Research paper

Simulated Flood Frequency Response to Forest Cover Removal for an Upstream Watershed in Central Taiwan

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【Summary】

The effect of forest harvesting on flooding is a controversial subject. Determining such effects is constrained by the ability to directly measure how forest harvesting affects stormflow responses to extreme events. Stormflow caused by extreme rainfall or snowmelt events must be subjected to a frequency analysis to adequately describe them. In this study, the modified Peatland Hydrologic Impact Model (PHIM) was used to simulate forested and clearcut conditions in an upland first-order watershed in central Taiwan. The results of simulations using 47 yr of precipitation records indicated that the overall daily average and maximum discharges were affected by clearing of upland forests in such watersheds; however, only the daily average discharge was significantly increased. In addition, the annual water yield increased by 11.2%, a difference that was statistically significant. Frequency analysis using the log-Pearson type III distribution showed that quantiles of discharge for events of a small recurrence interval of approximately 5 and 2 yr after removal of the forest cover appeared to significantly differ from that of the original forested conditions for the daily average and maximum discharges, respectively. Since the frequency analysis showed only small differences in quantiles for before and after forest removal for events with a large recurrence interval, the effects of forest cover on large floods in central Taiwan are considered negligible.

Key words: forest harvest effects, PHIM, frequency analysis, log-Pearson type III distribution.

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研究報告

模擬台灣中部上游森林集水區林木移除後對不同回歸週期暴雨流量的影響

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摘　要

森林砍伐後對集水區洪水水量的影響是相當具有爭論的課題，主要原因為缺乏森林對極端降雨事件所造成洪水改變的有效數據。極端降雨所造成洪水通常需借助於頻率分析，間接地推估不同回歸週期的洪水量。本研究將PHIM模式的UPLAND子模式修改後模擬蓮華池三號集水區森林移除後集水區流量的變化情形。由47年的降雨記錄所推估的結果顯示，台灣上游天然闊葉林小集水區的平均及最大日流量在林木砍伐後會有顯著的改變，且推估砍伐後的年平均流量增加約11.2%，並達到顯著水準，說明森林對集水區水量仍有所影響。頻率分析結果顯示，林木移除後，平均及最大日流量分別對小於5及2年回歸週期的洪水水量有顯著的差異，顯示對回歸期較大的洪水並未因森林砍伐而有顯著的水量改變，因而可推論森林對大洪水水量的影響相當有限。

關鍵詞：森林砍伐效應、PHIM、頻率分析、對數皮爾森第三型分佈。

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INTRODUCTION

Undisturbed, natural forests have long been considered to be the optimal land use condition with vegetation cover to attenuate the effects of rainfall and snowmelt on streamflow peaks and flooding (Lu 1996, Cheng et al. 2001). While few argue with this statement, the extent to which flood peaks are attenuated, and importantly, the relationship between the attenuation effect and the magnitude of the storm event remain unclear. Furthermore, in many parts of the world there is considerable concern and debate about the effects of deforestation on flooding.

Current knowledge of watershed management indicates that eliminating vegetation usually reduces evapotranspiration (ET) and increases streamflow. However, the extent to which vegetation removal affects water yields is also highly associated with the amount of precipitation, the dominant vegetation, and the percentage of a watershed logged (Bosch and Hewlett 1982, Wheathead and Robinson 1993, Lu 1996, Cheng et al. 2001). Most studies indicated that logging increases flood peaks (Hewlett and Helvey 1970, Harr et al. 1975, Harr 1976, Swanson and Hillman 1977, Verry et al. 1983, Troendle and King 1987, Jones and Grant 1996, Thomas and Megahan 1998). On the other hand, many studies also showed no significant increase in the size of peak flows if clearcutting occurred without soil disturbance (Harris 1973, Rothacher 1973, Harr et al. 1975, Hornbeck et al. 1993). In contrast, a study by Cheng et al. (1975) in southwestern British Columbia recorded significantly reduced peak flows after clearcut logging due to disruption of subsurface channel networks by logging activities. Harr and McCorison (1979) concluded that various of harvesting methods might affect peak flows differently, and that peak flows may be larger, smaller, or unchanged after logging depending on what part of the hydrologic system is altered and by how much. In addition, when more water remains in the soil as storage in the clearcut area, less precipitation is needed to fill the storage capacity and cause runoff. Hess (1984) pointed out that changes in peak flows depend upon the soil moisture conditions when a storm occurs. If a storm occurs when soils are near saturation, a high percentage of precipitation is immediately available for runoff, and the peak flow will increase. Therefore, when soils are near saturation, peak flows are not significantly affected by the presence or absence of vegetation.

