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Catena 46 (2002) 285–307

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Frequency and spatial distribution of landslides in a mountainous drainage basin: Western Foothills, Taiwan

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Received 29 November 2000; received in revised form 2 May 2001; accepted 31 May 2001

Abstract

Maps from 1904 and 1915 and air photographs from 1963, 1980, 1985, 1993 and 1996 provide a record of landslide incidence in a 92.1-km^2 drainage basin, a headwater tributary of the Cho-Shui River in Taiwan. Interpretation of landslide patterns from the early maps indicate that in four sub-basins (36 km^2) structural geological factors control chronic landsliding regularly reactivated by intense rains. Within these four sub-basins, all later air photographs reveal a continuing high incidence of landslides (with landslide densities of 3–11 ha/km^2). Air photographs taken in 1963, following extensive logging, in 1985, following highway construction, and in 1996, following the very large typhoon Herb event demonstrate the short-term effects of disturbance in these structurally weak sub-basins. Air photographs from 1980 and 1993 demonstrate recovery of the land surface from logging and highway construction impacts, respectively. For the adjacent sub-basins (56 km^2), two modes of response to perturbations were identified: six sub-basins (48 km^2) showed direct response to logging, road construction and typhoon Herb and five sub-basins (8 km^2) were more buffered and showed some lagged responses. Even this last category of sub-basins is more active than the average for Taiwan, where the mean landslide density is 0.84 ha/km^2. It is proposed that, for the 92.1-km^2 Hoshe basin, the ‘formative event’ sensu Brunsden [Z. Geomorphol. Suppl. 79 (1990) 1] is one that produces approximately 200 ha of landslides, a value that has been equaled or exceeded in each of the periods of study (1963–1980, 1980–1985, 1985–1993 and 1993–1996). Logging activity, major road construction, and extreme typhoon and earthquake events produce short-term acceleration of landslide incidence. In principle, recovery

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PII: S0341-8162(01)00157-6

rates of the land from pulsed perturbations of about 20 years for logging activity and about 8 years for major road construction may also be suggested.

Keywords: Land use; Landslides; Formative events; Recovery time; Taiwan

1. Introduction

'Within each tectono-climatic regime landforms are produced by specific process events. Such events are called formative events' (Brunsden, 1990, p. 18). In central Taiwan, formative events are dominated by slope failure, specifically bedrock landslides (Densmore et al., 1997; Hovius et al., 2000). The hierarchy of formative events suggested by our observations in the Western Foothills (Ho, 1988) includes:

(i) deep seated structural failure as a result of progressive creep and toppling of weak Miocene sandstones and shales,
(ii) slope failure associated with annual high intensity precipitation from typhoons, and
(iii) pulsed events induced by logging, road construction and rare, 50–100 year frequency typhoons, such as Typhoon Herb, which hit the study area in 1996. Most recently, the large Chi-Chi earthquake of 1999 also left its mark on the landscape.

Surprisingly, Hovius et al. (2000) found no evidence for the influence of earthquakes on landslide incidence in the Central Range during the period 1991–1996. In this study, we have quantified the frequency of formative events and mapped locations of slope failures between 1963 and 1996 in a 92-km^2 basin. Because most of the data are taken from air photographs, the nature and magnitude of the formative events can only be estimated. Even so, the data obtained are of interest because of the spatial resolution achieved at each of five cross-sections in time.

2. General context

Taiwan was formed by the collision of an island arc with the Asian continental margin (Chai, 1972). The south-central region of the island (the Western Foothills as defined in Ho, 1988), is underlain by Miocene sandstones and shales. Tight and asymmetric folds and low angle thrusts have deformed the rocks into elongate, nearly parallel anticlines and synclines (Fig. 1). Two sets of strike-slip faults, striking WNW and NNE, respectively, help to determine the locations of landslide activity. Frequent earthquake activity reinforces this geological influence, as illustrated by the 1999 earthquake. The warm and humid climate is dominated by heavy and intense precipitation. More than 70% of annual rainfall occurs in the summer season between July and September. Significant weathering and mass wasting occur island-wide especially in hilly and mountainous areas.

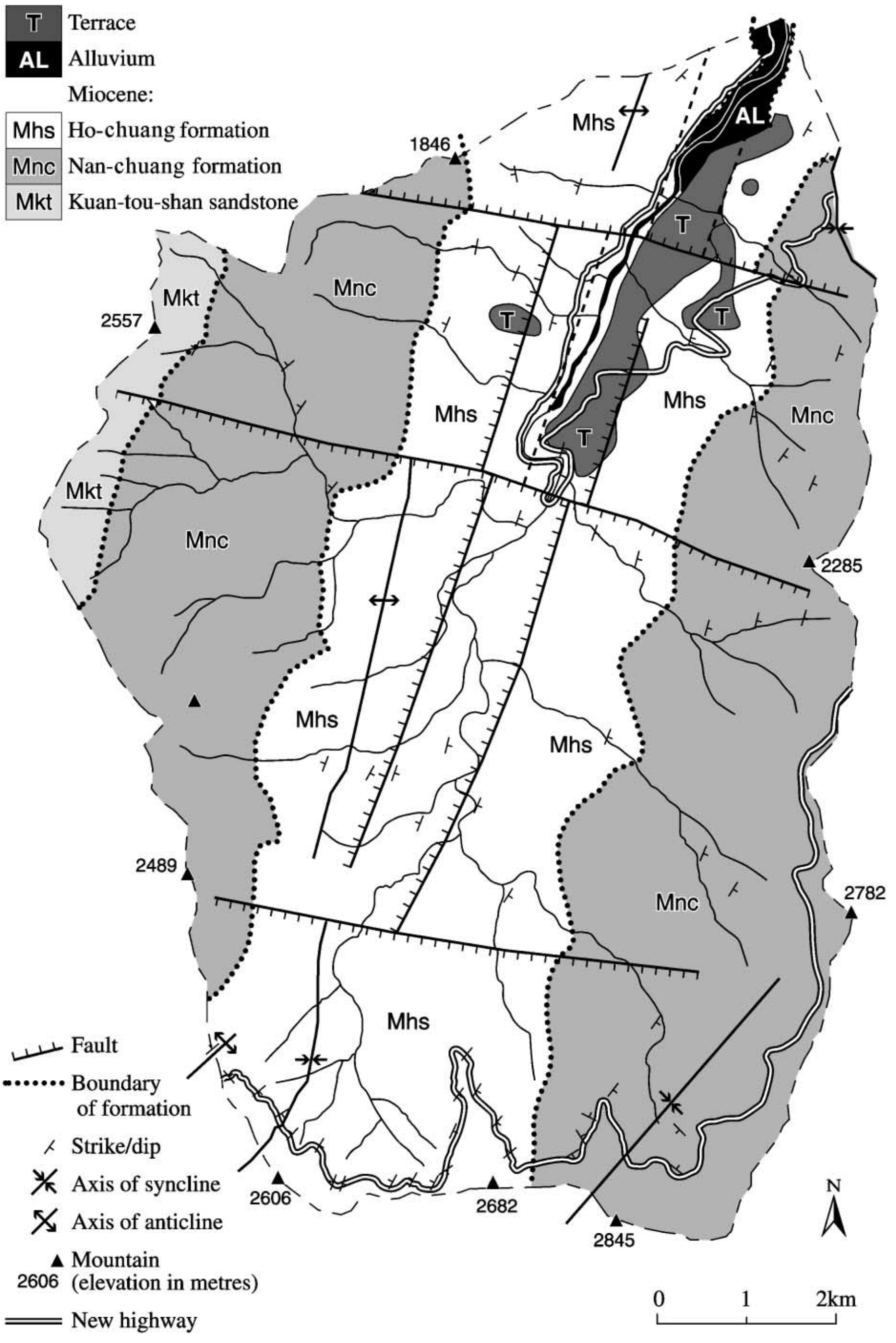

Fig. 1. Geological structure of the Ho-she Basin (modified after Wang and Lin, 1982).

