

**Threshold Conditions for Channel Initiation  
in a Humid Forested Mountain:  
an Approach from Hydro-geomorphic Observations**

**Tsuyoshi HATTANJI**

A dissertation submitted to the Doctoral Program  
in Geoscience, the University of Tsukuba  
in partial fulfillment of the requirements  
for the degree of Doctor of Philosophy in Science

January 2004

# Contents

	<b>Page</b>
<b>Contents</b>	<b>i</b>
<b>Abstract</b>	<b>iii</b>
<b>List of Tables</b>	<b>vi</b>
<b>List of Figures</b>	<b>vii</b>
<b>List of Photographs</b>	<b>x</b>
<b>Chapter I Introduction</b>	<b>1</b>
<b>I-1</b> Hydro-geomorphic processes in humid forested mountains	1
<b>I-2</b> Channel initiation models	3
<b>I-3</b> Thresholds for channel initiation based on observations	6
<b>I-4</b> Objective and approach	7
<b>Chapter II Study area</b>	<b>10</b>
<b>II-1</b> Topography and geology	10
<b>II-2</b> Climate	11
<b>Chapter III Investigation of channel heads</b>	<b>13</b>
<b>III-1</b> Methods	13
<b>III-2</b> Type of channel heads	14
<b>III-3</b> Area-slope relationship	16
<b>Chapter IV Observations of hydro-geomorphic processes</b>	<b>17</b>
<b>IV-1</b> Hydro-geomorphic properties of investigated watersheds	17
<b>IV-2</b> Spatial distribution of stream flow	19
<b>IV-2-1</b> Methods	19
<b>IV-2-2</b> Results	20
<b>IV-3</b> Rainfall-runoff response at channel heads	22
<b>IV-3-1</b> Methods	22
<b>IV-3-2</b> Results	23

	<b>Page</b>
<b>IV-4</b> Pressure head of subsurface water in a slope segment	25
IV-4-1 Methods	25
IV-4-2 Results	26
<b>IV-5</b> Bedload transport and rockfall	27
IV-5-1 Methods	27
IV-5-2 Results of bedload observation	28
IV-5-3 Results of rockfall observation	30
<b>Chapter V Discussion</b>	<b>33</b>
<b>V-1</b> Relationship between drainage area and discharge	33
<b>V-2</b> Relationship between rainfall and peak discharge	36
<b>V-3</b> Critical discharge for bedload transport	40
<b>V-4</b> Thresholds for channel initiation by bedload transport	42
V-4-1 Equations	42
V-4-2 Channel heads and calculated thresholds	44
<b>V-5</b> Effect of type of channel head on erosion rate	47
<b>Chapter VI Conclusions</b>	<b>49</b>
<b>Acknowledgements</b>	<b>51</b>
<b>References</b>	<b>52</b>
<b>Tables</b>	<b>62</b>
<b>Figures</b>	<b>80</b>
<b>Photographs</b>	<b>121</b>
<b>Appendices</b>	<b>132</b>
Appendix A Index of symbols	132
Appendix B Calculation of return period	134

## Abstract

One of the primary issues on landform evolution in mountainous terrains is what rainfall and topographic conditions affect the location of channel heads. Although many studies discussed channel initiation based on models or field observations, analysis filling the gap between models and observations is required for the better understanding of channel initiation mechanism. Many researchers focused on the conditions of shallow landsliding in humid forested mountains, while few studies discussed the role of bedload transport below channel heads. The aim of the present study is to analyze the thresholds for channel initiation by bedload transport based on the hydro-geomorphic observation in channel heads.

The investigated area is located in the eastern Ashio Mountains, eastern Japan (Awano Town, Tochigi Prefecture). The area is underlain by Triassic bedded chert, and characterized by dissected topography. Shallow landslides are rare in the investigated area. Mean annual air temperature is 12.5 °C, and average annual rainfall is 1,476 mm. Area-slope relationship in 24 channel heads shows an inverse correlation as  $A = 747 S_c^{-2.47}$  ( $R^2 = 0.56$ ), where  $A$  is source area ( $m^2$ ) and  $S_c$  is local channel gradient below a channel head.

