Typhoon-dominated Influence on Wood Debris Distribution and Transportation in a High Gradient Headwater Catchment

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Abstract: Wood debris is an important component of mountain streams. It causes serious damage and renders difficulty of water resource management in Taiwan. In this study, the quantity of wood debris and variation of migratory wood debris during flood events were examined. The downstream of Gaoshan Creek and Qijiawan Creek, located at Central Taiwan, was selected as the study area. The distribution and dynamic of wood debris in a high gradient headwater catchment were quantified using field surveys. A formula of critical depth for wood debris entrainment was used to evaluate the wood debris migration during three flooding events. In the study area, wood abundance and unit volume increased downstream, and wood density decreased downstream within a channel network. The channel morphology, riparian vegetation, and wood debris characteristics were found to influence the wood storage. As a result, the wood debris has an irregular accumulative distribution in the steep stream, and it migrates easily in the stream because of a high flow discharge. Strong relationships between the channel width and wood debris variables are discovered. Moreover, wood debris has a tendency to accumulate at sites with low stream power and wood debris dams, topographical notches, and unique geological structures. Our findings assist in the understanding of the effects of channel characteristics on distributions of wood debris in steep stream systems.

Keywords: Wood debris; Spatial distribution

characteristics; Wood debris migration; Flood events

Introduction

The woody materials falling into stream banks or channels from sources such as dead trees are referred to as wood debris. This debris is common throughout forested stream systems. Recent studies have highlighted the ecological and geomorphological importance of wood debris to forested stream ecosystems. Wood debris can create and alter channel hydraulics, channel morphology, sediment transport, organic matter storage, aquatic habitat complexity, and biological communities (Bilby 1981; Chen et al. 2006; Gurnell et al. 2002; Keller and Swanson 1979; Manners and Doyle 2008; Montgomery et al. 1995). Transportation and storage of wood debris are evidently influenced by a bank's characteristics (Latterell and Naiman 2007). In small streams, wood debris produced by forest dynamics and hillslope processes are retained, remaining on the valley floor (Harmon et al. 1986; Nakamura and Swanson 1993; Seo et al. 2010), and may be transported during regular floods (Harmon et al. 1986; Seo et al. 2010). In medium and large streams, wood debris is primarily generated by bank undercutting in the adjacent riparian zone (Martin and Benda 2001; Seo et al. 2010). In areas with sufficient stream power, wood debris has a

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higher potential to mobilize with increasing discharge as the stream size and depth increase (Baillie et al. 2008; Bilby and Ward 1989; Chen et al. 2006; Seo et al. 2010).

Tropical cyclones, such as typhoons, occur frequently in tropical regions and trigger numerous landslides, introducing large amounts of wood debris into streams and rivers (Wohl et al. 2009; Wohl and Ogden 2013). However, the presence of wood debris may be regarded as undesirable from a flood protection perspective because it markedly increases the probabilities of hydraulic structure damages or waterway blocks. For instance, Shihmen Reservoir, located in the northwestern portion of Taiwan, was unable to function effectively because a large amount of wood debris was trapped in the reservoir following Typhoons Aere and Haima in 2004. The total volume of salvaged wood in the reservoir impoundment zone was 54,000 m³ (Lu and Hwang 2006). Moreover, the floods following Typhoon Morakot in 2009 contributed to a total 3.8–8.4 Tg of wood debris spread along the coast and transported to the ocean around Taiwan (West et al. 2011). The wood debris not only damaged roads and bridges, but also severely affected human life, fisheries, and agriculture. Figure 1 shows the wood debris disasters in Eastern Taiwan following Typhoon Morakot. The wood debris accumulated behind the bridge and filled the harbor.

A literature review indicates that ecological programs have attempted to enhance our understanding of how wood debris contributes to habitat quality, aesthetics, and water quality. Moreover, wood debris introduces significant burdens on flood protection, and especially endangers the safety of hydraulic structures. Examining the distribution of wood debris before and after flood events in a headwater catchment is the main concern when reducing the risks of damage toward flood control structures. Literature discussing the carbon export in Taiwan after Typhoon Morakot is scant (Hilton et al. 2008; West et al. 2011). There are currently no specific studies that have indicated the wood storage characteristics and entrainment in Taiwan. Therefore, this study extensively explores the quantities of wood debris stored in a steep mountain stream and threshold of flood to trigger the transport of wood debris downstream. A

forested mountain stream was selected as the study area. The aims of this study are as follows: (a) Quantify the characteristics of wood debris (spatial distribution and accumulative distribution); and (b) demonstrate the transportation of wood debris (mobility and relationship with unit stream power) in steep mountain streams.