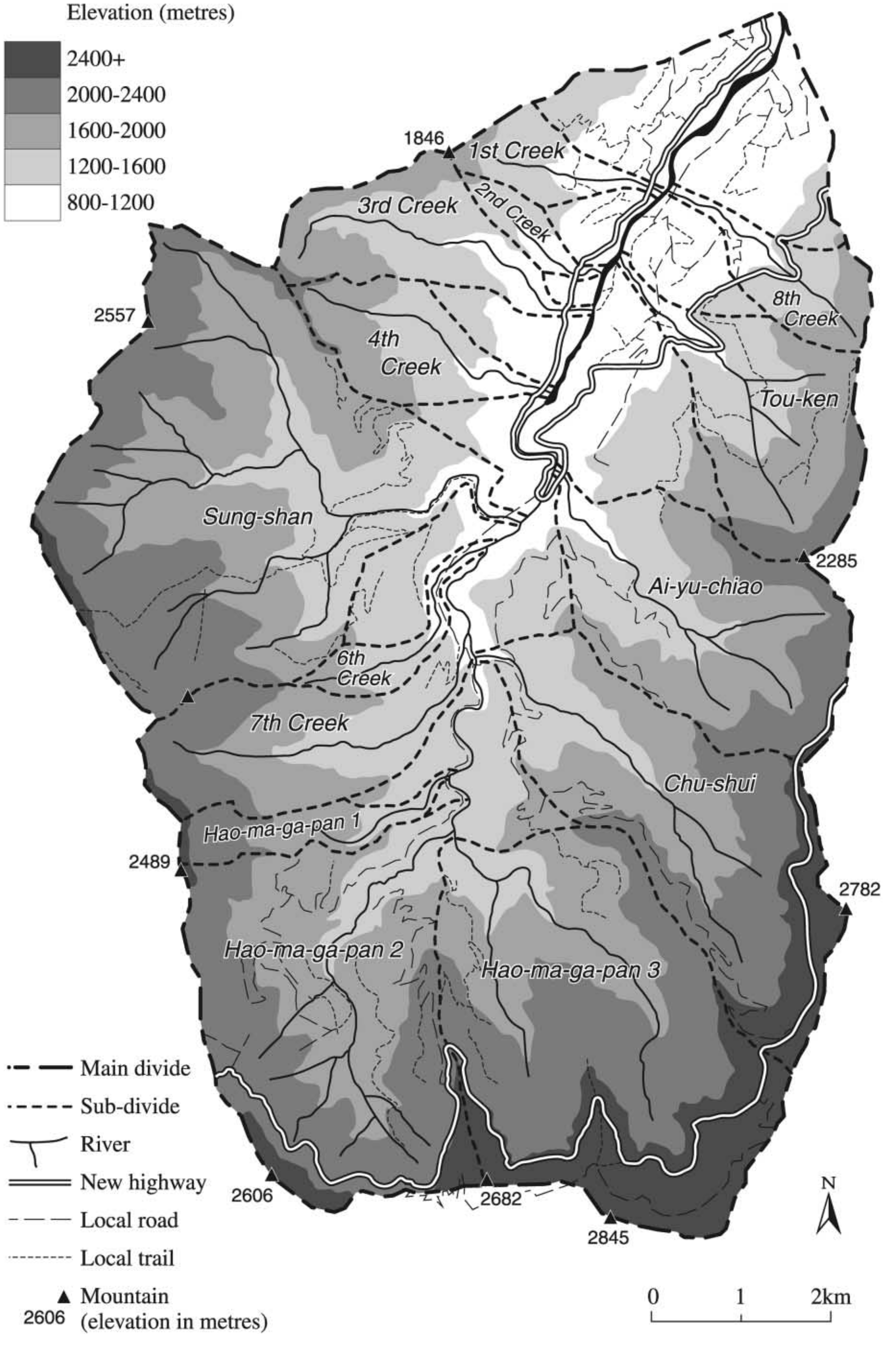

Fig. 2. Relief of the Ho-she Basin.

Lee (1980) pointed out that there were 7810 landslides within 22 watersheds upstream of reservoirs in Taiwan. Wu et al. (1989) investigated over 9500 km^2 of central and eastern Taiwan, and estimated that there were 2535 landslides covering 8100 ha in area. The frequency of landslides (number of landslides per unit area) is 0.27/km^2, and the density of landslides (area of landslide per unit area) is 0.84 ha/km^2. Hsieh (1996) made a second investigation of landslides island-wide and found that there were 2546 landslides covering 8049 ha in area. The frequency and density seemed consistent with the study of Wu et al. (1989), however, 60% of the landslides were assessed as being in danger of reactivation. Chang (1993) summarized the causes of landslides in Taiwan as weak rock, pronounced run-off concentration, undercutting and deepening by stream reclamation and road construction.

3. Study region (see insert in Fig. 3)

Ho-she River rises on the slopes of Ali-shan in central Taiwan. It is the source of Chen-yu-lan River, which is one of the main tributaries of Cho-shui River, the largest river in Taiwan. Ho-she River drains an area of 92.1 km^2, and is underlain by inter-bedded Miocene sandstones and shales. The rock is extremely fractured by joints and cleavages from folding and faulting (Lin, 1996). The basin ranges from 800 to 2800 m.a.s.l., 10–50° in slope and 200–1000 m/km^2 cell in relief (Fig. 2). The average altitude, slope and available relief of the basin are 1630 m, 33°20′ and 570 m,

Table 1

Annual precipitation of Ali-shan from 1963–1996 (mm)

1963	4475.1	1972	5881.2	1981	4117.4	1990	5019.3
1964	2821.6	1973	3782.6	1982	3502.8	1991	3094.0
1965	3769.1	1974	4519.8	1983	4071.2	1992	4627.9
1966	5713.6	1975	4720.0	1984	3229.7	1993	2641.8
1967	3014.6	1976	4728.6	1985	4133.4	1994	4037.7
1968	3787.1	1977	5167.4	1986	3476.4	1995	2673.1
1969	3746.2	1978	4754.6	1987	3588.3	1996	3552.5
1970	2925.0	1979	4117.9	1988	3666.6		
1971	3067.4	1980	2239.6	1989	3654.7	Average	3891.7

Number of typhoons from 1963–1996

1963	2	1972	1	1981	5	1990	5
1964	0	1973	2	1982	3	1991	4
1965	3	1974	3	1983	2	1992	4
1966	4	1975	3	1984	4	1993	1
1967	4	1976	1	1985	4	1994	4
1968	3	1977	3	1986	–	1995	1
1969	4	1978	3	1987	6	1996	1
1970	1	1979	1	1988	4		
1971	4	1980	1	1989	1		

respectively. Due to the representativeness of its relief, land use and land cover, a part of the watershed has been dedicated to research. This part of the watershed was donated to Taiwan National University by the Bureau of Forestry and is now maintained by the university as a research forest. Relatively intense, short duration rainfall events are common in and around the basin. Annual rainfall is about 3890 mm on average (1963–1996; Table 1) and is concentrated in July to September. Most of the rain comes from typhoons lasting 20 or more hours and short duration, heavy summer convectional thunderstorms. The torrential rainfall associated with Typhoon Herb, which reached 1094 mm in 24 h (July 31 to August 1, 1996) triggered a series of debris flows. Great damage was caused with the loss of many orchards, roads and bridges in addition to 24 fatalities.

