DISSERTATION

THE RELATIONSHIPS OF FOREST AND WATERSHED CHARACTERISTICS TO SOIL WATER RETENTION, STORM RUNOFF, EROSION, AND WAVE ATTENUATION IN VIETNAM

Submitted by

Bao Quang Tran

Department of Forest, Rangeland, and Watershed Stewardship

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2009

COLORADO STATE UNIVERSITY

December 18, 2008

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY BAO QUANG TRAN ENTITLED "THE RELATIONSHIPS OF FOREST AND WATERSHED CHARACTERISTICS TO SOIL WATER RETENTION, STORM RUNOFF, EROSION, AND WAVE ATTENUATION IN VIETNAM" BE ACCEPTED AS FULLFILING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate work

DANIEL E. BINKLEY

EILEEN HELMER

PAUL F. DOHERTY, JR

Advisor MELINDA J. LAITURI

Department Head MICHAEL J. MANFREDO

Abstract of Dissertation

THE RELATIONSHIPS OF FOREST AND WATERSHED CHARACTERISTICS TO SOIL WATER RETENTION, STORM RUNOFF, EROSION, AND WAVE ATTENUATION IN VIETNAM

Forests can have a profound impact on the hydrological cycles. Numerous studies in Vietnam, and elsewhere have examined the effects of vegetation cover and geomorphology on hydrological processes at both watershed and regional scales, but the effects of forests in water yield, regulating seasonal water flows, and soil erosion are still in debate. This dissertation focuses on obtaining a deeper understanding about how forests, weather and geomorphology affect hydrological responses and soil erosion in Vietnam.

Dissertation is a collection of four independent studies. The first study characterizes soil water retention of four forest types representing different levels of forest degradation. The results suggest that soil water retention, a function of soil moisture, bulk density, and soil depth; varies among forests, and it depends primarily on litter cover, vegetation cover, and porosity. Forest soil moisture can be predicted by a regression model, with the root square mean error of 3%.

The second study investigates effects of watershed characteristics on runoff in 15 typical watersheds. The watershed factors, which include watershed size, shape, slope and elevation difference, forest cover and distribution, are analyzed in relation to increasing and decreasing peak flow, and daily streamflow variation, in which forest cover and distribution, shape, and elevation difference are found to be significant impacts on storm runoff. Relationships between peak discharge and initial flow and rainfall are statistically significant in this study.

The third study is to define minimum forest areas for protection soils from erosion. A soil loss prediction equation and soil loss tolerance of 10 ton $ha^{-1}yr^{-1}$ are used to generate an erosion risk map and vegetation index for Vietnam. Required forest areas are calculated by comparison erosion risk with vegetation index.

Finally, wave attenuation is analyzed in relation to initial wave height, cross-shore distances, and mangrove forest structures. From these relationships, minimum mangrove band width for coastal protection from waves is defined and ranges from 40 m to 240 m depending on mangrove structures.

Bao Quang Tran
Department of Forest, Rangeland, and Watershed Stewardship
Colorado State University
Fort Collins, CO 80523
Spring 2009

Acknowledgments

This dissertation would not have been possible without the technical and emotional support of many people. I would like to first thank my advisor Dr. Melinda Laituri for her unbelievable thoughtfulness, her invaluable guidance, and her encouragement during my study and research.

My sincerest gratitude and appreciation is extended to my committee members, Dr. Dan Binkley, Dr. Paul Doherty, and Dr. Eileen Helmer for their helpful guidance, comments, suggestions, and friendship throughout the program. I also would like to thank Dr. Phillip Chapman and Dr. Jerry Vaske for their statistical consultations for my research, Robert Sturtevant for his helpful and value editing of my writing. It has been a great honor to work with all of them and other faculty, staff, and students at Colorado State University as well.

I would like to thank Dr. Vuong Van Quynh, my mentor at Forestry University of Vietnam, who has contributed so much to this work and my development as a scientist since I was an undergraduate student. I am deeply indebted to him for providing me with his experience and knowledge to help to finish this dissertation.

