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Effects of land cover changes induced by large physical disturbances on hydrological responses in Central Taiwan

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Abstract This study analyzes the significant impacts of typhoons and earthquakes on land cover change and hydrological response. The occurrence of landslides following typhoons and earthquakes is a major indicator of natural disturbance. The hydrological response of the Chenyulan watershed to land use change was assessed from 1996 to 2005. Land use changes revealed by seven remote images corresponded to typhoons and a catastrophic earthquake in central Taiwan. Hydrological response is discussed as the change in quantities and statistical distributions of hydrological components. The land cover change results indicate that the proportion of landslide relative to total area increased to 6.1% after the Chi-Chi earthquake, representing the largest increase during the study period. The study watershed is dominated by forest land cover. Comparisons of hydrological components reveal that the disturbance significantly affects base flow and direct runoff. The hydrological modeling results demonstrate that the change in forest area correlates with the variation of base flow and direct runoff. Base flow and direct runoff are sensitive to land use in discussions of distinction. The proposed approach quantifies the effect of typhoons and earthquakes on land cover changes.

Keywords Hydrology · Land cover change · Landslides · Remote sensing data · Disturbances · Monte Carlo simulations · Distinction

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Introduction

The interactions between land use/cover and underlying hydrological processes are frequently complex and dynamic (Uhlenbrook et al. 2001; Ashagrie et al. 2006). Quantifying the effect of land use changes on hydrological response is a current challenge in hydrological science (Ashagrie et al. 2006). Recently, numerous researchers have assessed the impact of land use/cover changes on

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hydrological cycles (Lorup et al. 1998; Chen and Li 2004; Chang 2004; Tetzlaff et al. 2007; Choi 2007; Lin et al. 2007a). The impacts of anthropogenic disturbances, such as land use changes induced by urbanization and industrialization, influence hydrological cycles (Turcotte and Malamud 2004; Barbaro 2007, Lin et al. 2007a, b; Saurral et al. 2008). On the other hand, the impacts of land use/cover changes induced by large physical disturbances such as wildfire, earthquake, and heavy rainfall influence hydrological processes (Walker 2002; Manga and Wang 2007; McMichaela and Hopeb 2007; Lane et al. 2008; Koi et al. 2008). However, few studies have examined the cumulative impacts of land use/cover changes induced by chronological disturbances such as typhoons and earthquakes on hydrological processes (Koi et al. 2008).

Taiwan is located in a subtropical region and sits on the Philippine plate at the Euro-Asian Plate junction (DeMets et al. 1990). Taiwan suffers disastrous earthquakes because of plate convergence as well as typhoons. Moreover, typhoons bringing enormous rainfall strike Taiwan every year from July to October. These two types of large physical disturbances cause land use/cover changes affecting watersheds, particularly land cover changes caused by landslides (Chung and Fabbri 2005; Guzzetti et al. 2005; Lin et al. 2008a, b) and by destruction of vegetation (Cheng et al. 2007; Chang and Feng 2008) in mountain watersheds in Taiwan. Extreme typhoon and earthquake events increase the incidence of landslides in the short term (Chang and Slaymaker 2002). Typhoons are different from earthquakes in forcing changes in land use/cover. Typhoons can significantly influence land use/cover changes such as landslides via the flow of accumulated rainfall and wind gradients. Moreover, typhoons invariably lead to recurrent land use/cover changes along an exposure aspect aligned with the typhoon path and abrupt changes perpendicular to the aspect (Lin et al. 2008a, b).

During 1996–2004, a series of large physical disturbances struck central Taiwan. The 21st September 1999 Chi-Chi earthquake that involved

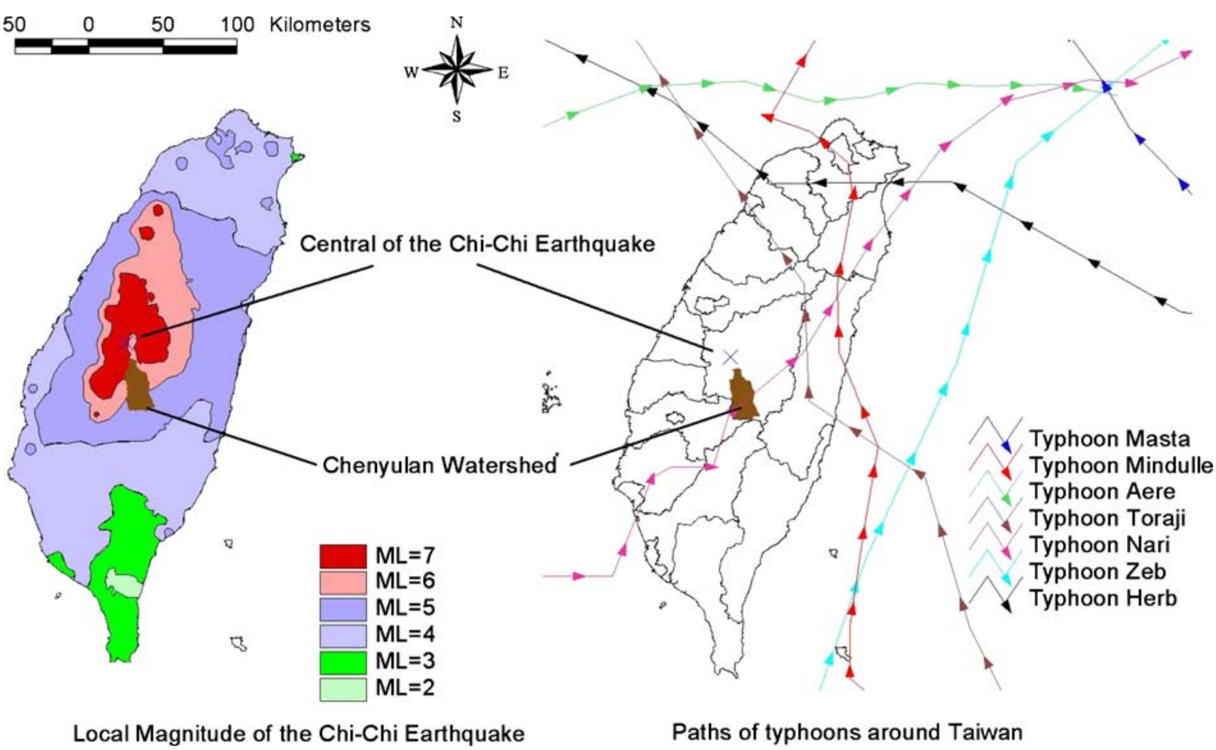

Fig. 1 Paths of typhoons and local magnitude of Chi-Chi earthquake in the study watershed