4. Method

A landslide (including slides, slumps, avalanches and debris flows) is not only a failure on the slope but also is the main agent supplying sedimentary material to rivers in Taiwan (Tucker and Bras, 1998). The area is of interest because of the damage caused by landslides triggered by typhoon Herb, logging and major road construction. This paper seeks to analyze the perturbation of landslides by natural processes and human agency over a 34-year period (1963–1996) based on air photo interpretation. Landslides which can be recognized in air photos (1:17,000–18,000) were plotted and transferred to a 1:25,000 topographic base map (Table 2). The earliest air photo was taken in 1963, in a period of heavy logging. The air photos of 1985 were taken during road construction in the

Table 2
Geomorphic data of Ho-she drainage basin

	Stream order	Length (km)	Area (km^2)	Highest elevation (m)	Lowest elevation (m)	Stream gradient (%)
1st Creek	1	1.67	1.48	1300	825	28.4
2nd Creek	1	1.26	0.59	1200	855	27.4
3rd Creek	1	2.86	3.27	1600	875	25.3
4th Creek	2	2.77	2.46	1650	908	26.8
Sung-shan R.	3	6.15	16.10	2000	1005	16.2
6th Creek	1	2.55	2.17	1520	1030	19.2
7th Creek	2	3.55	4.10	2100	1140	27.0
Hao-ma-ga-pan 1st R.	1	2.75	1.36	2489	1250	45.1
Hao-ma-ga-pan 2nd R.	2	5.08	10.01	2606	1310	25.5
Hao-ma-ga-pan 3rd R.	2	5.36	12.46	2862	1310	29.0
Chu-shui R.	2	4.35	8.72	1750	1165	13.4
Ai-yu-chiao R.	2	4.57	7.04	2150	975	25.7
Tou-keng R.	2	1.45	4.75	1130	848	19.4
8th Creek	1	0.98	2.19	1025	820	20.9
Ho-she R.	4	17.33	92.09	2225	755	8.5

watershed. The air photos of 1996 were taken just after a major typhoon event. Landslides were classified as landslide scars, chutes, slumps, and avalanches. They were divided into two categories, larger or smaller than 1 ha. It is difficult to identify small landslides and potential landslides under the tree canopy or in re-vegetated woodland. The area of landslides is calculated by planimetric grid unit with no adjustment for slope. All landslides on an air photograph of a given date were mapped and recorded, not only those newly appeared since the previous photo. The 1993 air photos excluded about 10% of the southernmost part of the basin. Therefore, estimates of landslide incidence had to be made by extrapolation from adjacent basins. Errors in these estimates are not greater than 10%.

5. Map and air photo analysis

5.1. Landslide distribution: pre-1963

The Ho-she drainage basin was designed as a research forest with relatively strict control on access. The earliest maps, drawn in 1904 (1:20,000) and 1915 (1:50,000) showed that some significant landslides had occurred in the head waters of Sung-shan River, 7th creek, Chu-shui River and Ai-yu-chiao River (Figs. 3 and 4). A few landslides were also distributed along the main channel of the Ho-she River. These two maps indicate the existence of slope failures prior to human interference. They appear to cover at least 100 ha, though it is difficult to assess the accuracy of landslide depiction on maps that were drawn for an entirely different purpose. For this study maps provided evidence of the presence of large landslides caused by structural weakness in the bedrock.

5.2. Landslides on the 1963 air photographs

Landslides shown on the 1963 air photos were distributed more widely than in the earlier maps (Fig. 5). One hundred and four landslides covered 669 ha in area. The density of landslides in the Ho-she basin was 7.26 ha/km^2 (Table 3). The well-documented logging within the Research Forest began in 1956, reaching a maximum in 1964 and terminated in 1988. Eighty-five percent of the area had been logged by 1980. To the extent that the land use history of the Research Forest was representative of the Ho-she River basin, it is clear that the increased number and size of landslides were caused by intense precipitation on the deforested slopes.

5.3. Landslides on the 1980 air photographs

New slope failures were largely small landslides and channelized gullies. New landslide scars and chutes occurred only in the Hao-ma-ga-pan 2nd River basin (Fig. 6). There were 276 landslides on 307 ha (Table 3). The density of landslides had been reduced to 3.33 ha/

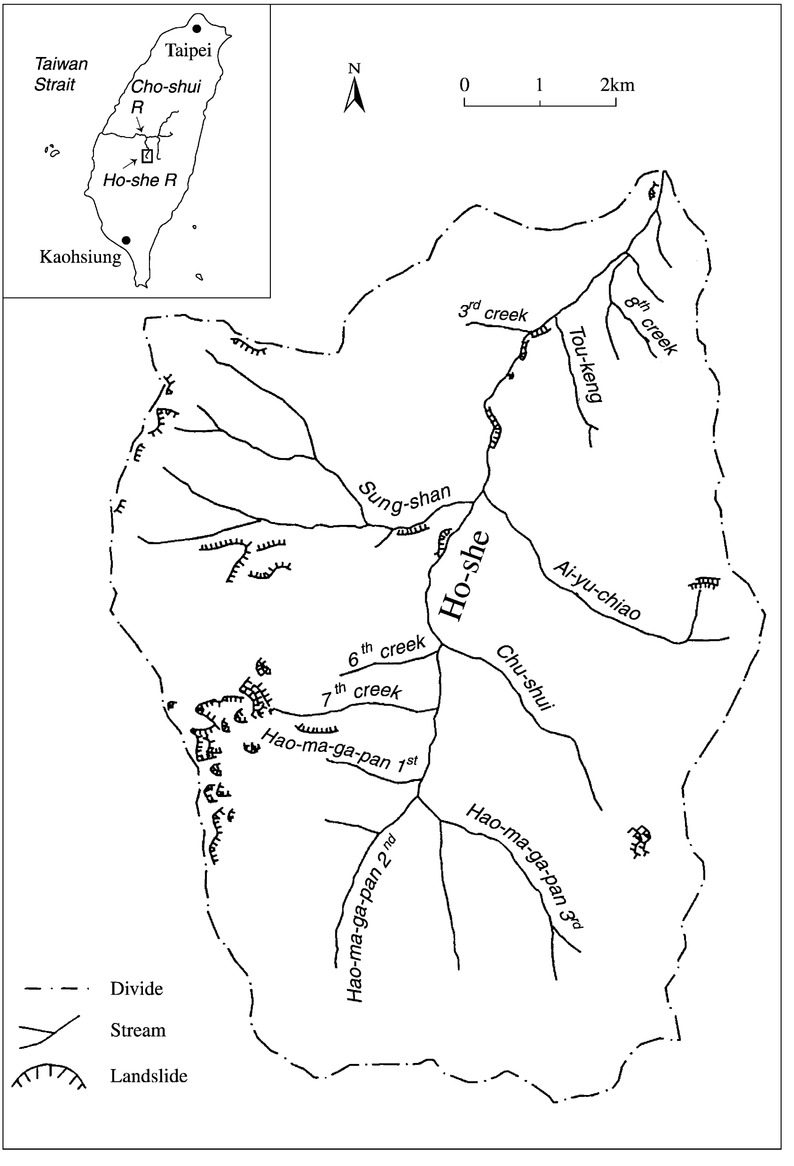

Fig. 3. Distribution of landslides in 1904.

km^2 and individual landslides were smaller except for the structurally controlled landslides noted under Section 5.1 above. Table 4 shows that landslide area had decreased by 362 ha during the 17 years (1963–1980) or at a rate of 21 ha/year, on the unlikely assumption that the rate was consistently reduced from year to year. This effect is interpreted as a result of the reduction in logging activity.