I wish to express my appreciation to the Ministry of Education and Training of Vietnam (MOET) for their financial support for my study at Colorado State University. I gratefully acknowledge the funding for my research provided by the Ministry of Agriculture and Rural Development of Vietnam (MARD). My dissertation would not have been possible without these crucial funding sources.

I would also like to extend thanks for the field and lab assistance of my colleagues at the Institute of Forest Ecology and Environment. Many thanks go to Vietnam International Student Association for the friendship and activities during my stay at CSU.

Finally, It is impossible to describe how deeply indebted I am to my family for their love and encouragement, especially my parents for inspiring me to excel intellectually, my beloved wife Minh Nguyet, and my cheerful son and daughter. I never would have accomplished this research without their invaluable supports.

Table of Contents

List of Figures

List of Tables

Chapter 1:

GENERAL INTRODUCTION

Forest cover has been recognized as one of the most effective entities for regulating seasonal water flow and preventing soil erosion (Bonell, 1993; Hudson, 1995). The impacts of deforestation on water quantity and erosion have been a serious environmental concern for centuries (Andreassian, 2004; Bruijnzeel, 2004; Sidle et al., 2006). In Vietnam, the forested area decreased from 14.3 million hectares (43% forest cover) in 1943 to 9.18 million hectares (27.2% forest cover) in 1990. This decline is due to conversion of forestland to agricultural uses and the extraction of forest products for socio–economic development (VEPA, 2002). Consequently, there has been an increase in barren land, soil erosion, landslides and flooding throughout the country (Lung et al., 1995). A new afforestation program, called Five Million Hectares Afforestation Program (5MHAP), has been adopted since 1998 with the aim of increasing forest cover to 40% by 2010 (Clement et al., 2008).

The general assumption in Vietnam is that total water supply, or river flow, to areas downstream from forested areas is higher than from alternative land use areas. However, few rigorous long-term studies have examined the relations between water and forestation activities at the watershed and regional scales. There have not been enough hydrological studies to fully understand the linkages between forests and water (Phuong et al., 2006). Some watersheds can sustain some forest cover loss, while in other sites there is limited forest cover. In other situations, the existing vegetation cover was removed for reforestation causing the soil water retention to decline (Quynh, 2006). Therefore, more comprehensive research would be needed for a better understanding of these scientific debates.

1.1. Research Objectives

Each of three main chapters in this dissertation was designed independently from the others. The general objective of these chapters was to improve the understanding of the hydrological response to forests in the topographically and climatologically complex country of Vietnam. Specific objectives include:

a) to quantify soil water retention in four forest types; statistically analyze effects of forest structure, rainfall on soil moisture, and to develop regression models to predict forest soil moisture; and to estimate the capability of these forest types to prevent surface runoff.

b) to determine influences of watershed characteristics, forest cover, and forest distribution on storm runoff responses of 15 representative watersheds in Vietnam; and to determine peak discharge of these watersheds by the predictors of initial flow, rainfall, and rain intensity.

c) to identify the roles of forest cover on soil erosion prevention; and to produce a map of required forest areas for protection of soil from erosion in the mountainous areas of Vietnam.

d) to analyze the relationship of mangrove forest to wave attenuation; and to define minimum mangrove forest band width for coastal protection from waves in Vietnam.

1.2. Dissertation Structure

The dissertation is organized in six chapters, including this introduction and the conclusion in the last chapter. The four primary chapters (i.e., chapter 2, 3, 4, 5) corresponding to four objectives above will be separately submitted for publication.

Chapter 2 characterizes effects of forest degradation on soil water retention in Northern Vietnam. In Vietnam, natural forest degradation is mostly human caused. Forests are classified based on their biomass or structures. The study uses soil moisture data of 40 forest plots in 60 consecutive days in 2006 to assess variations in soil moisture retention in four main forest types reflecting different levels of degradation. They are moderate forest, poor forest, regeneration forest, and mixed shrub and grass. To quantify the relationship between environment factors (i.e., forest structure, rainfall, topography) and soil moisture, regression models will be developed and validated.