Figure 1 The wood debris disaster in Eastern Taiwan following Typhoon Morakot: (a) amount of wood debris spread across and accumulated on the Taimali river; (b) the wood debris filled the harbor during Typhoon Morakot. The engineering trucks and the man provide scale in the figure.

1 Study Area and Methods

1.1 Study area

The study area is downstream of Gaoshan Creek and Qijiawan Creek. It is located at the Qijiawan catchment in Shei-Pa National Park in Central Taiwan (Figure 2). The catchment area and the length of the study area within Gaoshan Creek are 21 km² and 1.8 km, respectively. The channel widths range from 3 to 45 m with a mean channel

Figure 2 Location map of the study reach showing basic catchment and morphological characteristics. The symbols on the map show information concerning the survey region.

Figure 3 The hydrological records in the Qijiawan catchment. (a) shows the annual and monthly rainfall, and the annual mean precipitation at the Taoshan rainfall station (2006 to 2010) was 2,451 mm; a high daily precipitation event was 495 mm (typhoon Jangmi); (b) shows the mean monthly rainfall variability and its error bar; (c) Flow discharge was measured at the Qijiawan creek water stage, and the mean daily flow discharge was 5.8 m³/s (2006 to 2010). High flow events in typhoons Jangmi was 317 m³/s (2008-09-28); (d) shows the mean monthly discharge variability and its error bar; The Yousheng creek water stage missed the flow discharge from July 27 to October 19, 2008; therefore, the short-dash-line only performed the discharge measured at the Qijiawan creek water stage.

width of 17 m. The altitudes within the Gaoshan creek catchment range between 1,730 m and 3,790 m with a mean altitude of 2,577 m. The channel gradients range between 0.002 m/m and 0.335 m/m. The catchment area and the length of the study area within Qijiawan Creek are 53 km² and 1.3 km, respectively. The channel widths range from 16 to 84 m with a mean channel width of 39 m. The altitudes within Qijiawan Creek range between 1,690 m and 3,880 m with a mean altitude of 2,133 m. The channel gradient ranges between 0.0009 m/m and 0.139 m/m.

The dominant land cover within the study area consisted of native forest (60%) and forest plantations (28%). Other minor land cover included herbaceous vegetation (6%), bare land (4%), and shrubs (2%). The native forest is primarily conifer trees, such as *Tsuga chinensis* var. *formosana* (storage volume, 599 m³/ha) and *Abies kawakamii* (storage volume, 391 m³/ha) and conifer mixed broadleaf (storage volume, 285 m³/ha). The plantations are primarily artificial conifer (storage volume, 156 m³/ha) (Figure 2). The local geological strata consisted of Alluvium, Paileng Formation Meitzulin Member (thick-bedded quartz sandstone intercalated argillite), Shuichangliu Formation (argillite and slate), and Chiayang Formation (slate with thin-bedded siltstone). The stratigraphic age ranged from Holocene to Eocene (Chang et al. 1997).

The locations of the Taoshan rainfall station (24°23'21"N, 121°17'47"E) and Qijiawan creek discharge station (24°19'56"N, 121°17'38"E) are also indicated in Figure 2. Figure 3 shows the hydrological records of rainfall and discharge from January 2006 to December 2010. The annual rainfall in the study area is highly variable. It ranges from 1,640 and 3,252 mm (from 2006 to 2010), with a mean annual rainfall of 2,451 mm (Figure 3(a)). Figure 3 (b) shows the mean monthly rainfall and its error bar; 61% of rainfall occurs from June to October. The variability of error bar was influenced by the typhoons from July to October; particularly in September. Typhoons Sinlaku and Jangmi carried heavy rainfall to the study region in September 2008. The peak flow discharge and mean annual discharge were 317 m³/s and 86 m³/s, respectively. The dominant severe weather events in the Qijiawan catchment during the last 5 years were Typhoon Fung-wong in July 2008 (total

rainfall of 559 mm), Typhoons Sinlaku and Jangmi in September 2008 (total rainfall of 877 mm and 648 mm, respectively), and Typhoon Morakot in August 2009 (total rainfall of 659 mm), as shown in Figure 3(c). Discharge occurred primarily from June to October (73%). This indicates that, in the study area, June to October is the wet season and November to May is the dry season (Figure 3 (d)). The hydrological characteristics are highly variable in the Qijiawan catchment. The mean annual rainfall from 2006 to 2008 was 2,983 mm, but decreased to approximately 1,330 mm from 2009 to 2010. A diversity of wood debris is expected in the study area because of the progression of these variable rainfall events.