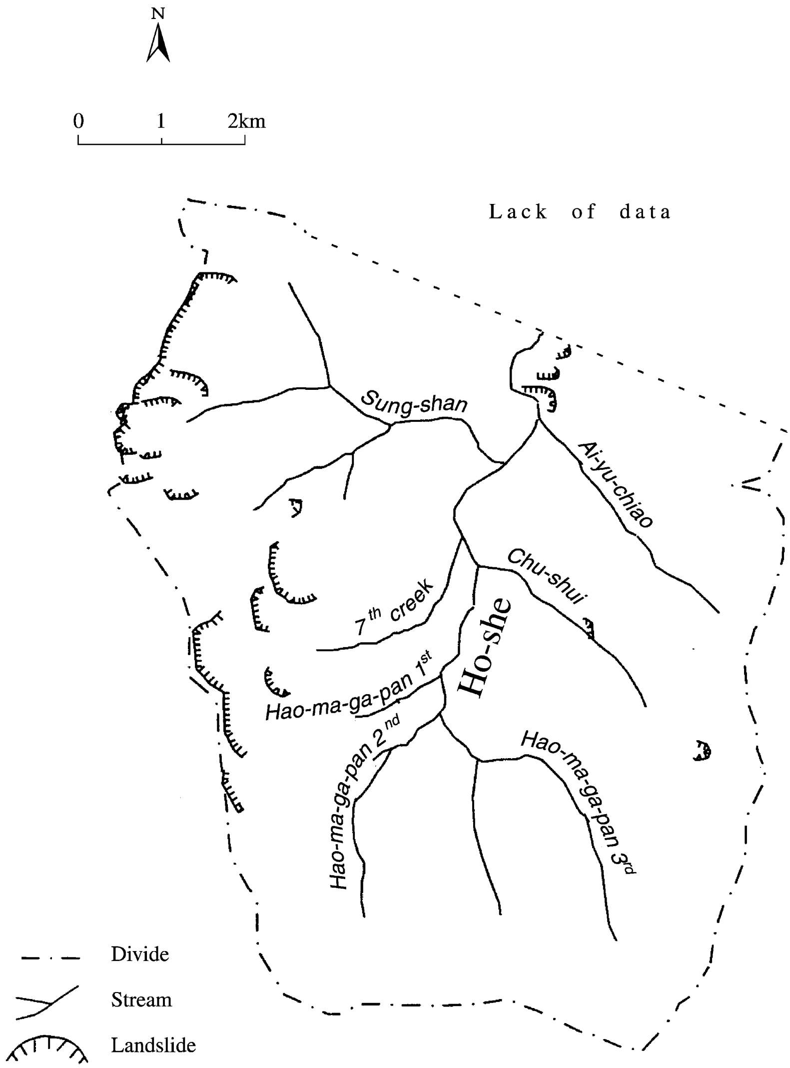

Fig. 4. Distribution of landslides in 1915.

5.4. Landslides on the 1985 air photographs

A new road from east to west was completed across Taiwan in September, 1980 to promote economic prosperity in east Taiwan (Wang and Lin, 1982). The new road passed through the eastern and southern parts of the basin. Debris talus deposits were formed by engineering disposal along the new road (Fig. 7). There were 193 landslides covering 426 ha (Table 3). Landslide density was increased to 4.63 ha/km^2; this increase was interpreted as resulting primarily from road construction. Table 4 shows that

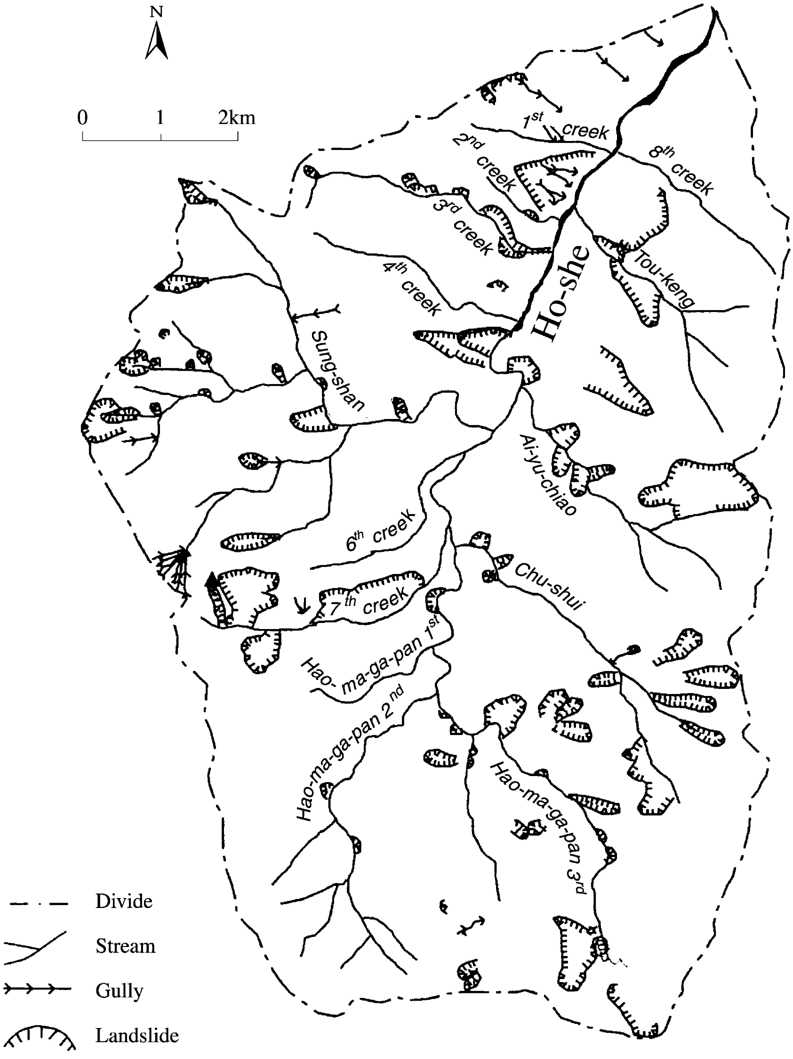

Fig. 5. Distribution of landslides in 1963.

landslide area had increased by 119 ha during the 5 years (1980–1985) or at a rate of about 24 ha/year.

5.5. Landslides on the 1993 air photographs

The effects of road construction had declined by this time. Debris deposits along the new road had become vegetated and several chutes had recovered (Fig. 8). A few new landslide scars and chutes were identified, but the total was reduced to 141 landslides covering 189 ha (Table 3). Landslide density had been reduced to 2.24 ha/km^2; mainly as a

Table 3
Number and area of landslides in Ho-she drainage basin

Name of river	Drainage area (ha)	1963				1980				1985				1993				1996			
		N	*F*	*A*	*D*	*N*	*F*	*A*	*D*	*N*	*F*	*A*	*D*	*N*	*F*	*A*	*D*	*N*	*F*	*A*	*D*
1st Creek	148	5	3.38	4	2.70	1	0.68	4	2.70	0	0	0	0	0	0	0	0	2	1.35	6	4.05
2nd Creek	59	1	1.69	4	6.78	0	0	0	0	2	3.39	2	3.39	0	0	0	0	2	3.39	2	3.39
3rd Creek	327	9	2.75	17	5.20	14	4.28	9	2.75	14	4.28	11	3.36	11	3.36	12	3.67	12	3.67	19	5.81
4th Creek	246	0	0	0	0	2	0.81	2	0.81	4	1.63	3	1.22	9	3.66	15	6.10	9	3.66	18	7.32
Sung-shan R.	1610	30	1.86	149	9.25	40	2.48	53	3.29	35	2.17	44	2.73	12	0.75	37	2.30	51	3.17	76	4.72
6th Creek	217	0	0	0	0	7	3.23	3	1.38	0	0	0	0	5	2.30	2	0.92	4	1.84	4	1.84
7th Creek	410	2	0.49	115	28.05	15	3.66	62	15.12	14	3.41	44	10.73	11	2.68	30	7.32	12	2.93	53	12.93
Hao-ma-ga-pan 1st R.	136	0	0	0	0	9	6.62	3	2.21	1	0.74	3	2.21	1	0.74	2	1.47	1	0.74	2	1.47
Hao-ma-ga-pan 2nd R.	1001	2	0.20	5	0.50	61	6.09	33	3.30	38	3.80	66	6.59	34[a]	3.40	20[a]	2.00	40	4.00	43	4.30
Hao-ma-ga-pan 3rd R.	1246	11	0.88	67	5.38	49	3.93	29	2.33	44	3.53	76	6.10	38[a]	3.05	25[a]	2.00	40	3.21	47	3.77
Chu-shui R.	872	12	1.38	60	6.88	19	2.18	18	2.06	10	1.15	55	6.31	24	2.75	25	2.87	31	3.56	46	5.28
Ai-yu-chiao R.	704	4	0.57	81	11.51	24	3.41	53	7.53	6	0.85	36	5.11	20	2.84	11	1.56	16	2.27	20	2.84
Tou-keng R.	475	1	0.21	20	4.21	6	1.26	6	1.26	1	0.21	21	4.42	2	0.42	8	1.68	13	2.74	16	3.37
8th Creek	219	1	0.46	0	0	0	0	0	0	1	0.46	31	14.16	1	0.46	3	1.37	1	0.46	11	5.02
Interfluve	1539	26	1.69	147	9.55	29	1.88	32	2.08	23	1.49	34	2.21	7	0.45	16	1.04	14	0.91	17	1.10
Ho-she R.	9209	104	1.13	669	7.26	276	3.00	307	3.33	193	2.10	426	4.63	175	1.90	206	2.24	248	2.69	380	4.13

N: Number of landslides, *F*: frequency (landslides/km^2), *A*: area of landslides (ha), *D*: density (ha/km^2).