the rupture of the Chelungpu Fault occurred at 1:47 A.M. local time (17:47:18 GMT the previous day), with its epicenter at 23.85°N and 120.78°E and a depth of 6.99 km (Fig. 1). The estimated magnitude of the earthquake was ML = 7.3 (ML: local magnitude or Richter magnitude), and the rupture zone, as defined by aftershocks, measured approximately 80 km north–south by 25–30 km down-dip (Roger and Yu 2000). The earthquake significantly changed landscape patterns in central Taiwan, particularly in the area near the epicenter. Since 1999, following the Chi-Chi earthquake, the rate of expansion of landslide areas in central Taiwan has increased 20 times (Lin et al. 2003, 2008a, b) due to the numerous earthquake-created extension cracks, which increase landslides during heavy rain, created on hill slopes by the Chi-Chi earthquake (Lin et al. 2006a, 2008a, b). During 2000, Typhoon Xiangsane passed through eastern Taiwan but did not bring heavy rainfall events, and in 2001, Typhoon Toraji brought torrential rains and wind gusts of up to 90 miles per hour that caused significant property damage and fatalities. These typhoons, particularly Toraji, caused major landslides and debris flows in central Taiwan. Typhoon Mindulle, with a maximum wind speed of 200 km/h, a radius of 200 km, and maximum rainfall of 166 mm/h (June 29–July 2, 2004), produced heavy rainfall that fell across eastern and central Taiwan. Moreover, the cumulative impacts of the above disturbances on land use resulted from disturbance magnitudes and paths, but were not always evident in spatiotemporal variation in land use/cover (Lin et al. 2006b; Chang et al. 2007). Another big typhoon, named Aere, also approached the area on August 24–25, 2004, bringing approximately 320 mm of rainfall per day and also causing extensive debris flows (Tsutsui et al. 2007). Typhoon Matsa on August 3–6, 2005 dumped torrential rainfall of up to 1,270 mm, causing mudslides and moderate damage across the island. Disturbances such as those described above lead to the creation of complex patterns of land use/cover or cause changes in land cover in disturbed regimes. However, understanding the impacts of such disturbances on landscape patterns is essential for managing or restoring disturbed areas.

To understand the hydrologic effects of land cover changes, it is better to use a long-term hydrologic model than a single-event hydrologic model (Calder 1993; Kim et al. 2005). Importantly, the long-term impact of land use change on water quantity is dominated by the cumulative effects of frequent small storm events rather than by rare large storm events. This study assessed the relationship between land cover conversion and hydrological variables caused by natural disturbances, such as earthquakes and typhoons. The study classifies the land cover types using remote images obtained after large-extent disturbance and assessed the distinction level of the probability distribution frequencies (PDFs) of hydrological variables. Mote Carlo simulations were performed for the effects of land cover change on hydrologic response. To evaluate land cover impact, the model was coded to generate the surface runoff (direct runoff), base flow, total runoff, evapotranspiration, and infiltration of the watershed. The relationships among land use changes and hydrological variables were determined in the study watershed.

Methods and materials

Analyzed watershed and data

The Chenyulan watershed located in Nantou County, central Taiwan is a typical mountainous drainage watershed with a north–south orientation. The watershed has an area of 449 km^2, average altitude of 1,540 m, slope of 32°, and relief of 585 m/km^2 (Fig. 1). The main course gradient is 6.1%, and over 60% of the tributaries of the watershed have gradients steeper than 20% (Chang 1997). Slate and meta-sandstone are the dominant lithologies in the metamorphic terrain (Lin et al. 2003). Based on the relative quantities of slate and meta-sandstone, the metamorphic strata in the east of the study area are divided into the Shihpachuangchi, Tachien Meta-Sandstone, Paileng Meta-Sandstone, and Shuichangliu strata (Lin et al. 2003). In the sedimentary terrain (western part of the study area), sandstone and shale dominate, including the Nankang, Nanchuang, and KueiChulin Formations (Lin et al. 2003).

Steep slope, weak rock, and continuous heavy rainfall are major causes of slump sand debris flows.

At 01:47′12.6″ on September 21, 1999, an earthquake of magnitude 7.3 on the Richter scale and with a focal depth of 8.0 km struck central Taiwan. The cause of this event, known as the Chi-Chi earthquake, was movement of the Chelungpu fault. The epicenter was located at 23.87°N and 120.75°E, near the Chenyulan watershed in south Nantou County. Iso-contour maps of the earthquake were reproduced from Central Weather Bureau data. Figure 1 illustrates a map of the Chi-Chi earthquake. The earthquake caused surface ruptures along 100 km of the Chelungpu fault in a north–south direction and 10,000 landslides that seriously altered landscapes in central Taiwan, particularly near the epicenter.

Before the Chi-Chi Earthquake, Typhoon Herb swept across northern Taiwan from July 31 to August 1, 1996. This event brought maximum daily rainfall of 1,170 mm at its center and 850 mm over the Chenyuland watershed. A year after the Chi-Chi earthquake, Typhoon Toraji swept across central Taiwan from east to west, bringing maximum wind speeds of 138.90 km/h, together with 55.65-km/h winds over a radius of 180 km on July 30, 2001. The lowest pressure at the center of the storm was 965 hPa. The typhoon brought extremely heavy rainfall, ranging from 230 to 650 mm/day, and triggered more than 6,000 landslides. The maximum hourly rainfall was approximately 130 mm/h. After crossing central Taiwan, the typhoon became a tropical storm. The torrential rainfall associated with Typhoon Toraji washed away soil already loosened by the Chi-Chi earthquake and changed landscape patterns in central Taiwan.

Table 1 shows the first and second largest 24- and 48-h rainfall events during 1996 to 2005. All maximum rainfall events were associated with typhoons. Seven typhoons occurred from 1996 to 2005, with two occurring in each of the years 2001 and 2004. No heavy typhoons occurred during 1999–2000 or 2002–2003. To understand the effects of typhoons or the Chi-Chi Earthquake, Table 1 lists the time series and dates of the typhoons, earthquake, and remote images. Seven states are defined based on seven remote images

Table 1 Information and records of disturbances and remote images

Image (date)	Disturbances	24-h[a]: mm (date)	24-h[b]: mm (date)	48-h[a]: mm (date)	48-h[b]: mm (date)
State I (1996/11/8)	Typhoon Herb	459 (1996/7/31)	319 (1996/8/1)	778 (1996/8/1)	320 (1996/8/2)
State II (1999/ 3/6)	Typhoon Zeb	326 (1998/10/16)	106 (1998/10/15)	432 (1998/10/16)	326 (1998/10/17)
State III (1999/10/31)	Chi-Chi earthquake	(1999/9/21)			
State IV (2001/11/20)	Typhoon Toraji[c] and Nari[d]	616[c] (2001/7/30)	237[d] (2001/9/17)	653[c] (2001/7/30)	617[c] (2001/7/31)
State V (2003/12/17)	Heavy rainfall	111 (2003/6/7)	95 (2003/8/30)	128 (2003/6/7)	126 (2003/6/8)
State VI (2004/11/19)	Typhoon Mindulle[e] and Aere[f]	288[e] (2004/7/4)	215[f] (2004/8/24)	444[e] (2004/7/4)	406[f] (2004/8/25)
State VII (2005/11/11)	Typhoon Matsa	350 (2005/8/4)	251 (2005/8/5)	601 (2005/8/5)	302 (2005/8/6)

[a]The highest rainfall
[b]The second highest rainfall
[c]Typhoon Toraji
[d]Typhoon Nari
[e]Typhoon Mindulle
[f]Typhoon Aere

to represent the land use/cover of watershed in different time. The first of the remote images collected after 1996 is named state I, and the others are named sequentially according to time.