As stated above, peakflow discharge or stormflow volumes were found to increase or decrease following timber harvesting in many papers, but with nearly no reference to the recurrence intervals associated with such changes especially in tropical or subtropical regions where vegetation grows very fast. There are good reasons for the absence of such information. Much of our empirical data comes from paired watershed experiments in which watersheds are calibrated over time first mostly for discharge, then forest treatments (clearcuting, etc.) are applied, and the effects are observed over time. Although such analyses seem to work well enough in determining the effects of forest cover on the annual water yield, they are inadequate to determine the effects on the frequency characteristics of streamflow events. Several paired watershed experiments were monitored for several years, and continue to be, in an effort to determine the long-term effects of forest cover changes on streamflow characteristics. However, the data record is not significantly long for either the calibration or treatment period to determine the actual effects of forest cover on events over a range of recurrence intervals.

One method of estimating forest cover effects on a long-term basis is by using computer simulation models. Models are simplified representations of actual hydrological systems that allow us to study the function and response of a watershed to various inputs, and with a good choice of suitable models may allow us to predict hydrological events. The modified Peatland Hydrologic Impact Model vers. 4.0 (PHIM 4.0) (Lu et al. 1994, Lu 1997) which is appropriate for simulating the hydrologic response of many 1st-order watersheds was applied to predict and compare the effects of representative scaled timber harvesting operations on the peak discharge. Long-term datasets of paired watersheds in the Lienhuachih Experiment Forest, in central Taiwan, were used here to attempt to better understand the relationship between timber harvesting, forest cover, and discharges from a small upland watershed. A standard frequency analysis using the log Pearson type III (LP3) distribution was adopted to qualitatively compare the annual discharge of the targeted watershed for periods before and after timber harvesting. Because of the short-term datasets and the changing vegetative cover conditions of the harvested watershed over time, the traditional approach which analyzes observed streamflow datasets has serious limitations. By simulating long-term streamflow records for watersheds that are clearcut and comparing those records with those from an un-harvested watershed, datasets can be generated to develop frequency curves for a watershed in which all conditions are the same except for the forest cover. This was the approach taken here, and it is the subject of this paper.

MATERIALS AND METHODS

Model description

The PHIM is a deterministic, lumped-parameter, continuous-simulation computer model for predicting water yield and streamflow from undisturbed and harvested upland and peatland watersheds. It was developed and modified by the University of Minnesota, College of Natural Resources, USDA Forest Service North Central Forest Experiment Station, and the Minnesota Department of Natural Resources Division of Minerals. Version 4.0 was used as the simulating model; it includes 5 submodels: UPLAND, PEAT, MINE, CROUTE, and RROUTE. The 1st 3 submodels are appropriate for simulating the hydrologic response of several 1st-order watersheds in the northern Lake States which often consist of forested uplands, peatlands, and in some instances mined peatlands. CROUTE is a submodel for channel routing. RROUTE is a submodel for reservoir routing. These submodels are independent of each other and are called by the driver of the model. In this study, only the UPLAND submodel after modification was used.

The UPLAND submodel simulates the water budget for general soil upland areas. Basically, it adopts a water budget approach and simulates hydrologic processes which occur in a forested watershed. All processes are then linked mathematically so that the conservation of mass principle is not violated. The upland area is divided into several homogeneous slope segments of 1 m in width at the downslope end in the original model. However, because the shape of most upstream watersheds in Taiwan is extremely narrow, the original algorithm does not accurately reflect the true conditions in Taiwan. In this study, the segments were modified to be 1 m in width and 2 m in longitudinal direction. Therefore the watershed was divided as an $m \times n$ matrix, where m is the maximum width of the watershed measured in meters and n equals half the maximum longitudinal length also in meters. The soil profile within each slope segment is divided into 3 layers: shallow subsurface flow layer (SSFL), the lower root zone (LRZ) and the lower boundary control volume (LBCV). Hydrological components used in the UPLAND submodel includie: precipitation (PPT), potential ET, actual ET (AET), upper canopy interception amount (UI), lower shrub interception amount (UI), net rainfall (NRAIN), snow water equivalence (SWE), snowmelt (SMELT), surface runoff (QS), lateral flow (Q), and soil moisture content (θ), as shown in Fig. 1. Water budgets were applied to all components involved from the top canopy to the LBCV and from the highest to the lowest segment sequentially. The accumulated discharge from all segments was treated as the simulated discharge from the target watershed. The description of the various estimation procedures for UPLAND can be found in Lu et al. (1994) and Lu (1997).