[a] Head watershed data are not available but estimated from adjacent basins.

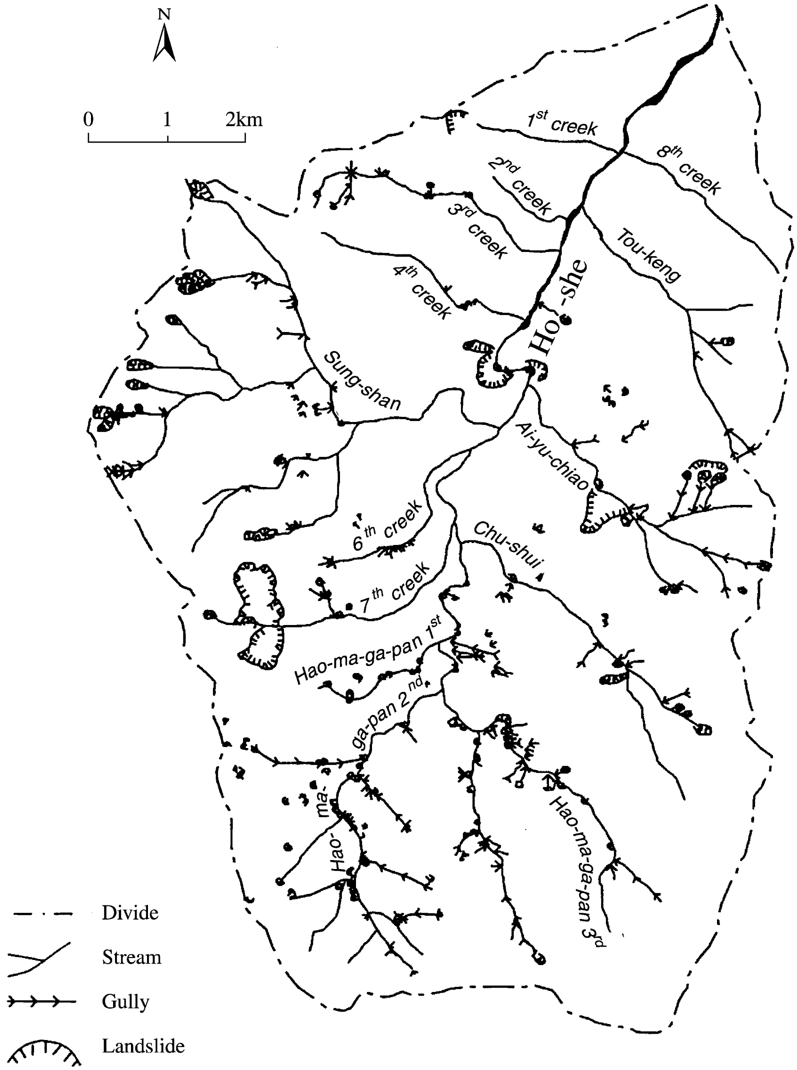

Fig. 6. Distribution of landslides in 1980.

result of recovery from the impact of road engineering works. Table 4 shows that landslide area decreased by 220 ha during the 8 years (1985–1993) or at a rate of about 27 ha/year.

5.6. Landslides on the 1996 air photographs

On July 31 and August 1, 1996, Typhoon Herb brought intense rainfall of 780 mm/h, and a total of 1094 mm in 24 h. Chutes on debris talus were enlarged and transported

Table 4
Landslide area changes (1963–1996) (in ha)

Name of river	1963–1980		1980–1985		1985–1993		1993–1996	
	+	–	+	–	+	–	+	–
1st Creek				4			6	
2nd Creek		4	2			2	2	
3rd Creek		8	2		1		7	
4th Creek	2		1		12		3	
Sung-shan R.		96		9		7	39	
6th Creek	3			3	2		2	
7th Creek		53		18		14	23	
Hao-ma-ga-pan 1st R.	3		0			1	0	
Hao-ma-ga-pan 2nd R.	28		33			46[a]	23[a]	
Hao-ma-ga-pan 3rd R.		38	47			51[a]	22[a]	
Chu-shui R.		42	37			30	21	
Ai-yu-chiao R.		28		17		25	9	
Tou-keng R.		14	15			13	8	
8th Creek	0		31			28	8	
Interfluve		115	2			18	1	
Ho-she R.		362	119			220	174	

[a] Estimated from adjacent basins.

debris to streams and flooded their lower courses (Fig. 9). In addition, almost all tributaries experienced landslides in their headwaters. There were 248 landslides covering 380 ha, and the landslide density increased to 4.13 ha/km^2 (Table 3) almost entirely because of the effect of Typhoon Herb. The effects of the 1996 event in the vicinity of the junction of the Chu-shui and the Hao-ma-ga-pan rivers and in the headwaters of Sung-shan River are shown in Figs. 10 and 11, respectively. A summary map of old and new landslides and debris flows activated by typhoon Herb is found in Fig. 12. Table 4 shows that landslide area increased by 174 ha during the 3 years (1993–1996) or at a rate of about 58 ha/year.

6. Comparison of landslides over time

1963, 1985 and 1996 landslides were more widely distributed than in 1980 and in 1993 (Fig. 13). Logging, road construction and typhoon Herb are thought to be responsible for the acceleration of landslide activity. Logging, which affected a large area and had a minimum of environmental constraints, appears to have had the largest immediate impact, creating a landslide density of 7.26 ha/km^2.

Slope failures generated by intense rainfalls during the frequent typhoons (92 in 34 years; see Table 1) and occurring on structurally weak rocks give rise to an average background measure of landslide density for this climato-tectonic region. This landslide density has at no time during the study period fallen below 2.24 ha of landslides/km^2 for the whole Hoshe basin. This compares with a mean of 0.84 ha/km^2 for Taiwan (Wu et al.,