Chapter 3 assesses effects of watershed characteristics on storm runoff in 15 watersheds in Vietnam. The storm runoff indices (i.e., variation and changes of peak flow rate) are statistically analyzed in relation to watershed factors including slope, elevation difference, size, shape, forest cover and forest distribution. Hydrological data used for analyses are rainfall and hourly stream flow in 2005 recorded at watershed outlets. This chapter also presents the relationship between storm runoff response and initial flow, rainfall, rainfall intensity and season interaction by adapting a previous model (Hewlett et al., 1977).

Chapter 4 defines areas requiring forest cover for protection soil from erosion in uplands. In this chapter, a soil loss equation was used to set criteria for defining forest areas (Quynh et al., 1996). An erosion risk map of Vietnam was produced by applying spatial analysis and interpolation to original input data layers as long-term monthly rainfall, DEM, and soil porosity. The required forest area is defined based on a mathematical and spatial comparison of erosion risk map and soil loss tolerance for tropical region (10t ha^{-1} yr^{-1}) with vegetation index.

Chapter 5 analyzes wave attenuation in coastal mangroves in Vietnam. Minimum mangrove band width for coastal protection from waves is defined by analyzing the relationship mangrove structures and cross-shore distances to wave. The data used for this analysis includes 32 mangrove forest plots located in five locations in two coastal regions of Vietnam.

Chapter 6 is "Conclusions and Recommendations". The results of the work are summarized according to the objectives stated above. Included are recommendations for future research directions for more accurate predictions, more feasible applications and better understanding of hydrologic responses to forest cover in tropical regions, especially in Vietnam.

Appendices include reference tables on data, results, statistical analyses and scenario prediction of different chapters.

1.3. Potential Contributions of the Vietnam study

This is one of the first comprehensive studies conducted on forest - water relationships in Vietnam. This study intends to improve our understanding of the effects of forests and watershed characteristics on soil water retention and flow regimes, respectively. It will help us better understand the consequences of deforestation on water storage at the watershed scale.

This study provides comprehensive applications for designing and planning forest resource management in Vietnam by defining required forest structure (criteria) and size for both mountainous and coastal regions.

In the past, there was no appreciation of the spatial and temporal analyses of erosion risk mapping and watershed hydrology in Vietnam. This is an in-depth study using spatial analysis and geographical information systems (GIS). These techniques facilitate the calculation of watershed factors and produce several maps at both watershed and regional scales.

REFFERENCES

Andreassian, V., 2004. Waters and forests: from historical and controversy to scientific debate. Journal of Hydrology, 291, 1-27.

Bonell, M., 1993. Progress in the understanding of runoff generation in forests. Journal of Hydrology, 150, 217-275.

Bruijnzeel, L.A., 2004. Hydrological function of tropical forests: not seeing the soil for the trees? Journal of Agriculture, Ecosystems and Environment, 104, 185-228.

Clement, F., and Amezagab, J.M., 2008 (in Press). Afforestation and forestry land allocation in northern Vietnam: Analysing the gap between policy intentions and outcomes. Journal of Land Use Policy, 687: in Press.

Hewlett, J. D., J. C. Fortson, and G. B. Cunningham, 1977. The effect of rainfall intensity on storm flow and peak discharge from forest land, Water Resource Research, 13(2), 259-266.

Hudson, N.W., 1977. Soil Conservation. Cornell University Press, Ithaca, New York.

Lung, N.N., and Hai, V.D., 1996. Preliminary results of research on watershed protection effects of some vegetation types and the main principles of protection forest establishment. Agriculture Publishing House, Hanoi.

Niem, H., 1994. Effects of forests on water run-off. Meteorology and Hydrological Newsletter, 7.

Phuong, V.T., and Dam, J.V., 2006. Linkages between forests and water: a review of research evidence in Vietnam. ETFRN NEWS 45/46: Forests, Water and Livelihoods, European Tropical Forest Research Network.