Site description

The Lienhuachih Experimental Watershed no. 3 was selected for this study. It is a 4.10-ha natural hardwood forest watershed located in Yuchih Township of Nantou County (120°54'3"N, 23°55'30"W) of central Taiwan (Fig. 2). Elevations of this watershed are 666~781 m, and the average slope, length of the main stream, compactness, form factor, and aspect are 57.5%, 142 m, 0.58, 2.03 and SE, respectively. The geology is composed of alternations of sandstone and shale sequences, and the soil type can be classified as yellow shale-derived sandy clay loam with an average depth of about 80 cm. However, in some places, the soil may be as deep as 1.5 m (Kao

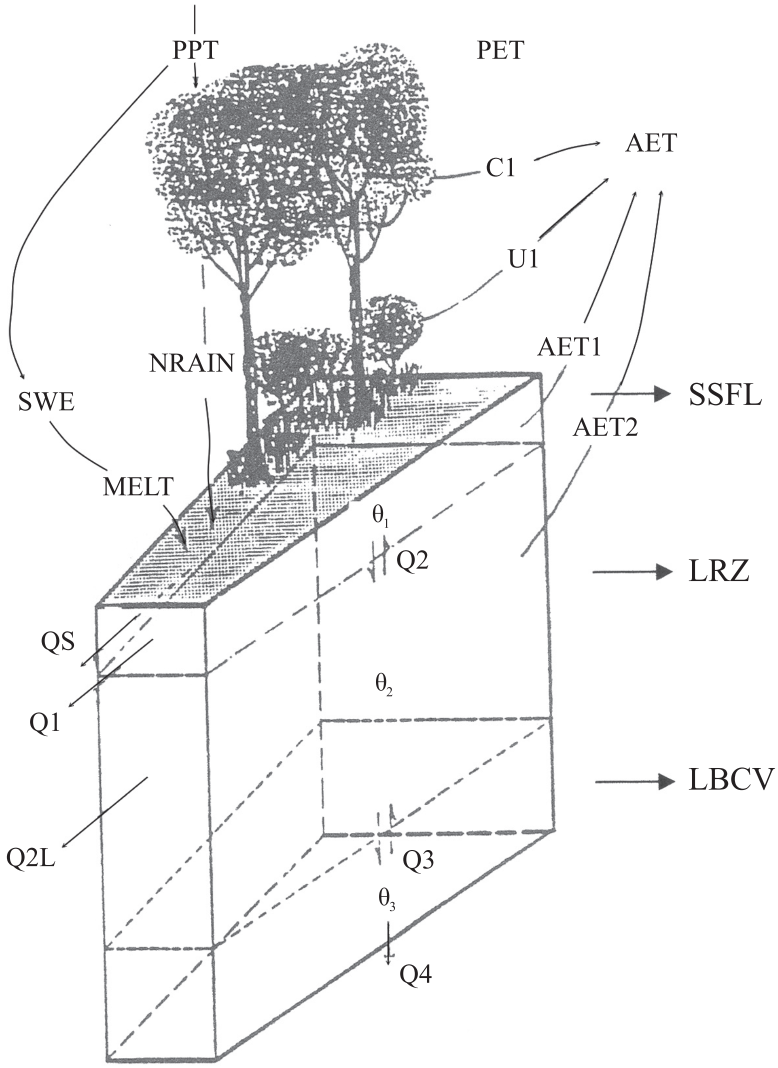

Fig. 1. Water budget components represented by the UPLAND submodel. SSFL, shallow subsurface flow layer; LRZ, lower root zone; LBCV, lower boundary control volume; AET, actual evapotranspiration (cm time^{-1}); AET1, soil water depletion by ET from SSFL (cm time^{-1}); AET2, soil water depletion by ET from LRZ (cm time^{-1}); CI, interception lossses from overstory vegetation (cm time^{-1}); UI, interception losses from understory vegetation (cm time^{-1}); MELT, snowmelt (cm time^{-1}); PPT, gross precipitation for each time interval (cm time^{-1}); NRAIN, net precipitation (cm time^{-1}) = PPT - (CI + UI); PET, potential evapotranspiration (cm time^{-1}); QS, subsurface runoff, flow above the mineral soil when the SSFL is complteed saturated (m^3 time^{-1}); Q1, Laterial flow from the SSFL (m^3 time^{-1}); Q2, Vertical flow from the SSFL to the LRZ (m^3 time^{-1}); Q2L, laterial flow from the LRZ (m^3 time^{-1}); Q3, vertical flow at the base of LRZ (m^3 time^{-1}); Q4, vertical flow at the base of LBCV (m^3 time^{-1}); SWE, snow water equivalent (cm); θ_1, average volumetric water content of SSFL (cm cm^{-1}); θ_2, average volumetric water content of LRZ (cm cm^{-1}); θ_3, average volumetric water content of LBCV (cm cm^{-1}).