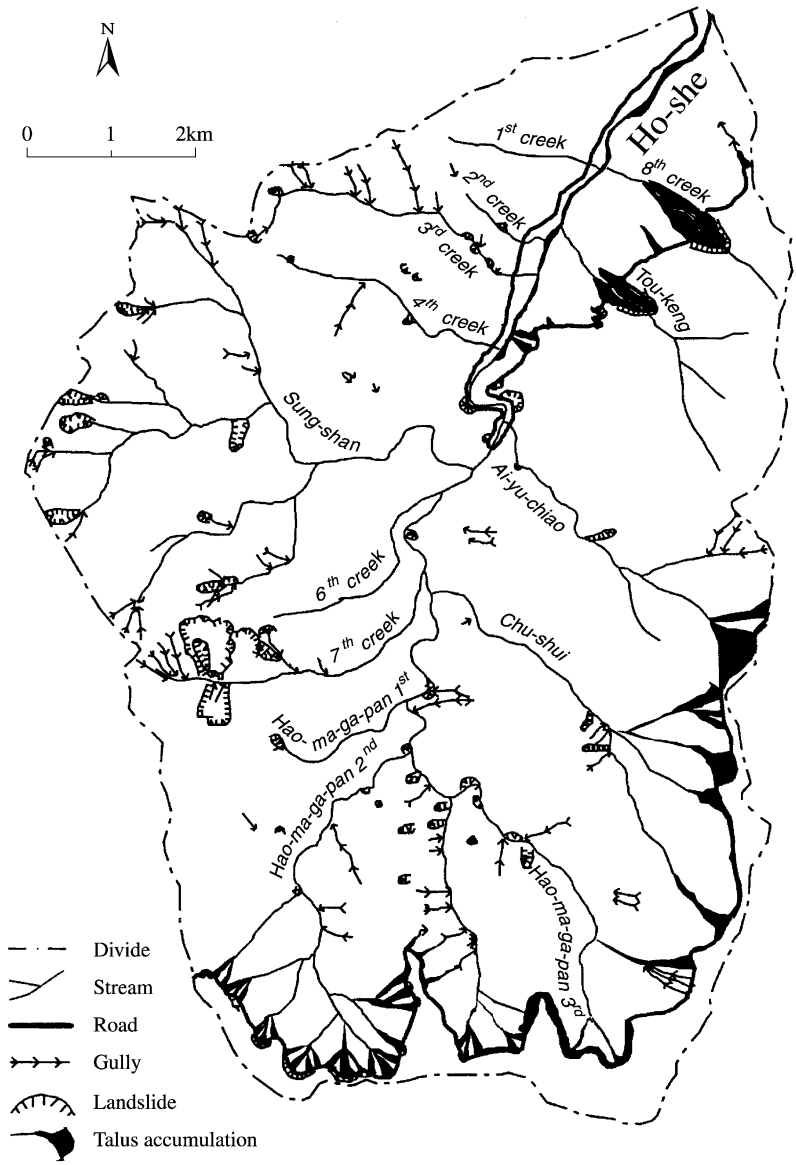

Fig. 7. Distribution of landslides in 1985.

1989). The greater than average activity for the Hoshe basin is not surprising given the relief and weakness of the bedrock.

If we assume that the figure of 2.24 ha/km^2 is close to the density created by the 'formative event' (sensu Brunsden, 1990) for the Hoshe basin when unaffected by human activity or extreme, i.e. 100 year recurrence interval typhoons, then we can make

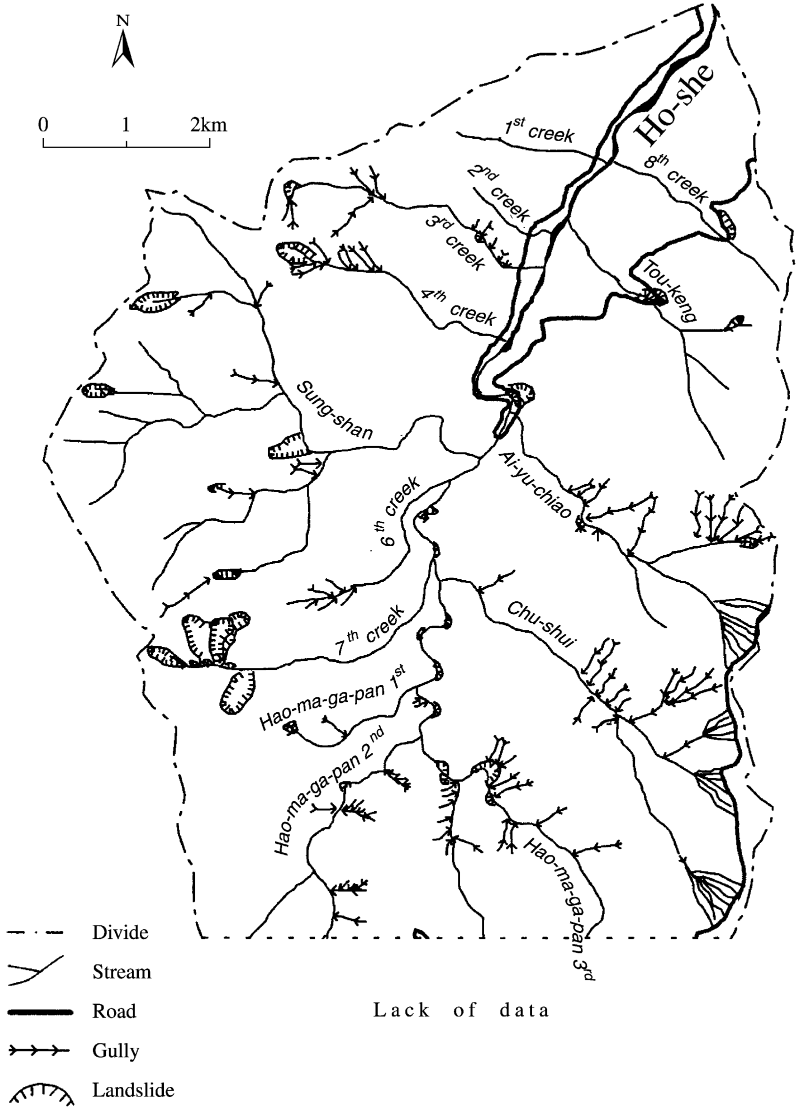

Fig. 8. Distribution of landslides in 1993.

some rough estimates of the influence of logging, road construction and typhoon Herb on the basin. The effect of logging, as measured on the 1963 photos, tripled the incidence of slope failures and even in 1980, the landslide density remained 50% higher than the background count. By 1985, and with the building of the east–west highway, landslide density had increased to double that of the background count. By 1993, landslide density was reduced to the lowest level recorded, close to the average

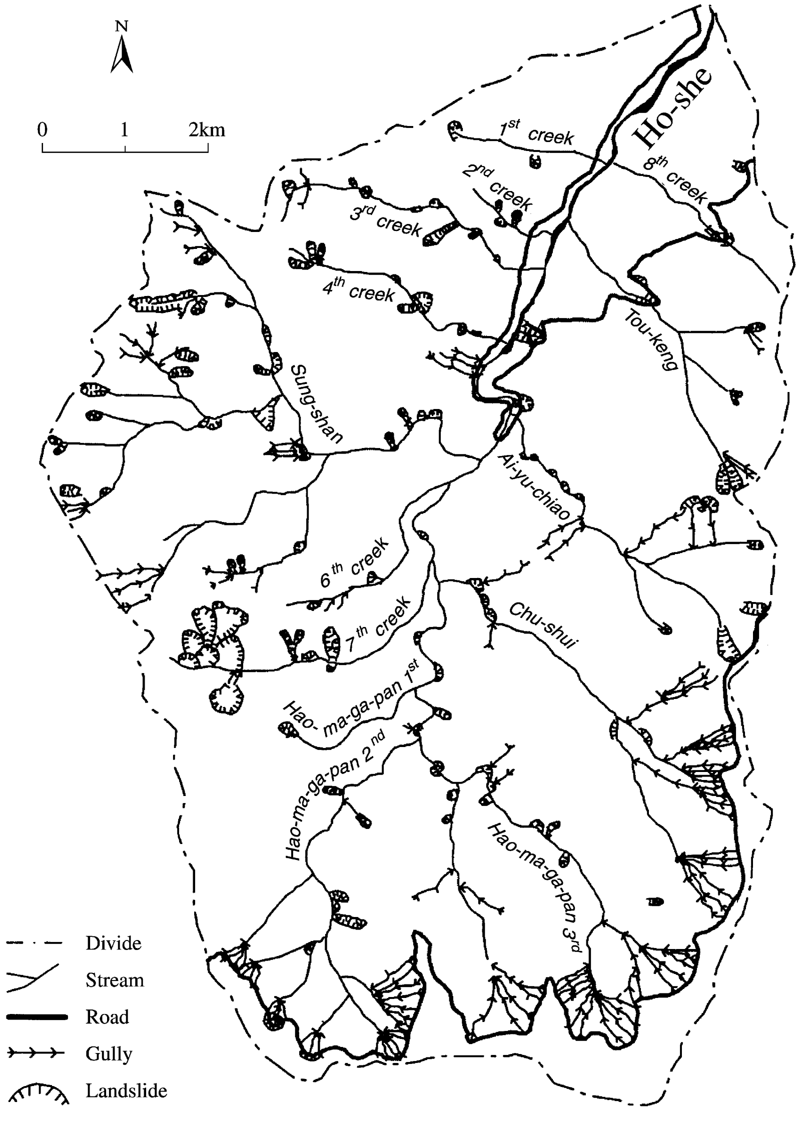

Fig. 9. Distribution of landslides in 1996.

formative event condition. In 1996, with the impact of typhoon Herb, landslide density was doubled.