Land cover images and classification

SPOT images with cloud zero percentage cloud coverage were purchased from the Space and Remote Sensing Research Center and used for watershed land cover classification for the dates March 6, 1999, October 31, 1999, November 27, 2000, and September 21, 2001 before and after the earthquake and typhoons. The SPOT images were first classified via supervised classification with maximum likelihood and fuzzy methods using ERDAS IMAGINE software using 1/25,000 black and white aerial photographs and ground truth data (Lin et al. 2006b). Subsequently, the classified images and geographical data (roads, buildings, slopes, and band ranges) of the watersheds were used to construct the knowledge base in the Knowledge Engineer of IMAGINE software for final SPOT image classification. The IMAGINE user manual presented the theorems underlying the above image classification methods in greater detail. Moreover, kappa values were calculated to assess the final classification accuracy. The final accuracy assessment of each SPOT image used 747 pixels, with the accuracy assessment using between 30 and 475 pixels per training class. Table 2 lists the total accuracies and kappa values of the land cover classifications. In this study, the land cover categories were forest, grassland, farmland, buildup, landslide, and river sand. All accuracies and kappa values exceeded 82% and 0.77, respectively.

Simulation processes and hydrological model

This section describes the simulation of the hydrological component. First, a weather generation model (Pickering et al. 1988) was applied to produce a daily weather database comprising historical weather statistics for the period 1981 to 2005. The model is used to assess the impact of climate change and land use change (Tung and Haith 1995; Tung et al. 2006; Lin et al. 2007a) and to generate daily temperature and precipitation data for a 300-year period. These daily data were used as inputs in the hydrological model. Monte Carlo is used to simulate 300 years of land cover in each land cover state and to analyze the change in hydrological components.

The hydrological model employed in this study is the generalized watershed loading functions (GWLF) model developed by Haith and Shoemaker (1987). This model has previously been used to assess the effects of land use change on water resource supplies and hydrological cycles (Tung and Lee 2001; Lin et al. 2007a). The water balance is simulated on a daily basis. The model included lumped and distributed parameters for simulating base flow, direct runoff, and stream flow in the watershed. Data inputs included daily rainfall and temperature, and the data output were all hydrological components. The effects of land use change are described by the curve number method, which is used to estimate direct runoff in the model. The water mass balance zones are both unsaturated and saturated. In the unsaturated zone, water mass balance is calculated based on infiltration, evapotranspiration, percolation into the saturated zone, and initial moisture in the unsaturated zone. Infiltration comprises rainfall minus direct runoff. Moreover, evapotranspiration is estimated as the moisture in the unsaturated zone and potential evapotranspiration is calculated by the Hamon equation and cover coefficients (Hamon 1961; Tung and Lee 2001). The cover coefficients differ according to land use. The base flow from the saturated zone was estimated using a linear function with a regression coefficient. All hydrological components are presented in units of depth (centimeters). The GWLF model was introduced in the detailed model equations in the GWLF user manual (Haith et al. 1992).

Distinction level

Seven land cover states derived from SPOT images were assumed to represent different hydrological properties in different years. This study examined whether different land cover caused by disturbing events such as typhoons and earthquakes can be identified based on hydrological components. A simple means of achieving such a differentiation involves measuring output

PDF. Monte Carlo simulations revealed the frequency distributions of all seven land cover states. Eckhardt et al. (2003) presented a method for comparing pairs of land covers by two PDFs. This study follows the procedure of Eckhardt et al. as described below. The comparison method assumed that output variable y is partitioned into N intervals. By normalizing the interval $y_i(i = 1 \ldots N)$ to the number of model runs per Mote Carlo simulation, the probabilities $p[y_i](i = 1...N)$ of finding the value of variable y in one of the intervals yi can be calculated. Let $p[y'(A)]$ denote the probability of land cover A; the calculated value of y lies in the interval y', and $p[y'(B)]$ is the corresponding probability for land cover B. The probability $p[y'(A,B)]$ of two model runs yielding a model response y in the interval y' is:

$$p\left[y'(A,B)\right] = p\left[y'(A)\right] \times p\left[y'(B)\right]. \tag{1}$$

The overall probability $P_y(A,\ B)$ of two independent realizations of land covers A and B yielding the same result with respect to y is obtained by summing all intervals:

$$P_y\,(A,B) = \sum_{i=1}^{N} p\left[y_i(A,B)\right] = \sum_{i=1}^{N} \left\{p\left[y_i(A)\right] \times p\left[y_i(B)\right]\right\}. \tag{2}$$

The $P_y(A,\ B)$ can be normalized with respect to max $\{P_y(A,\ A),\ P_y(B,\ B)\}$. The distinction of outputs from different land cover is assumed to be calculated as:

$$D_y\,(A,B) = 1 - \frac{P_y(A,B)}{\text{Max}\left\{P_y(A,A) \times P_y(B,B)\right\}} \tag{3}$$

where $D_y(A,B)$ is the distinction of hydrological variable y between land covers A and B. If two identical frequency distributions are compared, then $D_y(A,B) = 0$. If the distributions do not overlap, then $D_y(A,B) = 1$.

Eckhardt et al. (2003) noted that a common problem associated with similarity is how to define the significance criterion. Eckhardt et al. (2003) analyzed similarities among land cover change scenarios in an artificial catchment. A distinction level is defined as 0.9 and exits in the event of a proportional shift from grassland to forest. This study considers a real case of this phenomenon. In real cases, it is impossible for the hydrological difference to be large when distinction equals 0.9. Furthermore, in the case described by Eckhardt et al. (2003), a 25% proportional shift from pasture to forest was presented at the statistical significant level below 0.1. Consequently, it was inappropriate in this study to apply the standard of Eckhardt et al. (2003). Moreover, a distinction value of 0.1 is frequently selected as the typical standard for representing certain change. For example, if a standard normal distribution with zero mean and one standard deviation is compared with another normal distribution, the distinction is approximately 0.1 when the normal distribution has a mean of 0.6 with no change in the standard deviation or when the standard deviation equals 1.2 with no change in the mean.

The hydrological comparison is conducted in this study analyzed four components: evapotranspiration, base flow, direct runoff, and stream flow. To understand the impact of land cover on these components, two comparisons of the impact of these components are made, as follows. The conversion from one state to another over time is analyzed first, and then states I and III are taken as references for analyzing the other states. State I is the starting point of the analysis, while state III is the state immediately following the Chi-Chi earthquake. The purpose of the first comparison, which is of a temporal transition from one state to the next, is to determine how the effects of hydrological components differ between two disturbances. Furthermore, the second comparison analyzes the effects of typhoons and earthquakes, as well as disturbance history. Larger disturbance may be associated with increased differences between dissimilar hydrological components.

Results

Results of land use analysis

Statistics of land covers in each state provide a basic tool for characterizing land cover changes.