Runoff observation was conducted in a third-order basin (CL basin) and two first-order watersheds (C1 and C3) in CL basin. Discharge was manually measured at 19 sites in CL basin for seven cases of base-flow condition and two cases of storm-flow condition. Flumes and water-depth probes for automatic runoff observation were installed at the downstream side of channel heads in C1 watershed (C1L), the downstream side of channel heads in C3 watershed (C3U), and the confluence with third-order stream in C3 (C3L). Tensiometers were

installed on a slope segment in C3 watershed. Hydrological observations were conducted mainly from June to October for three years (2000 – 2002). Bedload transport was simultaneously observed with the bedload traps installed at the three sites (C1L, C3U and C3L) from 11 June 2000.

Manual measurement of discharge at 12 springs in CL basin showed a strong correlation ( $R^2 = 0.79$ ,  $p < 0.001$ ) between drainage area and spring discharge during the largest storm flow. Observation of subsurface water in the slope segment revealed generation of subsurface storm flow. Since surface topography controls the flux of subsurface storm flow, the spring discharge, affected by subsurface storm flow, increases with increasing drainage area.

In the case that the peak discharge,  $Q_p$ , produced by a storm event is linearly proportional to the drainage area,  $A$ , and effective rainfall intensity,  $I_R$ , the rainfall-runoff equation is expressed by  $Q_p = k_p I_R A$ , where,  $k_p$  is a dimensionless coefficient on runoff peak generation. Relationship between rainfall intensity and peak specific discharge,  $Q_p/A$ , at the two channel-head sites (C1L and C3U) was analyzed with simple least squares linear regression. The maximum 4-hour rainfall,  $R_4$ , which maximizes the coefficient of determination ( $R^2 = 0.85$ ), is suitable for the effective rainfall intensity in the investigated area. This analysis yielded the rainfall-runoff equation of  $Q_p/A = 68.7 \times 10^{-6} (R_4 - 0.014)$ .

Plots of bedload yield against peak discharge indicated that bedload yield abruptly increases when peak discharge exceeds a critical value,  $Q_{cr}$ . Critical discharges,  $Q_{cr}$ , were estimated to be  $0.035 \text{ m}^3 \text{ s}^{-1}$  at C1L site and  $0.007 \text{ m}^3 \text{ s}^{-1}$  at C3U site. These values of critical discharge satisfy a power function of channel gradient, that is  $Q_{cr} = 0.0036 S_c^{-2.37}$ .

In the condition that the peak discharge produced by a storm event,  $Q_p$ , is

equal to the critical discharge for bedload transport,  $Q_{cr}$ , thresholds for bedload transport is expressed by  $AS_c^{2.37} = 52.4 / (R_4 - 0.014)$ . In comparison with the observed area-slope data at 24 channel heads and the above thresholds for bedload transport,  $R_4 = 90$  mm (equivalent to 3-year rain) appears to be the critical rainfall for bedload transport immediately below the channel heads. In most channel heads except for some steep channel heads, bedload transport occurs in relatively frequent rainfall (return periods of less than 30 years).

**Key words:** channel initiation, hydrogeomorphology, bedload transport, runoff generation, chert, humid forested mountain, return period

## **List of Tables**

	<b>Page</b>
Table 1: Return period of rainfall	62
Table 2: Topographic characteristics of channel heads	63
Table 3: Drainage area and altitude of 19 observation sites	65
Table 4: Hydro-geomorphic properties of the investigated headwater basins	66
Table 5: Antecedent precipitation and runoff condition on the day of observation	67
Table 6: Stream discharge at 19 observation sites	68
Table 7: Observation periods for stream discharge, bedload yield and rockfall in the investigated headwater basins	71
Table 8: Comparison of bedload yield among three observation sites	72
Table 9: Coefficients of the regression lines of spring discharge on source area	73
Table 10: Rainfall and peak discharge of storm events at three observation sites	74
Table 11: Peak discharge and bedload yield at three observation sites	77