7. Spatial variations in landslide incidence

There appear to be three categories of sub-basins within the Hoshe basin that have different responses (Table 5): Group A, which is structurally unstable, is affected by

Fig. 10. Debris torrent, tributary to the Chu-shui River (photo by J.-C. Chang: March 14, 1997).

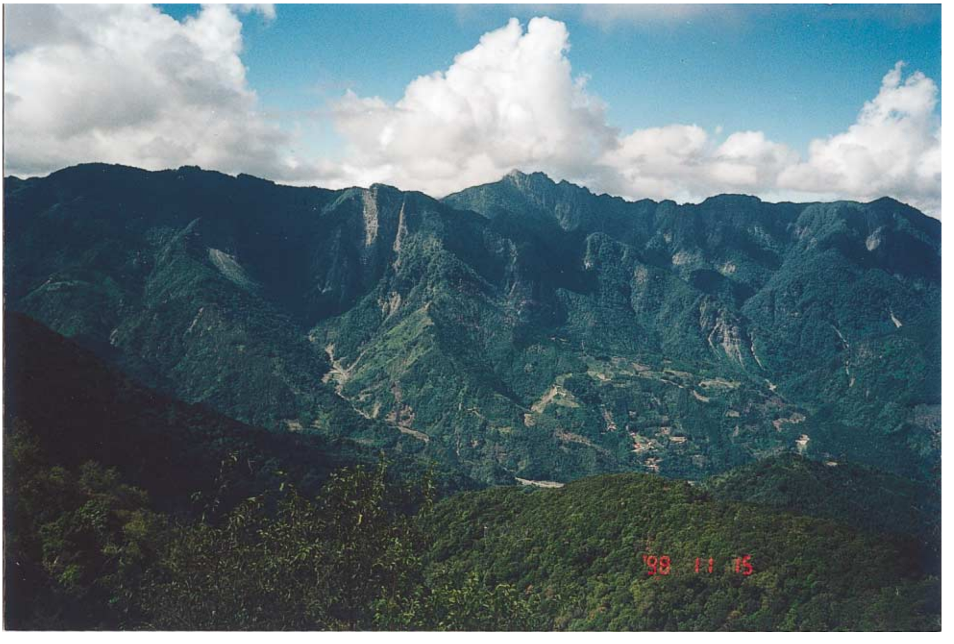

Fig. 11. Landslides in the headwaters of Sung-shan River basin (photo by J.-C. Chang: November 15, 1997).

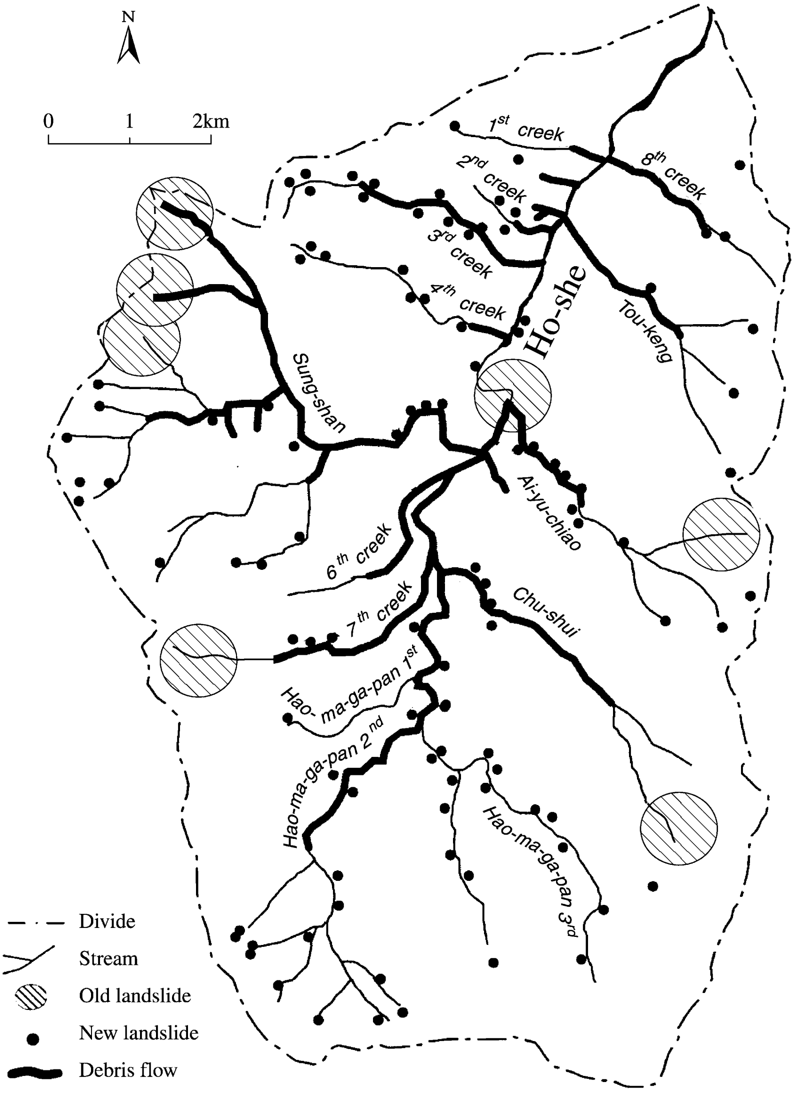

Fig. 12. Cumulative distribution of landslides and debris flows in the Ho-she Basin (as of 1997).

logging and typhoon Herb and only marginally by road construction; Group B is affected by logging, road construction and typhoon Herb; and Group C is relatively stable.

Group A includes the sub-basins of Sung-shan River, 7th Creek, Chu-shui River and Ai-yu-chiao River and covers about 36 km^2. This group of basins stands out in the 1904 and 1915 maps as having substantial landslide development. During the 1963–1996 period, landslide density in these basins varies from about 11 to 3 ha/km^2 (mean landslide

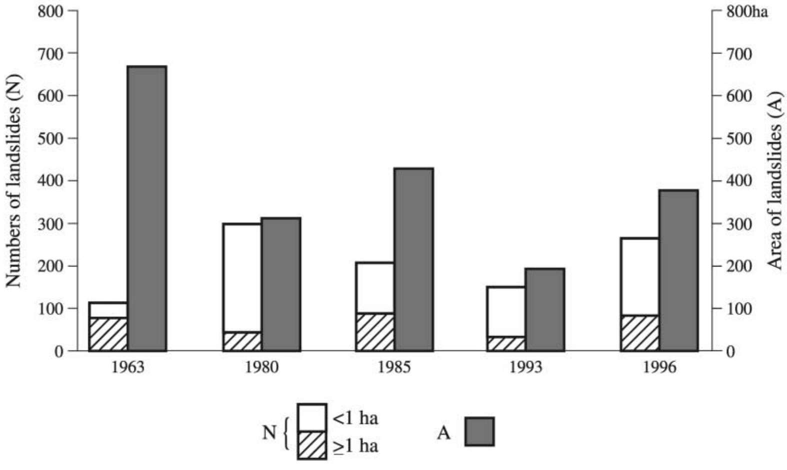

Fig. 13. Number and area of landslides (1963–1996).

density is 7.4 ha/km^2) and the Chu-shui basin is the only one affected by road construction, specifically in the uppermost part of the basin. Landslide density does not fall below 1.5 ha/km^2 in any of the sub-basins.