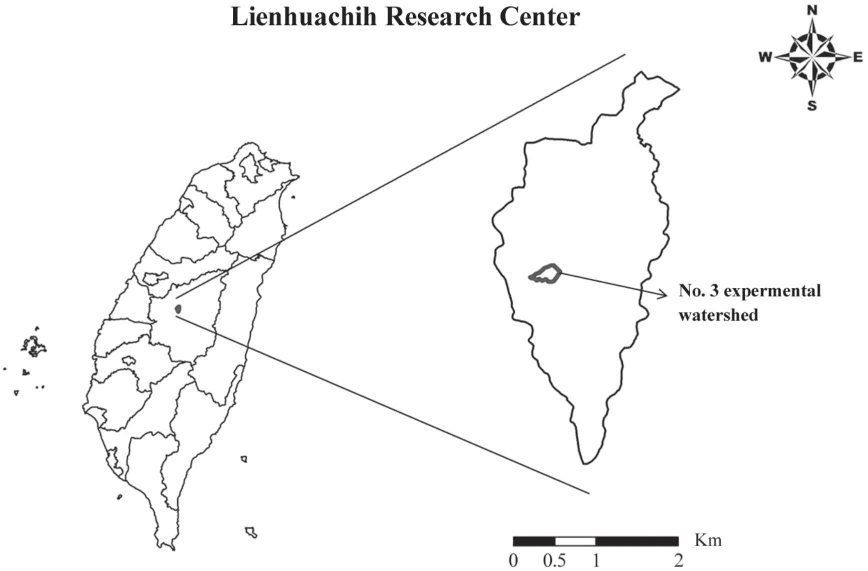

Fig. 2. Location of the study area.

et al. 1978, Lu et al. 2009).

The average yearly temperature, total rainfall, total evaporation, and average relative humidity are 20.8℃, 2285.0 mm, 839.1 mm, and 87.1%, respectively for the Lienhuachih area in general (Lu et al. 2008). Detailed climatic conditions and discharge of watershed no. 3 during the study period are given in Table 1.

The canopy cover of this watershed is nearly complete and can roughly be classified into upper, middle, and lower layers, however, with no evident separation between layers. The upper layer is composed of large trees from 48 species in 39 genera and 22 families dominated by Kawakami chinkapin (*Castanopsis kawakamii* Hay) and Chinese cryptocarya (*Cryptocarya chinensis* Hemsl) with average heights of > 5 m, while trees at > 15 m in height are very common. The middle layer is dominated by boxleaf Eugenia (*Syzygium buxifolium* Hook) and randaishan cinnamon tree (*Cinnamomum subavenium* Miq) with an average height of 3~5 m. The lower layer is composed of shrubs of shade-tolerant species or seedlings of trees of the higher layers. The trees in the watershed mostly belong to the Lauraceae and Fagaceae. It is generally accepted by ecologists that the forest in this area is a climax vegetation community (Lu 1997).

Establishing meteorological and hydrological input files

The daily records of precipitation (mm), and maximum and minimum air temperatures (℃) are the required meteorological inputs. Those required data were obtained from the nearby Lienhuachih Weather Station. Historical records from 1961 to 2007 of rainfall and air temperatures were adopted as the basic input for generating long-term streamflow records. Other required hydrological and topographic parameters for input into the UPLAND submodel could be obtained from field studies, GIS and topographic maps, and previous studies (Koh et al. 1978, Rawls et al. 1982, Lu and Tang 1995, Lu 1997). The input values of parameters were calibrated by the observed discharge from 1981 to 1985 and evaluated by the *t*-test.

Table 1. Climatic conditions for the Lienhuachih area (January 1961 to December 2007)

	Total rainfall (mm)	Average[1)] daily temp. (℃)	Average daily max. temp. (℃)	Average daily min. temp. (℃)	Average[1)] relative humidity (%)	Total[2)] ET (mm)	Average Discharge (mm)	Average radiation (MJ/m^2)
Jan	47.7	14.8	21.0	10.2	85.8	55.7	0.057	277.18
Feb	86.1	16.1	22.0	11.5	87.1	56.7	0.296	289.89
Mar	103.6	18.3	24.1	13.8	87.0	75.5	0.646	346.89
Apr	138.2	21.1	26.5	16.9	87.2	83.5	0.550	387.03
May	322.4	23.2	28.1	19.2	88.4	84.5	2.398	419.67
June	510.3	24.4	29.0	20.4	88.4	86.5	6.775	400.98
July	373.1	25.2	30.2	20.9	86.3	108.2	4.609	485.44
Aug	402.2	24.8	29.7	20.7	88.0	97.2	6.633	430.82
Sept	196.0	24.1	29.0	19.8	88.0	89.9	2.066	394.26
Oct	45.8	22.4	27.6	17.9	86.8	83.4	0.436	373.58
Nov	24.4	19.5	25.2	15.0	86.5	65.6	0.346	307.34
Dec	33.3	16.1	22.2	11.3	85.4	52.4	0.072	300.47
Avg.		20.8	26.2	16.5	87.1		2.054	367.80
Total	2285.0					939.1		

[1)] Average of daily 09:00, 14:00, and 21:00 records before 1993.
[2)] Measured by an evaporative pan with a diameter of 120 cm.