1.2 Field surveys

In this study, wood debris was defined as wood pieces of at least 10 cm in diameter and 1 m in length (Andrus et al. 1988; Gippel 1995; Keller and Swanson 1979). Field surveys were performed to identify the wood debris in the study area, and the wood debris dimensions were recorded. The wood debris was classified according to the location and orientation during the surveys. The orientations between the wood debris and flow direction were recorded as follows: (a) parallel to the flow direction, (b) perpendicular to the flow direction, and (c) oblique to the flow direction. The locations were classified as follows: (a) adjacent to the floodplain, (b) bank edge, (c) across the channel, (d) partly across the channel, and (e) channel flow. All wood debris was measured for small-end diameter, large-end diameter, and length by using a tape measure. The two diameters were averaged to calculate mean diameter for individual wood debris. The volume of individual wood debris was calculated using Frustrum's formula (Harmon and Sexton 1996), assuming that the debris possessed a cylindrical shape.

$$V_w = l_w (A_b + A_t) / 2 \quad (1)$$

Where V_w is individual wood piece volume (m³); l_w is wood debris length (m); A_b is the area at the base of the wood debris (m²); and A_t is the area at the top of the wood debris (m²). The volumes of wood debris jams were used as the sum of the volume of individual wood pieces. If individual wood pieces in the wood debris jams were highly entangled and

difficult to measure, the width, height, and length were summed to give an approximate volume.

The first survey in the study area was conducted in January 2009. The wood debris within the bankfull channel and in the adjacent active floodplain was tagged. The characteristics of the wood debris were recorded. A second survey was performed following Typhoon Morakot in September 2009, and the tagged wood debris within the study reach was recorded. New wood debris was tagged, and data concerning the wood debris were recorded. The third survey was conducted in September 2010. Tagged wood debris was recorded, and new wood debris was tagged and measured. The characteristics of wood debris that moved between each survey were identified through comparisons between the results of each survey.

1.3 Data analysis

Two categories of factors were considered for analysis in this study. The wood debris characteristics category comprises wood length (l_w), wood diameter (d_w), abundance (pieces/100m), density (pieces/ha), piece volume (m^3), unit volume ($m^3/100m$), and volume/unit area (m^3/ha). The channel characteristics category comprises channel length (L), surveyed channel length (L_s), channel width (W), mean channel gradient (S), and creek catchment (A_c). The values of l_w and d_w were

collected from the field survey data. The channel lengths and widths were measured using rangefinder in the field, and the values of L , and S were extracted from a digital elevation model (DEM, $5m \times 5m$ spatial resolution). All analyses were performed using ANOVA within the SPSS software (version 12.0). This study uses linear regression to examine the relationship between the dependent variables (wood characteristics) and independent variables (channel characteristics). Pearson's correlation coefficient (r) was used to determine the relationship strength between the wood and channel characteristics. Regression results with p - values < 0.05 were considered significant.

2 Results

2.1 Characteristics of wood debris

The retrieved data indicate that 552, 618, and 1071 wood debris were tagged in January 2009, September 2009, and September 2010, respectively (Table 1). The abundance (ranging from 19 to 38 pieces/100 m), density (ranging from 90 to 175 pieces/ha), unit volume (ranging from 20 to 23 $m^3/100$ m), and volume/unit (ranging from 95 to 105 m^3/ha) increased during the survey periods, but the wood debris dimensions (length, mean wood debris size, and diameter) decreased.