Table 2 Land cover and classification accuracy (unit: ha)

		State I	State II	State III	State IV	State V	State VI	State VII
Date		1996/11/8	1999/3/6	1999/10/31	2001/11/20	2003/12/17	2004/11/19	2005/11/11
Land cover	Cultivated	4,754.48 (10.70%)	4,354.76 (9.80%)	5,455.24 (12.20%)	5,166.88 (11.60%)	5,738.44 (13.00%)	6,164.64 (13.80%)	6,394.48 (14.30%)
	Forest	35,797.76 (80.90%)	35,171.8 (79.40%)	33,461.8 (74.90%)	34,802.76 (77.90%)	34,351.12 (78.00%)	33,424.24 (74.90%)	33,256.28 (74.40%)
	Built-up	204.56 (0.50%)	197.32 (0.40%)	277.4 (0.60%)	239.4 (0.50%)	299.84 (0.70%)	310.32 (0.70%)	341.96 (0.80%)
	Grass	1,956.12 (4.40%)	2,314.28 (5.20%)	2,762.28 (6.20%)	2,211.84 (4.90%)	1,773.12 (4.00%)	2,690.24 (6.00%)	2,092.76 (4.70%)
	Landslide and river sand	1,555.04 (3.50%)	2,243.48 (5.00%)	2,747.12 (6.10%)	2,266.52 (5.10%)	1,892.00 (4.30%)	2,023.00 (4.50%)	2,610.08 (5.80%)
Overall accuracy (%)		82.07	86.26	84.46	84.86	83.87	84.86	87.25
Kappa values		0.7672	0.8125	0.8067	0.8036	0.8007	0.8071	0.8359

Value in parenthesis is the percent of whole watershed

Table 2 and Fig. 2 also lists the results for remote land cover images and classifications. However, the land cover classification from remote images cannot easily distinguish landslides from river sand. The problem involves both technological limitations and landslide location. Chang and Slaymaker (2002) pointed out the frequency and spatial distribution of landslides. Many new landslides result from typhoon events located near rivers. Bias in land use classification persists for large watersheds and rivers. Therefore, river sand and landslide are combined into a single term. This study used the following five land use types: cultivated land, forest, built-up areas, grasslands, river sand, and landslide. In terms of area, the different land use classifications follow the order forest, cultivated land, landslide, grassland, and urban areas. The proportion of forest area to the entire area decreased considerably, from 80.9% in 1996 to 74.4% in 2005. The forested area reduced during the transition from state II to state III. Following state III, the proportion of forest to the entire area increased to 78% in state V and then gradually decreased until state VII. Furthermore, the proportion of cultivated land to the entire area was 10–14%.The cultivated area slightly increased over time except in the case of state III. All land cover types other than forest and cultivated land represent low proportions of the entire area. The average proportions of landslide, grass, and built-up areas to the entire area in the watershed are 5.0%, 4.9%, and 0.6%, respectively.

Changes in land cover over time are described for transitions between states, for example states I–II, states II–III, etc (Table 3). Table 3 shows that the maximum conversion occurred for states II–III regardless of the change in the proportion of forest or cultivated land to the entire area, as demonstrated by analyzing the impacts of different disturbances on land use change. Landslide and river sand increased from state I to state II and state II to state III and decreased from state III to state IV and from state IV to state V. The transition from state IV to state V revealed a slight change in land cover. Especially, the proportion of forest land to the entire area decreased by 3.05% and that of grassland increased by 2.01% during the transitions from state V to state VI. Therefore, the major land

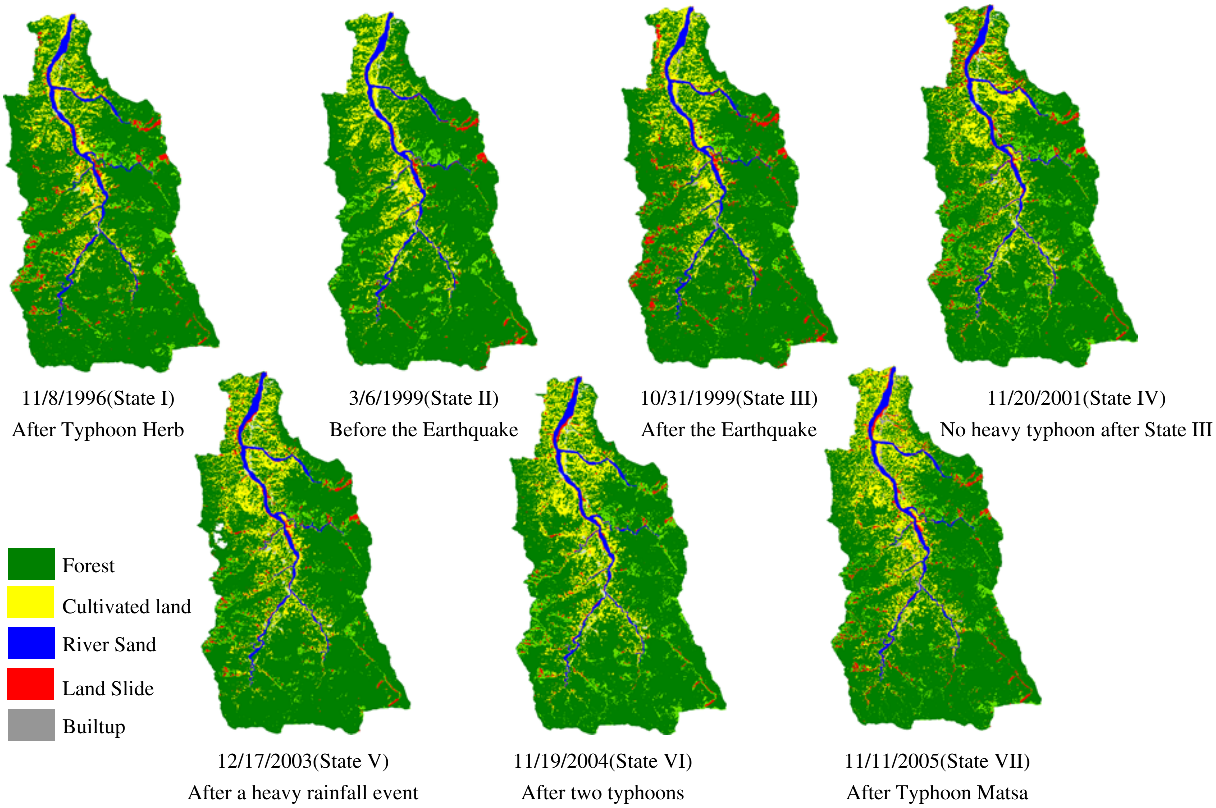

Fig. 2 Land covers from 1996 to 2005

Table 3 The percentage of land use changes between states

	Cultivated (%)	Forest (%)	Built-up (%)	Grass (%)	Landslide and river sand (%)
Transition with time					
States I–II	−0.91	−1.44	−0.02	0.81	1.55
States II–III	2.37	−4.58	0.17	0.95	1.08
States III–IV	−0.64	3.03	−0.08	−1.23	−1.07
States IV–V	1.46	0.09	0.14	−0.92	−0.78
States V–VI	0.79	−3.05	0.01	2.01	0.24
States VI–VII	0.49	−0.52	0.07	−1.35	1.31
Compared with state I					
States I–II	−0.91	−1.44	−0.02	0.81	1.55
States I–III	1.46	−6.01	0.16	1.76	2.63
States I–IV	0.82	−2.99	0.07	0.53	1.56
States I–V	2.29	−2.89	0.22	−0.39	0.78
States I–VI	3.08	−5.94	0.23	1.61	1.02
States I–VII	3.57	−6.46	0.30	0.26	2.33
Compared with state III					
States III–I	−1.46	6.01	−0.16	−1.76	−2.63
States III–II	−2.37	4.58	−0.17	−0.95	−1.08
States III–IV	−0.64	3.03	−0.08	−1.23	−1.07
States III–V	0.82	3.12	0.06	−2.15	−1.85
States III–VI	1.62	0.07	0.08	−0.15	−1.61
States III–VII	2.10	−0.45	0.14	−1.50	−0.31