Simulation of clearcutting conditions

Nine input parameters in the UPLAND submodel were adjusted to represent clearcut conditions: 1. overstory canopy cover percentage (OSC), 2. tall shrub canopy cover percentage (TSC), 3. lower shrub canopy cover percentage (LSC), 4. herbaceous cover percentage (HERBC), 5. maximum depth of rooting (YROOT), 6. the rooting distribution coefficient (BETA), 7. volumetric water content when the supply of water for ET is limiting (VWCL), 8. the volumetric water content when AET goes to 0 (VWCZ), and 9. the average infiltration capacity when soils are compacted (INFAV).

Changes to the canopy cover percentage represent the removal of vegetation. It was assumed that only 10% herbaceous cover was left after clearcutting. Changes in the effective rooting depth and soil water depletion patterns can be represented by the maximum depth of rooting or depletion. Soil water depletion extending to approximately 1.5 m was assumed for watershed no.3 before cutting, while evaporation seldom depletes soil water below a depth of 0.6 m (Barten 1988). Therefore, values of 150 and 60 cm were used as the maximum depth of soil water depletion before and after cutting. The rooting distribution coefficient, which is used to apportion AET between SSFL and LRZ and also to reflect the relative evaporation rate in PHIM 4.0, was estimated to have a value of 0.993 for the clearcut condition because the relative evaporation rate between forest soil and bare soil is about 2~2.5 (Gale and Grigal 1987). The actual ET to potential ET ratio (ETR) varies with both the volumetric water content and forest tree species. According to Leaf and Brink (1975), the volumetric water contents when the supply of water for AET is limiting for a forest stand and open area are $\theta_{FC}/2$ and θ_{FC} (θ_{FC}, field capacity), respectively. Volumetric water contents when AET goes to 0 for forest and open area are θ_{WP} (WP, wilt point) and $\theta_{FC}/1.33$, respectively.

In this study, it was assumed that soil compaction was not sufficient to decrease the infiltration capacity of the soil below rates of rainfall normally encountered. Therefore, the infiltration capacity remained unchanged.

Flood frequency analysis

1. Creating annual discharge series

Daily discharge levels before and after vegetation removal were simulated with the PHIM. The initial conditions (soil water content, water table elevation, and discharge) were determined from values of corresponding parameters on the last day of the previous year's simulation. Mean daily flows and maximum daily discharges were calculated or selected for each year to create an annual discharge series as the basic data for the frequency analysis.

2. Selection of the statistical distribution

Flood events, as far as we know, do not fit any 1 specific known statistical distribution. It is not known which of the many available distributions is the "true" distribution. However, to make the problem of defining flood probabilities tractable, it is necessary to assign a distribution. In this study, the LP3 was used to describe the annual flood series. The LP3 is recommended by the Water Resources Council (USWRC 1981) as the basic method of flood frequency analysis in the US. The probability distribution function for LP3 is in the form:

$$f(x) = \frac{\lambda^{\beta}(y - \varepsilon)^{\beta - 1} e^{-\lambda(y - \varepsilon)}}{x\Gamma(\beta)}; \qquad (1)$$

where $y = \log x$, $\lambda = (\beta)^{1/2}/S_y$, $\beta = [2/C_s(y)]^2$, $\varepsilon = \acute{Y} - S_y(\beta)^{1/2}$, S_y is the sample standard deviation, C_s is the coefficient of skewness, $\acute{Y}$ is the mean of y, and Γ is the gamma function.

The 1st step of analysis is to take the base-10 logarithms of the annual flood series. Then, the mean, standard deviation, and coefficient of skewness are calculated for the logarithmic data. The magnitude of the hydrologic event with return period, T, is represented as the mean (μ) plus the departure, $\triangle x_T$, of the variate from the mean. In addition, the departure can be taken as the product of the standard deviation and frequency factor (K_T), and they are functions of the return period and type of probability distribution which are used in the analysis. For the LP3 distribution, the magnitude of the hydrologic event can be approximated by:

$$y_T = \acute{Y} + K_T \times S_y \qquad (2)$$

The frequency factor depends on the return period and the coefficient of skewness.