Table 1 Characteristics of the woody pieces

	2009-01			2009-09			2010-09		
	Gaoshan creek	Qijiawan creek	Total	Gaoshan creek	Qijiawan creek	Total	Gaoshan creek	Qijiawan creek	Total
Total wood pieces	261	291	552	353	265	618	583	488	1071
Abundance (pieces/100m)	14.61	27.25	19.34	19.81	24.81	21.68	32.85	45.98	37.76
Density (pieces/ha)	99.92	82.41	89.86	135.53	75.05	100.76	224.73	139.05	175.48
Mean length*(m)	5.54 ± 3.90	4.66 ± 3.12	5.09 ± 3.55	4.89 ± 4.01	4.16 ± 2.79	4.59 ± 3.55	3.55 ± 2.88	4.19 ± 3.10	3.84 ± 3.00
Mean diameter*(cm)	36.68 ± 27.37	29.58 ± 21.91	33.04 ± 24.96	31.87 ± 22.63	26.13 ± 19.38	29.41 ± 21.47	27.44 ± 20.19	24.34 ± 17.73	26.03 ± 19.17
Mean wood debris size* (m^3)	1.07 ± 1.88	0.60 ± 1.96	0.83 ± 1.64	0.74 ± 1.35	0.48 ± 1.01	0.63 ± 1.22	0.60 ± 1.65	0.49 ± 1.28	0.55 ± 1.49
Total volume (m^3)	329.94	250.99	580.93	351.56	251.70	603.26	407.61	234.79	642.46
Unit volume ($m^3/100m$)	18.47	20.50	20.35	19.68	23.57	21.13	22.81	21.99	22.51
Volume/unit area (m^3/ha)	126.31	71.08	94.57	134.59	71.28	98.20	156.05	66.49	104.58

Note: For January 2009, September 2009, and September 2010, $n = 535$ (Qijiawan creek $n=274$, Gaoshan creek $n=261$), 618 (Qijiawan creek $n=265$, Gaoshan creek $n=353$), and 1069 (Qijiawan creek $n=484$, Gaoshan creek $n=585$), respectively. * Data are mean ± S.E. (standard error)

The wood debris dimensions at Gaoshan Creek were larger than those at Qijiawan Creek for all surveys.

Previous studies (Baillie et al. 2008; Bilby and Ward 1989; Chen et al. 2006; Irouméa et al. 2010; Montgomery et al. 1995) indicated that the channel characteristics play an important role in wood debris storage. The characteristics of wood debris were used to quantify the effects of channel characteristics. A significant correlation between channel width and wood debris was discovered among the independent variables of the channel characteristics category (Figure 4). The abundance and unit volume increased significantly with the channel width in the study area. The wood density decreased with the downstream distance.

Figure 4 Woody debris characteristics have a significant correlation with channel width. r indicates Person's correlation coefficient and the p -values signify degree of significance. Density (pieces/ha): $r = -0.213$, $p = 0.013 < 0.05$; unit volume ($\text{m}^3/100\text{m}$): $r = 0.291$, $p = 0.001 < 0.05$; abundance (pieces/100m): $r = 0.440$, $p = 0.000 < 0.05$.

2.2 Moved wood debris

Figure 5 shows the variations of the number and dimension of wood debris that entered and exited the study area. A summary of the wood debris characteristics from each field survey is shown in Table 2. The moved wood debris at Gaoshan Creek was more than that at Qijiawan Creek. The wood debris dimensions that entered and exited the study area ranged from 2 to 4 m in length and from 15 to 25 cm in diameter. Moreover,

the dimensions of wood debris at Gaoshan Creek were larger than those at Qijiawan Creek. This may be due to the wood debris collided with the channel bed, rocks, and each other, causing abrasions and reduced size. In total, 128 (55 m^3 ; $1.3 \text{ m}^3/100\text{m}$; $8.9 \text{ m}^3/\text{ha}$) and 554 (242 m^3 ; $8.5 \text{ m}^3/100\text{m}$; $39.4 \text{ m}^3/\text{ha}$) new wood debris entered the study area in September 2009 and 2010, respectively. A total of 61 of 552 tagged wood pieces (11%; 36.3 m^3 ; $1.3 \text{ m}^3/100 \text{ m}$; $5.93 \text{ m}^3/\text{ha}$) were transported downstream after Typhoon Morakot. Moreover, 17% of the tagged wood pieces (107 pieces; 73.8 m^3 ; $2.6 \text{ m}^3/100 \text{ m}$; $12.0 \text{ m}^3/\text{ha}$) were transported downstream before September 2010. Furthermore, the number of wood debris remaining at Gaoshan Creek was more than that of Qijiawan Creek. A wood jam normally begins with key wood debris that spans across a narrow channel. The trapped wood pieces create a new channel flow (Abbe and Montgomery 2003). The Shei-Pa National Park Headquarters sawed considerable key woods in Gaoshan Creek in July 2010 to prevent trapping large amounts of wood debris along the channel, facilitating the passing of small pieces of wood debris through the channel; thus, the quantity of retrieved wood debris and mobile wood debris increased dramatically.