cover change associated with the transition from state V to state VI can be considered to be the transformation of forest into grassland. The most obvious transformation occurred from state II to state III. The proportion of forest to the entire area reduced to 4.58% and that of cultivated land use increased to 2.37%. Human activity caused the change in cultivated land. The proportion of river sand and landslide to the entire area was 1.08%, representing a substantial change to land cover, but not the largest observed. In the case of states I–II, the proportional change in river sand and landslide was 1.55%. The second largest change was 1.31%, occurring in the case of the transformation of state VI to state VII. While the earthquake was major, it did not represent the biggest transition in terms of impact on land cover change. Conversely, Typhoon Zeb caused substantial change during states I–II. Apparently, the proportion of river sand and landslide to the entire area was already bad at state II. Consequently, a serious earthquake following a heavy typhoon may not significantly affect land use.

State I, in 1996, serves as a reference for analyzing long-term change. The maximum proportional change in river sand and landslide compared to state I during the past 10 years is 2.63% regardless of the effects of earthquakes and typhoons. Taking land use in state I as a reference, forest is the single largest category of land cover, with cultivated land only increasing significantly after state V. The proportions of landslide and river sand over total land cover from state I to state III and from state I to state VII were 2.63% and 2.33%, respectively. The conversion of forest was resulted mainly from a decade-long increase in cultivated land. Furthermore, no obvious evidence of difference exists between typhoons and the earthquake, both of which exhibit similar effects. The proportions of river sand and landslide to the entire area were 4.3% (at state V)–6.1% (at state III). No typhoons occurred during the transition from state IV to state V (2001/11–2003/12). Recovery, which is the proportional decrease in landslides, was observed during the transitions from state III to state IV and from state IV to state V. However, two typhoons, Toraji and Nari, occurred during the transition from state III to state IV. The watershed may have recovered from previous landslides if these typhoons had not occurred. However, the watershed can still recover from typhoon disturbances when it is its worst situation and the landslide area is at its maximum.

Taking state III (after the earthquake) as a reference, within 2 years, the proportion of forest to the entire area increased to 3.03%, as demonstrated at state IV. By state V, the proportion of forest to the total area increased to 3.12%. The effect of typhoons after the earthquake was thus insignificant in the case of forest. The forest area in states I, II, IV, and V exceeded that in state III. Specifically, the landslide and river sand area decreased 2.63% in state III–I, with decreases in other land use types ranging from 1.85% to 1.07%. The area of landslide and river sand was at its peak in state III. The area of landslide in Chenyulan watershed declined from state III to state V, but the area remains unstable. Consequently, evidence exists of a recovery of vegetation in the Chenyulan watershed.

Comparison of simulated hydrological components for different land uses

The model was validated using a series of monthly stream flow data for the Chenyulan stream gauging station from 1996 to 2001 (Fig. 3). The validation results demonstrate the good performance of the GWLF model except for the simulated stream flow in Jul-96 and Aug-96. The R^2 of the observed and simulated data was 0.89.

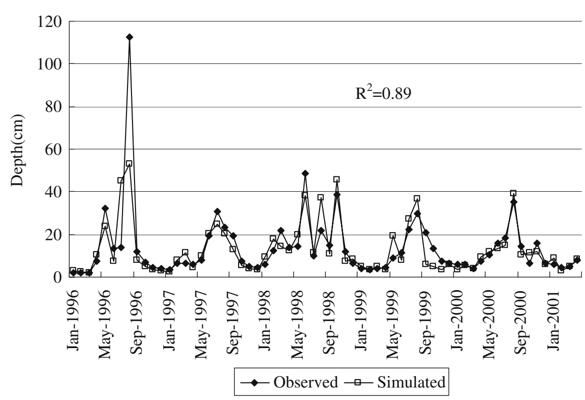

Fig. 3 Observed and simulated stream flow from 1996 to 2001

To examine the hydrologic impact of land use changes, the model was run using the land cover data sets to represent seven states of the watershed using the Monte Carlo simulation approach.

The results of hydrological component analyses involving four hydrological components, including evapotranspiration (ET), base flow (BF), direct runoff (DR), and stream flow (SF), during the three analysis periods (annual, wet, and dry season) for different states are presented. The wet season runs from May to October, and the dry season runs from November to April. Figure 4 compares the difference among four hydrological components during three periods, taking states I and III as references. Annual evapotranspiration and stream flow did not significantly differ among all states. Base flow decreasing and direct runoff increasing were observed in comparison with state I. The difference in direct runoff was 2–4%, while that in base flow was 2–6%. Due to the forest decreasing, the differences in states III–I and VII–I in direct runoff were larger than that with states II–I and V–I. Moreover, the difference in stream flow during the dry season was greater than the difference among states during the wet season. This phenomenon results from the limited ability of a watershed to retain rainwater during heavy rainstorms in the wet season.

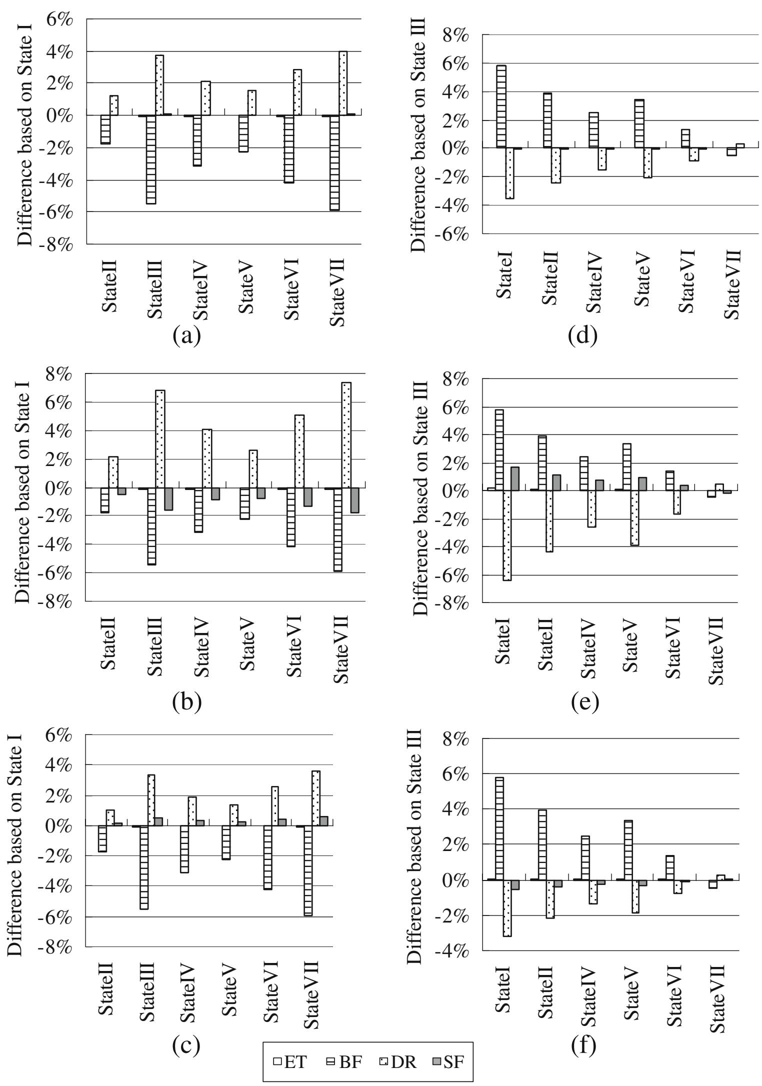

Fig. 4 Differences of four hydrological components compared with state I and state III. **a**, **d** Annual average; **b**, **e** in dry season; **c**, **f** in wet season