Values of frequency factors for different return years can be found in related tables (Kite 1977, Chew et al. 1988).

RESULTS AND DISCUSSION

The goodness of the simulation

The performance of the PHIM UPLAND submodel in simulating streamflow was judged by comparing simulated and observed annual water yields using the *t*-test. Table 2 gives the simulated results for the calibration years, and Fig. 3 shows the comparison between the simulated and observed discharges for the year 1985. The *t*-values show that the simulation was acceptable with 99% confidence. The accuracy of the prediction can also be referenced to Lu (1997). Results of the simulation also indicated that the following analyses were reliable. The capability of predicting hydrologic effects due to changes in vegetative cover or land use practices by the PHIM UPLAND submodel in the Lienhuachih area are thus proven.

The accuracy of the simulated discharges

Table 2. Observed and simulated annual water yields for the Lienhuachih no. 3 watershed

Year	Annual rainfall (mm)	Annual water yield (mm)		Sim./Obs.[1)]	*t*-value[2)]
		Simulated	Observed		
1981	2808	1338.67	1179.45	1.135	-1.056
1982	2236	761.75	693.76	1.098	-1.084
1983	2470	909.48	858.81	1.059	-1.096
1984	2215	850.25	757.80	1.122	-1.164
1985	2657	978.26	873.45	1.120	-0.869

1) The ratio of simulated (Sim.) and observed (Obs.) annual water yields.

2) Comparison between simulated and observed daily discharge values. The 95 and 99% confidence levels were 1.960 and 2.576, respectively.

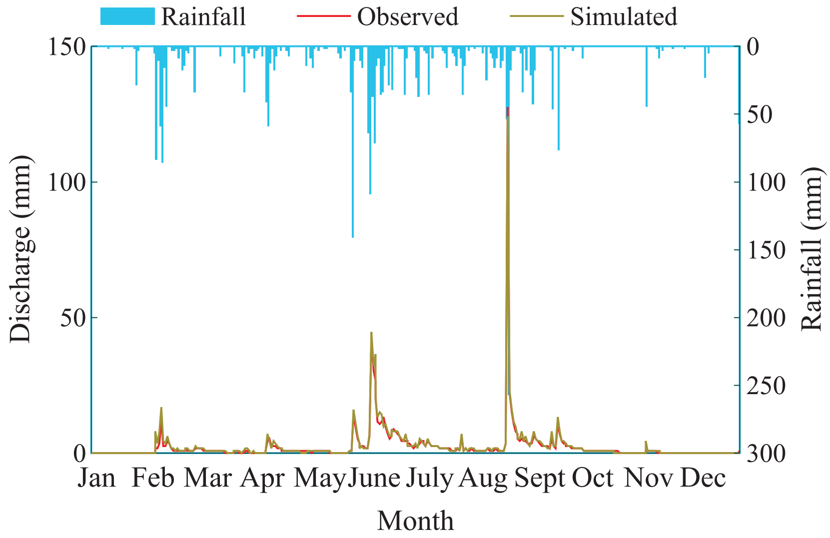

Fig. 3. Simulated and observed discharges for the year 1985.

is an important factor for judging the performance of the models. However, it is not the only judgment to determine how well a model fits special requirements. How reasonable and difficult it was to obtain values of input parameters, and the limitations of application are all interesting considerations. Values of input parameters and theirs description for the UPLAND submodel are tabulated in Table 3. It can be seen that all values were reasonable and could be obtained from field data or previous studies.

Once the values of the input parameters are calibrated, the discharges after clearcutting can be simulated by modifying values of some parameters as described in the previous sections. Table 4 lists the values of those upland parameters before and after adjustment for the clearcut conditions of Lienhuachih watershed no. 3.

Effects of forest harvesting on the daily discharge

The results of 47 yr of simulated runoff before and after vegetation removal are shown in Table 5. The simulated annual water yield significantly increased by 113.5 mm (t = 2.46) after vegetation removal. Increases

Table 3. Format of the UPLAND submodel and site description data for the hydrologic unit of the Lienhuachih no. 3 watershed