3 Discussion

3.1 Spatial distribution

The spatial distribution of wood debris is shown in Figure 6. These results provide qualitative and quantitative observations of the responses of wood debris to channel characteristics at a reach scale. The wood storage is proportional to flow discharge. Large streams typically have a greater capacity to entrain wood debris. Conversely, smaller streams display a lower capacity to move wood debris (Chen et al. 2006; Piégay and Gurnell 1997). The present results are consistent with those of previous studies. However, the present finding further indicates that both abundance and unit volume increase downstream because a discharge increases downstream. Moreover, wood density decreases downstream within a channel network. These trends can be correlated with increasing channel width and decreasing unit stream power.

Figure 5 Dimensions (length and diameter) of woody debris entered and exited in Qijiawan catchment. The dashed line in each box is mean line; the outer points show the 5th and 95th percentiles.

Table 2 Summary characteristics of wood debris moved

	2009-09			2010-09		
	Gaoshan creek	Qijiawan creek	Total	Gaoshan creek	Qijiawan creek	Total
Wood debris entered						
Total wood pieces	$n = 83$	$n = 45$	$n = 128$	$n = 302$	$n = 252$	$n = 554$
Mean length (m)*	5.41 ± 5.33	3.57 ± 2.66	4.76 ± 4.65	2.70 ± 2.05	3.96 ± 3.23	2.73 ± 2.73
Mean diameter (cm)*	27.16 ± 21.65	17.82 ± 7.32	24.88 ± 18.48	24.20 ± 17.58	23.35 ± 17.47	22.78 ± 17.52
Total volume (m ³)	46.63	8.05	54.68	126.24	115.96	242.20
Unit volume (m ³ /100m)	2.61	0.75	1.29	7.07	10.86	8.48
Volume/unit area (ha)	17.85	2.28	8.90	48.33	32.84	39.43
Wood debris exited						
Total wood pieces	$n = 39$	$n = 22$	$n = 61$	$n = 58$	$n = 49$	$n = 107$
Mean length* (m)	4.27 ± 2.90	4.35 ± 3.90	4.30 ± 3.27	6.06 ± 5.12	4.15 ± 3.05	5.18 ± 4.38
Mean diameter* (cm)	26.02 ± 15.79	26.99 ± 21.64	26.37 ± 17.95	30.47 ± 24.29	26.56 ± 19.37	28.68 ± 22.16
Total volume (m ³)	23.02	13.25	36.28	48.90	24.94	73.84
Unit volume (m ³ /100m)	1.29	1.24	1.27	2.74	2.34	2.59
Volume/unit area (ha)	8.81	3.75	5.91	18.72	7.06	12.02

Note: Wood debris recruited means the new wood debris was found in the study reach on September, 2009 and 2010; wood debris mobile means the tagged wood missing in the study reach on September, 2009 and 2010. * Data are mean $\pm$ S.E. (standard error).

In the first-order stream (Gaoshan Creek), over 45% of the wood debris was stored within the channel or along the bank (Table 3). A portion of the wood debris (approximately 30%) was distributed on or adjacent to the floodplain. The remainder often remained on the channel floor, across, or partly across the channel, blocking the original streamflow and assisting it in creating a new streamflow or new channel morphology such as wood steps. In the second-order stream (Qijiawan Creek), most of the wood debris (over 75%) was distributed on the adjacent floodplain, and the remainder was distributed on the bank edge.

3.2 Accumulative distribution

Figure 7 shows the temporal and spatial correlation of the wood debris with its channel width, vertical distance, and cumulative percentage. The rates of the cumulative percentage at Qijiawan Creek are higher than those at Gaoshan Creek in all our field surveys. Approximately 50%, 65%, and 60% of the wood debris at Qijiawan Creek was retrieved in January 2009, September 2009, and September 2010, respectively. The cumulative percentage increase is considerable (50% to 65%) but decreases significantly in the later stages (65% to 60%). The increase can be attributed to the large amounts of wood debris that washed into the

channel and was transported downstream during the floods induced by Typhoon Morakot. The decrease may be due to the operational management of wood debris by Shei-Pa National

Figure 6 A sketch map of woody debris spatial distribution along the study reach (not to scale).