Table 4 Ranks of hydrological distinctions

States	Ranks of hydrological differences compared with state I						Ranks of hydrological distinctions compared with state III					
	II	III	IV	V	VI	VII	I	II	IV	V	VI	VII
Annual												
ET	2	5	3	1	4	6	6	4	3	5	2	1
BF	1	5	3	2	4	6	6	5	3	4	2	1
DR	1	5	3	2	4	6	6	5	3	4	2	1
SF	2	5	3	1	4	6	6	4	3	5	2	1
Dry season												
ET	2	5	3	1	4	6	6	4	3	5	2	1
BF	1	5	3	2	4	6	6	5	3	4	2	1
DR	1	5	3	2	4	6	6	5	3	4	2	1
SF	1	5	3	2	4	6	6	5	3	4	2	1
Wet season												
ET	1	5	3	2	4	6	6	5	3	4	2	1
BF	1	5	3	2	4	6	6	5	3	4	2	1
DR	1	5	3	2	4	6	6	5	3	4	2	1
SF	1	5	3	2	4	6	6	5	3	4	2	1

ET, evapotranspiration, *BF* base flow, *DR* direct runoff, *SF* stream flow

Figure 4d–f shows the hydrological components during different periods (annual, wet season, and dry season) compared with state III. Base flow increased and direct runoff decreased during all periods except states III–VII. Similarly, the direct runoff of state III is nearly the highest for the survey period, and the base flow of state III approaches the lowest for the survey period. The effects of earthquake are directly linked to the changes in base flow and direct runoff, and therefore, base flow records its lowest value during the survey period and direct runoff records its highest value in state III.

To understand the relationships between the hydrological variables and land cover types, Table 4 lists the ranks of hydrological variables associated with land cover types. A higher number indicates larger difference and area. Table 4 also lists the ranks of hydrologic variables for the reference of states I and III. It also shows that the difference of state VII–I is largest. State II and state V approximated state I. Other states, such as states IV and VI, were gradual states. The right side of the table compares the results for state III. The rank was high when state I was compared with state III, indicating a significant difference in hydrological components. The components of state III were similar to those of state VII and state VII (Table 5). Briefly, the hydrological modeling results show that the rankings of hydrologic component difference are similar to that of forest area change. This similarity results from major land use type and forest change being related to hydrologic responses.

Distinction of hydrological components between two states

Figure 5 shows the distinction of four components in different states using a comparison

Table 5 Ranks of land cover changes

States	Ranks of land use change compared to state I						Ranks of land use changes compared to state III					
	II	III	IV	V	VI	VII	I	II	IV	V	VI	VII
Cultivated	1	3	2	4	5	6	2	1	3	4	5	6
Forest	1	5	3	2	4	6	6	5	3	4	2	1
Built-up	1	3	2	4	5	6	2	1	3	4	5	6
Grass	4	6	3	1	5	2	2	5	4	1	6	3
Landslide	5	6	4	1	2	5	1	4	5	2	3	6

between state I and state III. In the wet season, heavy rainfall resulted from typhoons or storms were generally concentrated within a short period. Changes in land cover significantly affect the base flow. The distinction analysis revealed that the effects of disturbances on base flow significantly exceeded the effects of direct runoff during the wet season. During the dry season, the change in land cover significantly affects stream flow, direct runoff, and base flow. The hydrologic distinctions of land cover change for monthly stream flow, monthly base flow, monthly direct runoff, and monthly evapotranspiration during the dry season were 0.25, 0.3, 0.3, and 0.15, respectively. During the dry season, base flow influences the ecological environment particularly significantly. The distinction of hydrological component distribution makes it easy to assess the hydrologic effect of different land covers, especially stream flow, compared to the distinction of the hydrological component (Fig. 4). Therefore, the proposed method can demonstrate distinct stream flow distributions.

Figure 6 shows the distinction among the transitions for different periods (annual, wet season, and dry season). Figure 6a shows that the

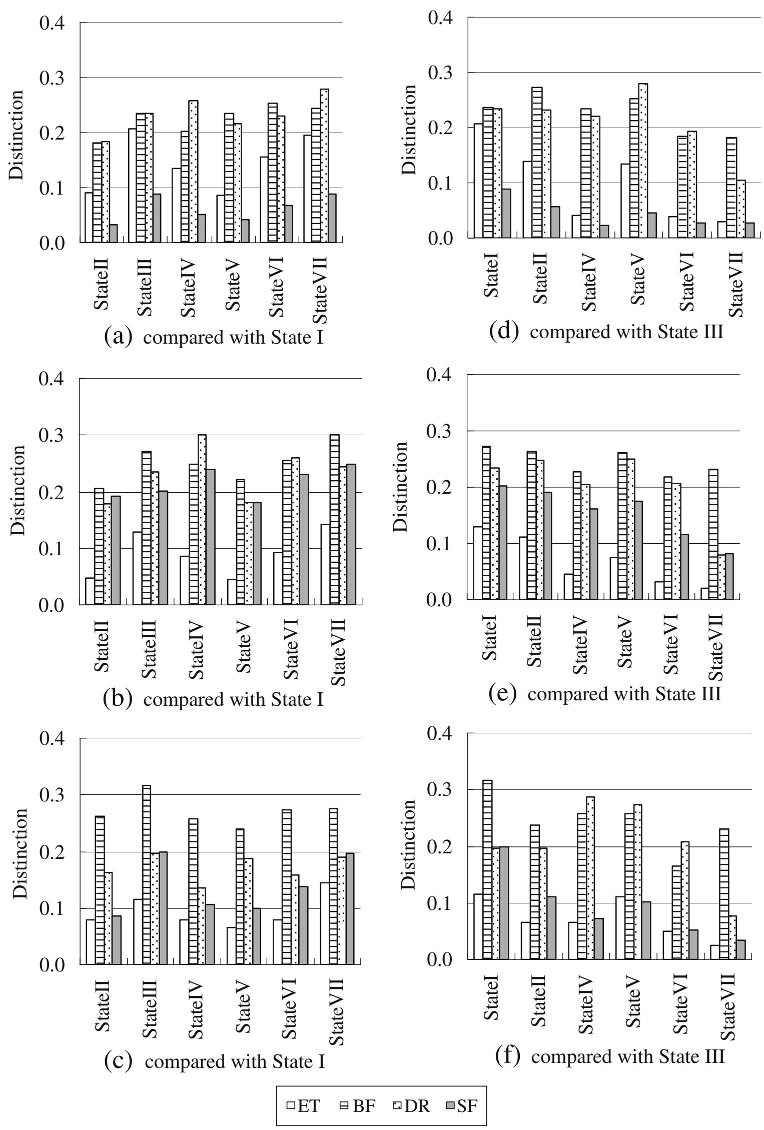

Fig. 5 The distinctions of four hydrological components compared with state I and state III. **a**, **d** Annual average; **b**, **e** in dry season; **c**, **f** in wet season