Characterization data			Description
WS-L3 UPLAND DATASET			Description of data file
95.0	3.30		Overstory cover % and max. interception capacity (mm)
80.0	1.20		Tall shrub cover % and max. interception capacity (mm)
40.0	1.00		Low shrub cover % and max. interception capacity (mm)
90.0	1.00		Herbaceous cover % and max. interception capacity (mm)
1	1		Month and day of the beginning of growing season
1	1		Month and day at the maturation of foliage
12	31		Month and day of the end of the growing season
0.0			Rain-freeze threshold temperature (℃)
0.0			Snow water equivalent (cm)
0.150	0.0		Melt rate coefficient and base temperature (℃), respectively
30.0	200.0		Depth to the base of SSFL and LRZ (cm), respectively
150.0			The maximum of depth of rooting (cm)
0.9750			Beta value for Gale's vertical root distribution
0.4810	0.2050	0.0510	θ_s, θ_{fc}, and θ_{wp} for SSFL, respectively
0.4080	0.3300	0.1200	θ_s, θ_{fc}, and θ_{wp} for LRZ, respectively
0.1030	0.0510		Soil water contents when water supply limits ET and ET
0.1650	0.1200		goes to 0 for SSFL and LRZ, respectively
0.060	0.197		Initial water contents for SSFL and LRZ, respectively
3.350	8.340		Cambell's b values for SSFL and LRZ, respectively
17.280	0.2300	0.230	K_{sat} for SSFL, impede horizon, and LRZ (cm h^{-1})
0.390			Drainable porosity
0.80			Infi1tration capacity (cm h^{-1})
4.10			Area of hydrologic unit (ha)
780.6			Discharge perimeter (m)
57.5			Average land slope (%)

Note: Column positions are free and variables within a row are separated by l or more spaces.
SSFL, shallow subsurface flow layer; LRZ, lower root zoon; LBCL: lower boundary control layer; ET, evapotranspiration.

mostly were coming from the savings of interception and ET losses on days with low rainfall amounts. The average annual daily discharge after forest removal increased by as much as 0.843 mm (30.76%) compared to the discharge before forest removal. Annual maximum daily discharges after forest removal increased by as much as 0.25 mm (0.80%). Although nearly all annual maximum daily discharges increased after vegetation removal, there was no statistically significant difference between the magnitudes of pre- and post-harvesting daily maximum runoff (t = 0.562) at the 95% confidence level. The simulated results confirmed the fact that there would be no available storage spaces in the soil layers for subsequent rainfall when soil moisture had reached saturation, and nearly all rainfall would become runoff. In this case, the percentage of canopy storage and rain water evaporation would be minor, and the ability of the forest to attenuate flooding would

Table 4. Values of parameters before and after parameter changes to reflect the effects of forest cover removal on streamflow for the Lienhuachih no. 3 watershed

Name of parameter[1)]	Forest cover removal		Units	Reference
	Before	After		
OSC	95.0	0.0	%	
TSC	80.0	0.0	%	
LSC	40.0	0.0	%	
HERBC	90.0	10.0	%	
YROOT	150.0	50.0	cm	Barten 1988, Lee 1980
BETA	0.975	0.993	---	Gale and Grigal 1987
SMRATE	0.0	0.0	cm (℃-d)$^{-1}$	Barten 1988
VWCL1	0.103	0.205	cm^3 cm^{-3}	Leaf and Brink 1975
VWCZ1	0.051	0.154	cm^3 cm^{-3}	Leaf and Brink 1975
VWCL2	0.165	0.33	cm^3 cm^{-3}	Leaf and Brink 1975
VWCZ2	0.12	0.248	cm^3 cm^{-3}	Leaf and Brink 1975
INFAV	0.8	0.8	cm h^{-1}	

[1)] OSC, overstory (> 3 m) cover percentage; TSC, tall shrub (1~3 m) cover percentage; LSC, low shrub (< 1 m) cover percentage; HERBC, herbaceous cover percentage; YROOT, the maximum depth of rooting or soil water-depletion depth; BETA, mean roots distribution coefficient; SMRATE, melt rate coefficient for the temperature index snowmelt equation; VWCL1, volumetric water content when water supply limits evapotranspiration (ET) in zone 1; VWCZ1, volumetric water content when actual ET (AET) goes to 0 in zone 1; VWCL2, volumetric water content when the water supply limits ET in zone 2; VWCZ2, volumetric water content when (AET) goes to 0 in zone 2; INFAV, infiltration capacity.

Table 5. Summary simulated results (47 yr) for the Lienhuachih no. 3 watershed before and after removal of forest cover

Item	Before			After			Increase
	Avg.	SD	Skew	Avg.	SD	Skew	
Annual precipitation (mm)	2285.0	515.08	0.022	---	---	---	---
Annual water yield (mm)	946.10	59.50	59.63	1052.06	56.21	0.985	113.53
Avg. daily discharge (mm)	2.739	75.23	1.278	3.582	66.59	1.035	0.843
Avg. max. daily discharge (mm)	15.16	7.333	0.943	15.41	7.189	0.895	0.25

be limited.