Table 3 Spatial distribution of wood debris locations and orientations

	2009-01			2009-09			2010-09		
	Gaoshan creek	Qijiawan creek	Total	Gaoshan creek	Qijiawan creek	Total	Gaoshan creek	Qijiawan creek	Total
Locations	n=261	n=291	n=552	n=354	n=265	n=619	n=584	n=484	n=1,068
Adjacent floodplain	12	83	50	51	75	62	28	77	50
Bank edge	57	13	34	35	24	30	44	22	34
Across channel	2	1	1	8	0	5	1	0	1
Partly across channel	0	0	0	2	0	1	6	0	3
Channel floor	29	3	15	4	0	2	21	1	12
Orientations	n=256	n=289	n=545	n=384	n=261	n=609	n=587	n=488	n=1,075
Parallel	45	36	40	41	44	42	36	35	36
Perpendicular	34	32	33	34	26	31	29	32	31
Oblique	21	32	27	25	30	27	34	32	33

Note: For 2009-01, 2009-09, and 2010-09. All data are presented as percentages.

Figure 7 Cumulative accumulation (upstream to downstream) of all woody debris during January 2009 (black line), September 2009 (dashed line), and September 2010 (dashed dotted line) in the studied reach, with stream longitudinal profile (square-black line); the vertical dashed lines indicate stream confluences. (II) is at the #1 and #2; (III) is at #3, and (IV) is at #6 in 8.

Park Headquarters. The four segments (Segments I to IV) in Figure 7 show the data regarding the rapidly accumulating wood debris. Figure 8 shows the corresponding photos to the sites of the segments. Wood debris has a tendency to spread and store in wide or braided channel sections because of a relatively low stream transport ability (Marcus et al. 2002). The increased channel width causes the accumulation of wood debris in Segment IV (#6 in Figure 8). Landslides along the stream introduce a significant amount of wood debris into the stream channel in Segment II (#1 in Figure 8). Riparian vegetation performs a key role in obstructing mobile wood debris in Segment III (#3

in Figure 8). The foregoing results indicate that channel width, landslides, and riparian vegetation enhance the accumulative distribution of wood debris in the study area.

3.3 Movement of wood debris

The movement of wood debris in streams is strongly related to its length; most pieces that move are shorter than the bankfull width (Lienkaemper and Swanson 1987; Warren et al. 2009). Chen et al. (2006) used the stability index (v), defined as the ration of wood debris length and channel width (l_w/W), to describe the stability of

Figure 8 Map of woody debris distribution in the studied reach. The woody debris distribution is schematic and not to scale. #1 and #2 show the riparian landslide and large wood debris deposited in front of the sandbar; #3 shows wood debris was obstructed by riparian vegetation; #5 describes a topographical notch; #6 shows amounts of woody debris spread along the channel with channel width increasing.

wood debris in relation to stream size. The results showed that the stability indices were 0.22, 0.20, and 0.17 for successive surveys in this study; therefore, a small ν indicates a high instability. Braudrick and Grant (2000) demonstrated that the stability of wood debris increases if it is parallel to the stream flow orientation in the channel. In the study area, more than 50% of the wood debris is perpendicular and oblique to the streamflow orientations in the study area (Table 3). Both the stability index value and the orientation of wood debris suggest that the wood debris in the study area is easily transported downstream during flood events. From January to September of 2009, 55 m³ (1.76 m³/100m, 127 pieces) of wood debris entered the study area, and 36 m³ (1.17 m³/100m, 61 pieces) exited the stream. From 2009 to 2010, 242 m³ (7.81 m³/100m, 560 pieces) of wood pieces entered and 74 m³ (2.38 m³/100m, 107 pieces) exited the study area. In our study area, 11% and 17% of the wood pieces were transported downstream during the flood events in 2009 and 2010, respectively. Irouméa et al. (2010) showed that 12% of the wood debris in the western coastal mountain of Valdivia, Chile, was transported downstream. Approximately 26% of the wood debris moved during floods in the 4-year survey at Adirondack Mountain, NY, USA (Warren and Kraft 2008). Our results indicate that the potential for wood debris movement in the high gradient catchment is stronger than that of other regions.