distinction of the transitions between states varies with hydrological components. Annual stream flow in transitions of land cover states exhibits little distinction. The distinctions between evapotranspiration in the transitions were all less than 0.1, with the exception of states II–III. The distinctions results show that distinction values for base flow and direct runoff were 0.15–0.31. Direct runoff exhibited the lowest distinction and base flow exhibited the highest distinction in states IV–V because slight change of forest area with significant landslide reductions and cultivated area increases. Figure 6b reveals that the distinctions of stream flow exceeded 0.1 except states IV–V in the dry season. However, the distinctions of base flow and direct runoff are similar. Figure 6c shows that the direct runoff and base flow between two states are significantly distinct during the wet season. The highest distinction value for direct runoff in states III–IV was 0.29, while that highest value for the distinction in base flow was 0.27.

Relationship among the change of land cover and hydrologic response

To evaluate the relationships among land cover changes, quantities, and distribution distinctions

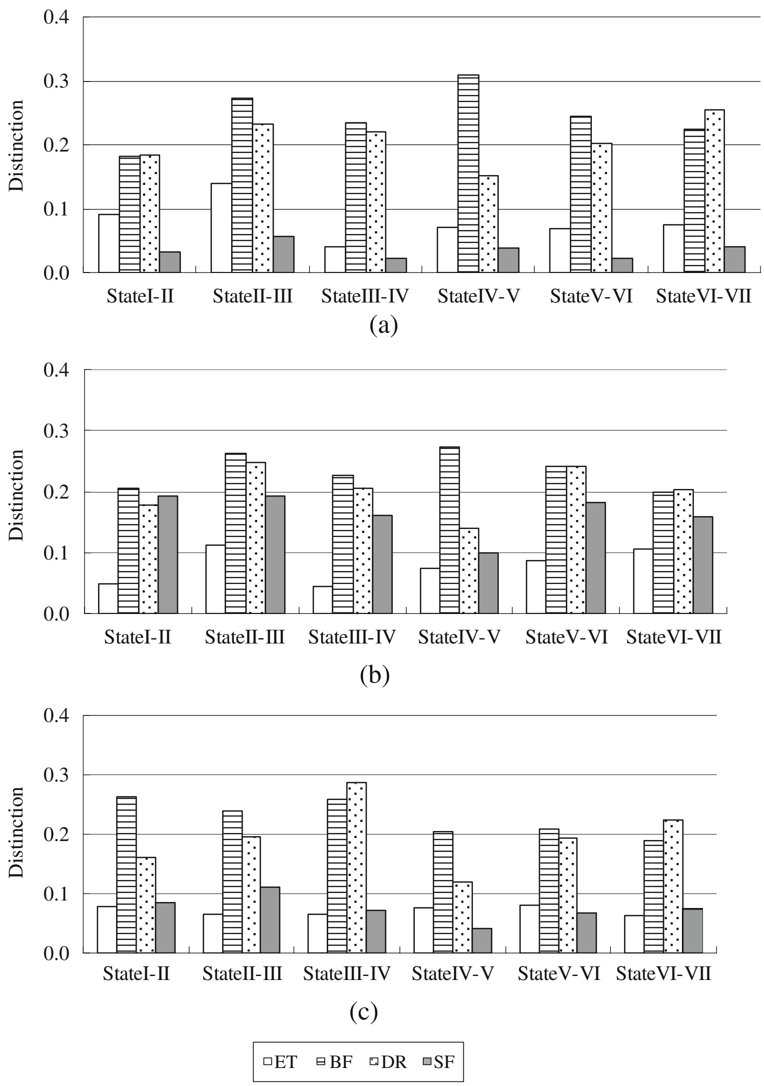

Fig. 6 The distinctions among states of four hydrological components. **a** Annual average; **b** in dry season; **c** in wet season

in hydrological components, owing to forest land as a proportion of total land cover changing considerably during the survey period, both direct runoff and base flow, which are the most sensitive, are discussed simultaneously. Based on state I, Fig. 7 shows the relationships between land use changes and rate of change of hydrologic components, including base flow and direct runoff, in circumstances where obvious dry seasons exist in the study area. Figure 7a shows a linear relationship between the percentage change in forest area and the difference in runoff compared to state I. The hydrological modeling results show that the main effect of hydrologic response was change in forest area. Figure 7b compares the base flow change rate with the change in forest area. Changes and distinctions in land cover exhibited a linear relationship. The correlation analysis result shows a strong relationship between base flow and area of forest cover. Therefore, change in land cover can significantly impact infiltration and thus reduce base flow. Undoubtedly, the rate of change in land use significantly influences hydrological component type.

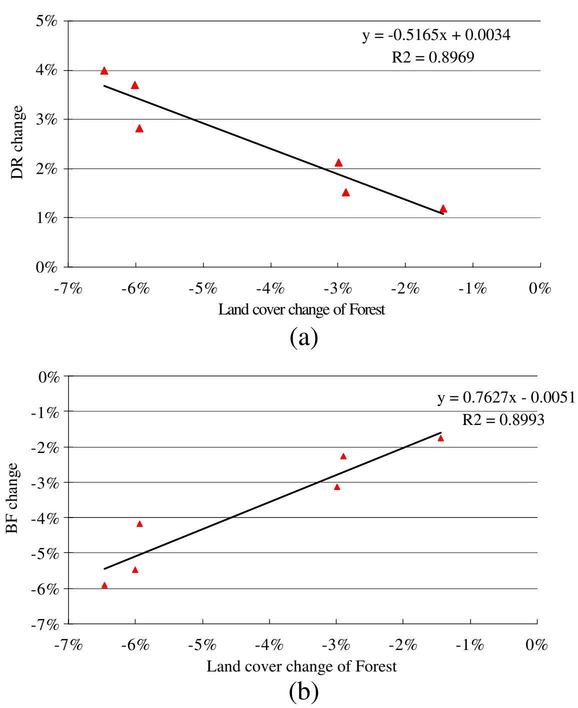

Fig. 7 Relationships between forest area change and hydrological components when compared with state I. **a** *DR* direct runoff and **b** *BF* base flow

Discussion

Effect of typhoons and the Chi-Chi Earthquake on land cover change

Landslides are a major natural hazard affecting mountainous terrain. The study of landslides has attracted global attention primarily owing to growing awareness of their socioeconomic impact (Saha et al. 2005). Remote sensing data can be used for various purposes in the study of landslides, including: landslide detection and classification, monitoring the activity of existing landslides, and slope failure prediction OR landslide prediction (Lee 2005). Simplest of all, distribution analysis only represents the direct mapping of landslide locations from remote sensing data. This type of analysis uses GIS to digitize landslides prepared from remote sensing images (Ward et al. 2000; Giriraj et al. 2008; Fox et al. 2008; Zomeni et al. 2008). Land use change may result from human activities and natural disturbance. In this paper, while changes in forest cover and landslides reflect the natural consequences of typhoons and earthquakes, clustering of cropland probably result from physical responses to physical variables (such as soil type) as well as social activities. Land use change is dominated by natural processes, such as the severe earthquake and seven typhoons affecting the study watershed. Natural disturbance led to increased landslide area and decreased forest area. Previous studies (Lin et al. 2006b, 2008a, b) indicated that landslides in the Chenyulan watershed were influenced by the Chi-Chi earthquake; however, the effect of the earthquake reduced over time. Lin et al. (2009) concluded that large disturbances, such as the Chi-Chi earthquake, create extremely complex heterogeneous landscape patterns. Notably, a disturbance may affect some areas but not others, and disturbance severity often varies significantly within an affected area. The results of land cover change also confirm that landslides in the Chenyulan watershed were impacted by the Chi-Chi earthquake (Lin et al. 2006b; Chang et al. 2007; Lin et al. 2009); however, the effect of the earthquake decreased over time (Chang et al. 2007; Lin et al. 2009).