In this study, we assumed that the forest was removed from the target watershed without causing any soil disturbance. Therefore, the major factor that influences the routing of moisture in soil layers and subsurface flow, i.e., the infiltration capacity, remained unchanged. If we changed the infiltration capacity to 1/2 of the original value, then the simulated annual water yield after vegetation removal would increase by as much as 137.5 mm. This discrepancy is mainly from an increase in surface runoff which is equal to net rain minus the infiltration capacity. Although surface runoff from vegetated watersheds rarely occurs, forest management practices such as road construction and timber harvesting can cause severe disturbances due to soil compaction, changing routes of subsurface flow, and concentrating surface runoff, thus tremendously increasing the possibility of surface runoff. Therefore, forest management without suitable conservation practices is thought to be the main reason for problems in downstream areas of a watershed.

Flood frequency response to forest harvesting

The estimated quantiles for rainfall runoff are shown in Tables 6 and 7. From the analytical frequency analyses, frequency parameters after forest harvesting differ from those before forest harvesting. After forest harvesting, the mean, the standard deviation, and the calculated skewness coefficient for the daily average discharge after taking the log increased. The net effect of these changes on the frequency parameters was that the frequency curve after forest removal was less steeply sloped. In addition, the frequency factor (K_T) which is a function of the skewness coefficient and the selected exceedence probability for the LP3 distribution (USWRC 1981) did not seem to show major differences between estimates before and after forest removal. Frequency curves estimated from a series of negatively skewed coefficients will show a convex shape (Landwehr et al. 1979).

Table 6. The estimated annual average daily discharge under different return years for the Lienhuachih no. 3 watershed

Return year	Before	After	Increase (mm)	Percent increase (%)
	------ (mm) ------			
2.0	2.4911	2.7131	0.2220	8.91
5.0	3.1179	3.2907	0.1728	5.54
10.0	3.4435	3.6007	0.1572	4.57
20.0	3.6691	3.8180	0.1489	4.01
25.0	3.7846	3.9316	0.1470	3.88
50.0	3.9939	4.0978	0.1039	2.60
100.0	4.1764	4.2129	0.0635	1.52

Frequency components for the LP3 distribution: before forest removal, mean = 0.3816, SD = 0.1310, Cs = -0.6727; after forest removal, mean = 0.4246, SD = 0.1083, Cs = -0.4398.

Table 7. Estimated maximum daily rainfall runoff discharge under different return years for the Lienhuachih no. 3 watershed

Return year	Before	After	Increase (mm)	Percent increase (%)
	------ (mm) ------			
2.0	13.409	14.374	0.965	7.20
5.0	20.724	21.211	0.487	2.35
10.0	24.983	25.177	0.194	0.96
20.0	26.301	26.372	0.071	0.27
25.0	32.959	32.997	0.038	0.11
50.0	37.115	37.130	0.015	0.04
100.0	42.851	42.864	0.013	0.03

Frequency components for the LP3 distribution: before forest removal, mean = 1.1329, SD = 0.2039, Cs = -0.1652; after forest removal, mean = 1.1616, SD = 0.1980, Cs = 0.1462.

This implies that there is a bound on the upper tail, while the lower tail is unbounded. Therefore, application of the LP3 distribution to negatively skewed data is limited for extreme events because the estimated quantiles would be unrealistically low.

Frequency analysis by the LP3 distribution revealed that quantiles of discharge for the daily average and maximum discharges with recurrence intervals of 2 and 5 yr or higher, respectively, fell into the 95% confidence interval estimated from "before forest removal" datasets. By plotting these quantiles on probability paper we found that the frequency curves before and after harvesting converged at a point with a magnitude of approximately 2- and 5-yr recurrence intervals for the daily average and maximum discharges, respectively. This implies that effects of forest harvesting on quantiles of rainfall runoff were not significant at the 95% confidence level for events with a recurrence interval of $\geq$ 2 yr.

CONCLUSIONS

The results of simulations using long-term meteorological records indicated that both the daily average and maximum discharges increased after forest cover removal, and the increases of the former were significant. However, when the frequency analysis for streamflow was compared before and after forest removal, there was no significant difference at the 95% confidence level. The annual water yield significantly increased following forest cover removal. This evidence suggests that even though water yield can increase as a result of forest harvesting, if forests are logged without major accompanying soil disturbance, the increases in discharge will be limited.

Frequency analysis of the annual maximum daily discharge, and annual average runoff discharge showed that only events with small recurrence intervals had relatively larger increases as a result of forest removal than did events with 50- or 100-yr recurrence intervals. The implication is that the frequency of flooding will be increased by logging of forests, but only for small storms, and vegetation has little or no effect on streamflow resulting from exceptional precipitation.

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