The critical depth for floatation can be calculated using the following equation (Braudrick et al. 1997):

$$d_c = r + r^2 \left[\frac{\pi(\rho_l/\rho_w - 1/2) - \sin^{-1}(d_c - r/r)}{\sqrt{2d_c r - d_c^2}} \right] \quad (2)$$

where r is the wood radius (m) and d_c is the critical depth for floatation (m). The Manning formula with d_c was used to calculate the threshold for wood movement. Three flood events, Typhoon Jangmi, Typhoon Morakot, and 0911 flood due to heavy rainfall, were selected to evaluate the entrainment of wood debris with given transport conditions. The discharges of Gaoshan Creek and Qijiawan Creek were estimated using the ratios of the specific catchment areas to catchment areas obtained from the Qijiawan Creek discharge station. The discharges for wood threshold were less than the discharges of the flood events, as

shown in Figure 9 (a). The threshold mean unit discharge is 0.34 m²/s (ranging from 0.05 to 2.3 m²/s) in the study region. These results indicate that regular flood events are significant factors that facilitate the entrainment and transport of wood debris in the study area.

Figure 9 Correlation between threshold unit discharges of wood entrainment and migration of wood debris during the Typhoon Jangmi and Morakot and regular flood event. (a) shows the wood entrainment threshold during the flood events; (b) shows the relationship between relative unit stream power ($N/m/s$) and variation of wood debris migration.

Moreover, unit stream power was used to represent the ability of streams to transport wood debris in the study area. Unit stream power was calculated using $\omega = \gamma q S$, where ω is the unit stream power ($N/m/s$), γ is the specific weight of water ($9,800 N/m^3$), q is the unit peak discharge of the flood event (m^2/s), and S is the mean channel gradient (m/m). Figure 9 (b) shows the unit stream power with the channel width for Gaoshan Creek

Figure 10 the migration of wood debris before and after the flood events at special geological structure in the study stream.

and Qijiawan Creek. The volumes of the moved wood debris are presented in size the data cycle to obtain direct comparisons. The volumes of wood debris stored along Gaoshan Creek were larger than those along Qijiawan Creek, which can be attributed to the tendency of wood debris to store along wide channels with low stream power (Baillie et al. 2008; Chen et al. 2006; Seo et al. 2010; Wyzga and Zawiejska 2005).

Moreover, the results show that the wood debris has a tendency to store at locations with certain channel characteristics. Sites with a wood debris dam development, topographical notch, and special geological structure had a relatively large amount of wood debris.

The two-braided wide channel in Qijiawan creek caused the velocities to decrease during the flood. Wood debris movement was suspended, causing gradual spread on the floodplain and lower transport ability (#6 in Figure 9 (b)). The volume of wood debris varied from 22 m³ to 64 m³ during the survey periods. Moreover, wood debris dam development is a key to reducing the potential migration of wood debris (Warren and Kraft 2008). It caused the volume of migratory wood debris to vary from 55 m³, 79 m³, to 41 m³ during the surveys (#4 in Figure 9 (b)). The topographical notch creates a slow flow zone. The wood debris is influenced by the slow flow and deposits in this zone when the wood debris is transported through this section. The survey shows that a significant variation in the volume of wood debris occurred because of the topographical notch. The volume varied sequentially from 55 m³, 117 m³, to 88 m³ (#5 in Figure 9 (b)). Furthermore, a special geological structure may recruit wood debris and increase its volume in a stream. Figure 10 shows that a large rock-accumulated wood debris during the flood events.

4 Conclusions

This study contributes to the quantification of wood debris characteristics, and shows the transportation of wood debris before and after flood events in a steep mountain stream. The study area is downstream of Gaoshan Creek and Qijiawan Creek, located at the Qijiawan catchment in Shei-Pa National Park of Central Taiwan. Field surveys were performed to identify the wood debris in the study area and the wood debris dimensions were recorded. As a result, the channel width, landslides, and riparian vegetation have a significant correlation with the cumulative distribution of wood debris in the study area. The channel width has an important role in wood debris storage. A correlation between channel width and wood debris variables is discovered. The ability of wood debris movement transportation is powerful in the steep stream system because of a relatively high unit stream power. Wood debris has a tendency to store along wide channels with low stream power. Moreover, the sites with development of wood debris dam, topographical notches, and unique geological structures have a relatively large amount of wood debris. The stability index value and the orientation of wood debris suggest that wood debris in the study area is easily transported downstream during flood events. Moreover, the critical depth for threshold of wood debris movement shows that the regular flood events are a significant factor in facilitating wood debris movement. It is demonstrated that the wood debris migration in the study area is greater than in other regions. These findings assist in the understanding of the effects of channel characteristics on the distributions of wood debris in steep stream systems.

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