 9.75 \times 10^4 \text{ m}^2$, and thus $f'(A) = 0$. Consequently,

$$h(A) = 1 \quad (25)$$

and

$$i(A) = 0 \quad (26)$$

These equations show that only channel widening accounts for the increase in channel area. In conclusion, at the early stage of channel development, headward erosion plays a major role in determining channel area whereas widening plays a subordinate role. At the late stage, the effect of headward erosion becomes negligible, and channel widening is solely responsible for channel expansion.

The inferred mode of channel development agrees with previously suggested models. Dunne (1980) has indicated that headward erosion is faster than side-wall erosion at the early stage of channel formation, whereas headward erosion declines at the late stage. As to Colorado Plateau in the United States and Volcanic Plateau in New Zealand, Blong (1970) and Laity and Malin (1985) note that gully elongation at the early stage will later be replaced by gully widening. The present study reveals that the shift from headward erosion to widening takes

place not gradually but abruptly. In the study area, the shift occurs when $A \approx 9.75 \times 10^4 \text{ m}^2$, if original valley density is around the average.

The decline of headward erosion in the late stage of channel development agrees with the concept of "the belt of no erosion" (Horton 1945) or "the geomorphological/hydrological control of the position of channel heads" (Montgomery and Dietrich 1989; Dietrich and Dunne 1993). Regarding these concepts, Dunne (1980) has indicated that channel elongation by landsliding or spring sapping leads to smaller catchment area above the channel head, which later prevents further channel elongation owing to reduced erosive force. To test this hypothesis, the relation between channel area (A) and the ratio of channel length to valley length (L/LV) was examined for the 334 cells (Figure 13). The result has shown that the L/LV ratio increases rapidly with A when $A < A^*$ ($< 9.75 \times 10^4 \text{ m}^2$), whereas it tends to be constant when $A \geq A^*$. The L/LV ratio for cells with $A \geq A^*$ is around 0.8, indicating that the majority of valley bottoms has already been occupied by channels. The ratio of 0.8 most likely represents the morphological and hydrological limit of channel elongation, at which channel heads are stabilized owing to reduced erosive force. Channel widening, on the other hand, continues even after the cease of channel elongation, accounting solely for channel-area increase at the late

stage.

In this paper, channel development with time was examined for the selected cells with similar valley length to minimize the effect of original valley density. As noted, however, the trend of the channel length—channel area relation for the selected cells is similar to that for all the cells, suggesting that the effect of valley density is weaker than the effect of time. This hypothesis needs to be confirmed in future work.

Conclusions

This paper has investigated the processes of post-glacial channel development on steep hillslopes of central Japan. Length, width, and area of channels were analyzed for more than eight hundred 500×500 m morphometric samples taken from eight river basins. The process of channel expansion was estimated based on location-for-time substitutions. The stages of channel development can be divided into two. At the early stage, headward erosion contributes to about 80 percent of the increase in channel area, and widening contributes to about 20 percent. These ratios do not change with time as long as channel area is smaller than the threshold value. At the late stage when channel area exceeds the threshold, only channel widening accounts for the increase in channel area. This change in geomorphic processes, from headward-erosion dominant to widening, results from the stabilization of the channel heads that have reached upper hillslopes.

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References

- Blong, R. J. 1970. The development of discontinuous gullies in a pumice catchment. *American Journal of Science* 268: 369–383.
- Dietrich, W. E. and Dunne, T. 1993. The channel head. In *Channel Network Hydrology*, ed. K. Beven and M. J. Kirkby, 175–219. Chichester: Wiley & Sons.
- Dunne, T. 1980. Formation and controls of channel networks. *Progress in Physical Geography* 4: 211–239.
- Ebisemiju, F. S. 1989. A morphometric approach to gully analysis. *Zeitschrift für Geomorphologie Neue Folge* 33: 307–322.
- Graf, W. L. 1977. The rate law in fluvial geomorphology. *American Journal of Science* 277: 178–191.
- Graf, W. L. 1982. Distance decay and arroyo development in the Henry Mountains region, Utah. *American Journal of Science* 282: 1541–1554.
- Hatano, S. 1979. Mapping of post-glacial dissected hillslopes and its application to landslide prediction. *Abstracts, the Japan Society of Erosion Control Engineering* 1979: 16–17. (J)
- Heede, B. H. 1970. Morphology of gullies in the Colorado Rocky Mountains. *Bulletin of the International Association of Scientific Hydrology* 15(2): 79–89.
- Horton, R. E. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* 50: 275–370.
- Inoue, K., and Oguchi, T. 1995. Effects of hillslope failure on stream bifurcation ratios and stream length ratios for the Matsumoto Region, Japan. *Geographical Review of Japan* 68A: 447–464. (JE)
- Japan Meteorological Agency, The 1959. *The precipitation of Japan: monthly averages*. Tokyo. (J)
- Joshi, V., and Kale, V. S. 1995. The contribution of sidewall erosion in the gully development. In *Indian geomorphology: landform and process*, ed. S. R. Jog, 43–55. New Delhi: Rawat Pub.
- Laity, J. E., and Malin, M. C. 1985. Sapping processes and the development of theater-headed valley networks on the Colorado Plateau. *Geological Society of America Bulletin* 96: 203–217.
- Malde, H. E., and Scott, A. G. 1977. Observation of contemporary arroyo cutting near Santa Fe, New Mexico, U.S.A. *Earth Surface Processes* 2: 39–54.
- Matsumoto, J. 1993. Global distribution of daily maximum precipitation. *Bulletin of the Department of Geography, University of Tokyo* 25: 43–48.
- Montgomery, D. R., and Dietrich, W. E. 1989. Source areas, drainage density, and channel initiation. *Water Resources Research* 25: 1907–1918.
- Oguchi, T. 1988a. Landform development during the Last Glacial and the Post-Glacial ages in the Matsumoto Basin and its surrounding mountains, central Japan. *The Quaternary Research (Tokyo)* 27: 101–124. (JE)