Earthquakes represent the biggest natural threat to watersheds and create large areas of landslide and river sand (the range of landslide and river sand area in this study was 3.5–6.1% of total area over a 10-year period). However, the change in landslide and river sand area as a result of Typhoon Herb was the smallest. The pre-earthquake effects of Typhoon Zeb caused an obvious disturbance, increasing landslide and river sand area by 1.5%. The proportion of landslide and river sand over total land cover before the Chi-Chi Earthquake in 1999 was 5.0%, increasing to 6.1% after the earthquake. Notably, two typhoons occurred during 2001, but neither caused an increase in landslide area, with the proportion remaining at 5.1%. During 2003, the proportion of landslide and river sand to entire area decline to 4.3% in the absence of any typhoon. Moreover, in 2005, the proportion of landslide and river sand to the entire area increased to 4.5% after Typhoons Mindulle and Aere. Moreover, in 2005, the proportion of landslide and river sand area to the entire area increased to 5.8% after Typhoon Matsa. Therefore, disturbances associated with typhoons and earthquakes caused changes in landslide and river sand under a certain range. Although the vegetation recovery was in progress on the Chenyulan watershed, the soil slope remained unstable. Consequently, typhoons in 2005 caused the hill slope to collapse again several years following Chi-Chi earthquake. The impacts of disturbances on the watershed landscape pattern were cumulative, but were not always evident throughout the entire landscape (Lin et al. 2006b; Lin et al. 2009). Improved vegetation recovery efforts should be implemented throughout the study watershed, particularly in landslide areas.

Effect of land use change on hydrologic response

The dynamics of surface hydrology, i.e., total water yield from a watershed, including surface runoff and base flow, in relation to changes in land use and soil quality, significantly impact water availability (Lal 1997; Kim et al. 2005; Tetzlaff et al. 2007; Saurral et al. 2008). Meaningful data aggregation should prioritize the preservation of the area percentages of different land use classes because land use/cover are the key data required by a water flux model (Bormann 2006). In this study, the GWLF model effectively simulated monthly stream flow, surface runoff, and evapotranspiration under land use change conditions. The predicted hydrological components (stream flow, direct runoff, and base flow) were impacted by the land use changes forecast using Monte Carlo simulations. Stream flow comprises direct runoff and base flow, where the former is primarily surface runoff and the latter is groundwater discharge to a stream. Direct runoff comprises the major portion of stream flow that occurs right during the rainy season, whereas base flow is the main source of stream water during dry periods (Zhand and Schilling 2006).

Simulation can predict some results related to the impact of land use change on water sources. The effect of land cover change was quantified using a hydrologic model. The simulation results imply that hydrologic distinction is more sensitive to land use change and the land cover deterioration increased hydrologic distinction. To evaluate the impact of land cover, the model was coded to generate the direct runoff, base flow, total runoff, and evapotranspiration of the watershed. The method of Eckhardt et al. (2003) is simple to implement and is employed here to demonstrate the distribution of the PDFs between two states. Hydrological patterns are compared in terms of their PDFs. The main objective is to assess whether the modeled hydrologic effects differ clearly among different types of land cover. The difference in stream flow distribution between two states increased, while the forest area decreased. Therefore, the proposed method can identify the difference of quantity of hydrological variables and obtain the distribution of the variables between pair states. The hydrologic distinctions of land use change are monthly base flow, monthly direct runoff, monthly stream flow, and monthly evapotranspiration, respectively. Typhoons and earthquakes caused changes in landslide under a certain range and the variation of hydrology variables. Direct runoff increases and base flow decrease when forest land changes to agricultural land or landslide (Lorup et al. 1998; Kim et al. 2005; Zhand and Schilling 2006; Barbaro 2007; Tetzlaff et al. 2007).

In this area, forest dominates land cover (matrix) and change in forest area is related to hydrologic response. The hydrological modeling results show that the main effect of hydrologic response (including base flow and direct runoff) was change in area of forest. Reduced forest coverage within a watershed prevents evapotranspiration, infiltration, and soil water storage, changing the dynamics of surface runoff, subsurface flow, and groundwater recharge. Deforestation affects upstream reservoirs and influences overall water balance through impacting runoff generation. Deforestation increases soil bulk density and penetration resistance and decreases infiltration rate and available water capacity (Lal 1997; Benito et al. 2003). The effects of reducing the forested area within a watershed are directly linked to changes in stream flow, including increased runoff volumes, peak discharges, runoff velocities and flooding, and decreased base flow. Zhand and Schilling (2006) demonstrated that the flow increase of the Mississippi River results mainly from its base flow being increased by land use change and accompanying agricultural activities in the Mississippi River basin during the last 60 years. Land use change in the basin has affected the hydrology of the basin, and more precipitation is being routed into streams as base flow than storm flow.

Conclusion

This study examined variation in hydrological components with land cover change using Monte Carlo simulation and paid particular attention to the distinction of the hydrological components. Sensor imaging offers an effective means of classifying land cover following the Chi-Chi earthquake and typhoons. A severe earthquake and seven typhoons affected land cover within the watershed. The natural disturbance increased landslide area and decreased forest area. Landslides in the Chenyulan watershed indirectly resulted from the Chi-Chi earthquake. The effects of the Chi-Chi earthquake and the seven typhoons on the watershed land cover in the study areas were cumulative, but not always obvious over the entire landscape. The variation of land cover within the watershed was sufficient to demonstrate that natural disturbances influenced the landslide affected area.

This study quantifies the influence of land use change on hydrologic cycles. The impact of hydrology declines due to recovery of landslide areas created following the Chi-Chi earthquake, and area of deforestation and landslide are good indices of disturbance. Two assessment methods are used to evaluate the total quantities and their distributions of hydrological components that influenced land cover change. Similarities among hydrological components may display different variations as a result of land cover change. In this study, base flow and its distribution are the most sensitive components to land cover change. The results of this study demonstrate that the variations in hydrological components are primarily caused by conversion of forest. The change in forest area displayed a simple linear relationship with difference in base flow and direct runoff. The effects of decreasing the forest area of the watershed increased direct runoff volume and flooding and decreased base flow. Therefore, this study concludes that land cover changes that are minor in relative spatial extent can significantly impact watershed hydrology.

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