## List of Figures

	<b>Page</b>
Figure 1: Approach to the threshold conditions for channel initiation based on the hydro-geomorphic observations	80
Figure 2: Topography and geology around the investigated area	81
Figure 3: Topographic map of the present study area	82
Figure 4: Average monthly rainfall and temperature at Kanuma	83
Figure 5: Monthly rainfall and temperature from 2000 to 2002 at Kanuma	84
Figure 6: Schematic representation of channel heads	85
Figure 7: Channels, unchanneled valleys and source areas	86
Figure 8: Definition of channel-head properties	87
Figure 9: Relationship between source area and local head slope at the channel heads	88
Figure 10: Relationship between source area and local channel gradient at the channel heads	89
Figure 11: Location of the investigated basins (C1, C3, and CL)	90
Figure 12: Location of the observation sites in CL basin	91
Figure 13: Topographic map of the investigated headwater basins	92
Figure 14: Profile of the slope segment A-A' in C1 watershed	93
Figure 15: Profile of the slope segment B-B' in C3 watershed	94
Figure 16: Spatial distribution of specific discharge in CL basin	95
Figure 17: Channel profiles of seven first-order basins	96
Figure 18: Temporal change in ephemeral channel length in seven first-order basins	97

	<b>Page</b>
Figure 19:	Storm-runoff hydrographs at the channel-head sites 98
Figure 20:	Subsurface-water responses in the slope segment B-B' 99
Figure 21:	Bedload yield in each observation period 102
Figure 22:	Cumulative transported bedload from 11 June 2000 105
Figure 23:	Seasonal change in the amount of rockfall in C3 watershed from 29 January 2000 to 4 May 2003 106
Figure 24:	Amount of rockfall in winter and meteorological data at the JMA observatory "Utsunomiya" 107
Figure 25:	Amount of rockfall and sediment yield at C3U in winter 108
Figure 26:	Area-discharge relationship in base-flow conditions 109
Figure 27:	Area-discharge relationship in storm-flow conditions 110
Figure 28:	Antecedent precipitation condition and coefficient of the regression lines of spring discharge to drainage area 111
Figure 29:	Coefficient of determination between maximum rainfall and peak specific discharge plotted against the duration of maximum rainfall 112
Figure 30:	Maximum 1-hour rainfall and peak specific discharge 113
Figure 31:	Maximum 24-hour rainfall and peak specific discharge 114
Figure 32:	Maximum 4-hour rainfall and peak specific discharge 115
Figure 33:	Relationship between peak discharge and bedload yield 116
Figure 34:	Critical discharge for bedload transport plotted against local channel gradient of each observation site 117
Figure 35:	Threshold conditions for channel initiation by bedload transport 118

	<b>Page</b>
Figure 36: Cumulative distribution of critical 4-hour rainfall for bedload transport in 24 channel heads	119
Figure 37: Annual bedload yield per unit area plotted against local channel gradient of observation sites	120

## **List of photographs**

	<b>Page</b>
Photo 1: Landscape of the investigated area	121
Photo 2: Head slope of a Type-G channel head (O16H)	122
Photo 3: A channel head of Type S (O38H)	123
Photo 4: The channel head in C1 watershed (C1H)	124
Photo 5: The channel head in C3 watershed (C3H)	125
Photo 6: A bedload trap and a flume at C1L site	126
Photo 7: A bedload trap and a flume at C3U site	127
Photo 8: A bedload trap and a flume at C3L site	128
Photo 9: A rockfall trap at R-1 site in C3 watershed	129
Photo 10: The bedload trap torn by debris at C3U site	130
Photo 11: The debris captured in the flume at C3U site	131