- Oguchi, T. 1988b. Differences in landform development during the Late Glacial and the Post-Glacial ages among drainage basins around the Matsumoto Basin, central Japan. *Geographical Review of Japan* 61A: 872-893. (JE)
- Oguchi, T. 1989. Some considerations on mountain slope dissection in the vicinity of the Matsumoto Basin, central Japan. *Abstracts, Japan Association for Quaternary Research* 19: 74-75. (J)
- Oguchi, T. 1992. Responses of drainage basins to the Pleistocene-Holocene climatic change: Japan and other mid-latitude regions. *Bulletin of the Department of Geography, University of Tokyo* 24: 51-73.
- Oguchi, T. 1994a. Late Quaternary geomorphic development of alluvial fan-source basin systems: the Yamagata region, Japan. *Geographical Review of Japan* 67B: 81-100.
- Oguchi, T. 1994b. Late Quaternary geomorphic development of mountain river basins based on landform classification: the Kitakami region, Northeast Japan. *Bulletin of the Department of Geography, University of Tokyo* 26: 15-32.
- Oguchi, T. 1996a. Factors affecting the magnitude of post-glacial hillslope incision in Japanese mountains. *Catena* 26. (in press)
- Oguchi, T. 1996b. Drainage density and relative relief in humid steep mountains with frequent slope failure. *Earth Surface Processes and Landforms* 21. (in press)
- Onda, Y. 1994. Seepage erosion and its implication to the formation of amphitheatre valley heads: a case study at Obara, Japan. *Earth Surface Processes and Landforms* 19: 627-640.
- Ono, Y., and Hirakawa, K. 1975. Glacial and periglacial morphogenetic environments around the Hidaka Range in the Würm Glacial age. *Geographical Review of Japan* 48: 1-26. (JE)
- Paine, A. D. M. 1985. 'Ergodic' reasoning in geomorphology: time for a review of the term? *Progress in Physical Geography* 9: 1-15.
- Schouten, C. J., and Rang, M. C. 1984. Measurement of gully erosion and the effects of soil conservation techniques in Puketurua Experimental Basin (New Zealand). *Zeitschrift für Geomorphologie Neue Folge Supplement Band* 49: 151-164.
- Schumm, S. A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin* 67: 597-646.
- Seginer, I. 1966. Gully development and sediment yield. *Journal of Hydrology* 4: 236-253.
- Selby, M. J. 1993. *Hillslope materials and processes*. 2nd ed. Oxford: Oxford University Press.
- Sugai, T. 1993. River terrace development by concurrent fluvial processes and climatic changes. *Geomorphology* 6: 243-252.
- Suzuki, H. 1971. Climatic zones of the Würm Glacial Age. *Bulletin of the Department of Geography, University of Tokyo* 3: 35-46.
- Tamura, T. 1987. 1: 10,000 Geomorphological map of a large-relief hilly land composed of Neogene volcanic rocks. *Annals of the Tohoku Geographical Association* 39: 222-223. (J)
- Tanaka, Y. 1990. Rock control in the evolution of cross-sections of the valley dissecting the coastal terraces, west of the Funka Bay, Hokkaido. *Transactions, Japanese Geomorphological Union* 11: 97-115. (JE)
- Tsukamoto, Y. 1973. Study on the growth of stream channel (I)—relationship between stream channel growth and landslides occurring during heavy storm. *Journal of the Japan Society of Erosion Control Engineering (Shin-sabo)* no. 87: 4-13. (J)
- Tuckfield, C. G. 1964. Gully erosion in the New Forest, Hampshire. *American Journal of Science* 262: 795-807.
- Yanai, S. 1989. Age determination of hillslope with tephrochronological method in central Hokkaido, Japan. *Transactions, Japanese Geomorphological Union* 10: 1-12. (JE)