Table 5
Landslide incidence in Groups A, B and C

	Area (ha)	1963	1980	1985	1993	1996
Group A—Structurally unstable, with logging, road construction and typhoon Herb effects superimposed						
Sung-shan R.	1610	149	53	44	37	76
7th Creek	410	115	62	44	30	53
Chu-shui R.	870	60	18	55	25	46
Ai-yu-chiao R.	700	81	53	36	11	20
Total	3590	405	186	179	103	195
Group B—Logging, road construction and typhoon Herb effects						
3rd Creek	330	17	9	11	12	19
H-2 R.	1000	5	33	66	20[a]	43
H-3 R.	1250	67	29	76	25[a]	47
Tou-keng R.	480	20	6	21	8	16
8th Creek	220	0	0	31	3	11
Interfluve	1540	147	32	34	16	17
Total	4820	256	109	239	84	153
Group C—Relatively stable						
1st Creek	150	4	4	0	0	6
2nd Creek	60	4	0	2	0	2
4th Creek	250	0	2	3	15	18
6th Creek	220	0	3	0	2	4
H-1 R.	140	0	3	3	2	2
Total	820	8	12	8	19	32

[a] Estimated from adjacent basins.

Group B includes the sub-basins of 3rd Creek, Hao-ma-ga-pan 2nd and 3rd rivers. Tou-keng River, 8th Creek and all the interfluves between sub-basins, covering a total of about 48 km^2. During the 1993–1996 period, landslide density in these basins varied from about 5 to less than 2 ha/km^2 (mean landslide density is 3.6 ha/km^2). On average, they show the effects of logging, road construction and typhoon Herb very clearly, but individual basins fail to respond to specific impacts. For example, Hao-ma-ga-pan 2nd River and 8th Creek were unaffected by logging and the interfluve area is scarcely affected by road construction. No landslides were found in 8th Creek basin in 1963 and 1980.

Group C includes the sub-basins of 1st, 2nd, 4th and 6th creeks and Hao-ma-ga-pan 1st River, an area of about 8 km^2 (mean landslide density is 2.0 ha/km^2). Only the basin of 4th Creek shows significant response with a delayed response to construction (1993) and a direct response to typhoon Herb.

Because tectonic effects were confined to Group A basins and because logging effects were limited to 1963 and 1980 photos, and road construction effects were limited to 1985 photos (with the notable exception of 4th Creek basin) and typhoon Herb effects were restricted to 1996 photos, it is possible to make an order of magnitude estimate of the relative impacts of each process as well as the duration of that impact. The overall conclusion is that in any one year, landslide incidence in Ho-she basin may be dominated by a variety of high impact, short-term perturbations, such as logging, road construction, individual typhoons of 100 year recurrence interval or greater and earthquakes. However, in terms of the long-term, millennial scale impact on landscape morphology, the structurally controlled failures and those generated by 'normal' typhoon rains are cumulatively more effective. This is what is meant by the formative events that produce the distinctive tectono-climatic regime landforms of this basin. It is important to note that this generalization refers to the proportion of the surface area of the landscape that is affected. This is not the same as the total work done on the landscape as we do not have data for volumes of sediment transported.

Spatially, Ai-yu-chiao, Sung-shan, Chu-shui, and 7th creeks have a higher mean landslide density than that of other tributaries (7.4 ha/km^2). Checking with the maps of 1904 and 1915 reveals that all of these basins were apparently active at the turn of the century. These higher landslide density regions of the basin are associated with the most unstable geological structure and can be thought of as primarily structurally controlled.

8. Landslides influenced by natural processes and human activities

Physical factors, including faulting, folding, steep slopes and torrential rainfall from typhoons control landslides in Ho-she drainage basin. Human activities, such as poor logging practices and overplanting on steep slopes accelerate landslide occurrence. By overlapping the landslide map on the cultivation map (Fig. 14), it is seen that most farms on gentle slopes and river terraces are unrelated to the larger landslides in the headwaters, but are located close to the smaller, shallow and dynamic landslides. Although it is not possible to correlate the density of landslides with precipitation and

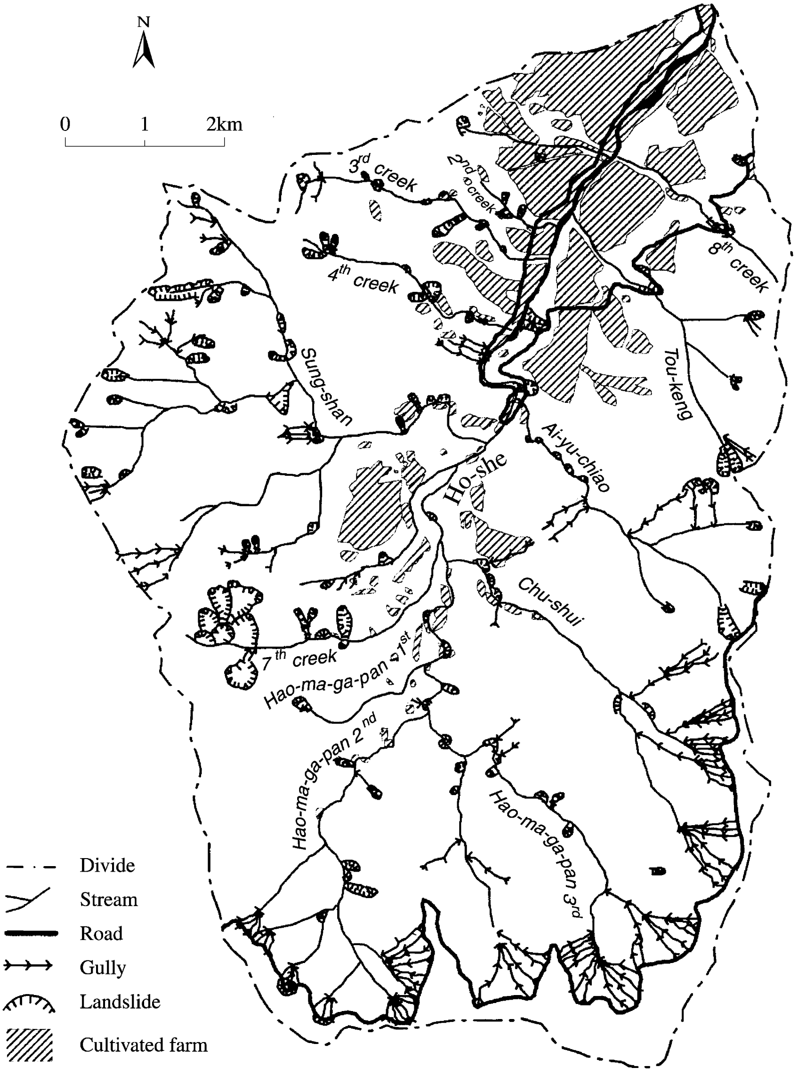

Fig. 14. Distribution of cultivated land and landslides in the Ho-she Basin in 1996.

areas of cultivated farms each year, the present data seem to show the effects of heavy logging. In addition, they imply that the basin can recover from logging in 20+ years and from road construction in 8 years. In contrast, the protection provided by soil conservation and engineering works such as restored vegetation, check dams, rock bolts, shotcrete and retaining walls help to diminish the landslides. Overall, geology and geomorphology are the basic factors controlling landslides in the long term, however, typhoon events, human activities including deforestation, farm cultivation, forestry restoration and prevention work are the key factors influencing the timing of landslide density changes in the short term.

9. Conclusion

Many factors have contributed to landslides in the Ho-she drainage basin. Intensive rock fractures and steep slopes resulting from faulting and folding are basic factors, whereas exceptional intensity storms, road construction and deforestation are important factors in the timing of landslides. It is clear that landslides increased in area due to deforestation in 1963, road construction in 1980 and the exceptional typhoon of 1996. However, landslide scars have recovered and are now diminished by natural and restored vegetation, soil conservation and engineering prevention. Geological, geomorphic and long-term climate characteristics are important in the long-term moulding of the landscape and are the factors that control formative events sensu Brunsden (1990). Dynamic changes associated with meteorological and anthropogenic factors over the last 30 years have made more obvious changes on the landscape but have been more short-lived.

Acknowledgements

The authors wish to thank Hae-his Song for his help on map processing and field work and appreciate I.Y. Chen for his stimulating discussion and help on air photo interpretation.

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