Quynh V.V., Lan, P.N., 1996. Capability to protect soil of different vegetation covers in Ham Yen, Tuyen Quang. Report for Vietnam – Swedish Cooperation Program, SIDA.

Quynh, V.V., and Bao, T.Q., 2006. Final Report: Defining minimum forest areas for provinces in Vietnam. Ministry of Agriculture and Rural Development, Vietnam.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., and Turkelboom, F., 2006. Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecology and Management, 224, 199-225.

Vietnam Environment Protection Agency (VEPA), 2002. State of the Environment in Vietnam 2001. Hanoi, Vietnam.

Vietnam Legal Document, 2007. Vietnam Forestry Development Strategy 2006-2020. Promulgated and enclosed with the Decision No. 18/2007/QD-TTg.

Whitehead, P.G. and Robinson, M., 1993. Experimental basin studies - an international and historical perspective of forest impacts. Journal of Hydrology, 145, 217-230.

Chapter 2

THE EFFECTS OF FOREST DEGRADATION ON SOIL WATER RETENTION IN NOTHERN VIETNAM

Abstract

This study characterized the forest soil water retention of four forest types in Thuong Tien natural reserve located in northern Vietnam: moderate tree volume forest, low tree volume forest, young regeneration forest, and mixed shrub and grass. Forty representative forest plots were selected to measure forest structure, topography, and soil properties. Daily soil moisture of 40 plots and rainfall were collected in a period of 60 consecutive days. Multivariate regressions were used to inspect the relationship between forest structures, soil porosity and forest soil moisture. The environmental factors having an effect on forest soil moisture are litter cover, vegetation ground cover, and soil porosity. Forest soil moisture can be predicted by the two regression models. Coefficients of determination (R^2) for soil moisture prediction model for a rainy day were 0.55 – 0.81. Those of the prediction model for a day without precipitation were 0.52 – 0.83. Main predictors of these models are rainfall, antecedent soil moisture and time interval (days). The root mean square error (RMSE) of the predicted values of the models is 3.03%. Forest soil water retention, a function of soil moisture, soil depth and bulk density, varies among the four forest types. The capability to retain water of forest types ranks from moderate tree volume forest (401mm), young regeneration forest (350mm), low tree volume forest (346mm), and grass + shrub (249mm). Forest soil water retention has monthly variability, depending on annual precipitation regime. The highest capability of water stored in soil is in August, and the lowest month is February. Monthly threshold rainfall and rainfall for reaching maximum saturation are defined for forest types. Moderate and low tree volume forest can prevent surface runoff or flood better than the other forest types.

2.1. INTRODUCTION

Deforestation has important consequences for hydrological behavior. Changes in forest structure (e.g., canopy closure, ground cover) directly or indirectly can cause changes in interception of precipitation, evapotranspiration and physical properties of soil (Shukla et al., 2003). Soil water retention which is an important soil hydrological property is influenced by soil structure (Fu et al., 2000), soil moisture and vegetation (Yimer et al., 2008). Changes in soil water retention will have a direct influence on surface runoff and on the hydrological regime of rivers. Effects of forest disturbances on hydrological processes in forest have attracted considerable attention from researchers and the general public during the last century.

The general objective of this study is to identify effects of forest degradation on soil moisture and soil water retention capacity. To meet this objective, the study selected 4 dominant forest types in Thuong Tien natural reserve (i.e., secondary forests with moderate and low tree volume; young regeneration forest; and grass + shrub) located in northern Vietnam and estimated their soil water retention. Selected forest types are representative of the different levels of forest degradation in the same area (Fig. 2.2). The soil moisture of the forest was analyzed in relation to the environmental factors (forest structure, soil porosity, and topography). This study will also develop prediction models of soil water moisture and define monthly threshold rainfall for corresponding forestry types.

A review of 94 catchments experiments by Bosch and Hewlett (1982) reveal that changes in vegetation resulted in changes in water yield. Yield increases due to deforestation and decreases due to reforestation. Researches in North America have concluded that cutting forest was causing decreases in both peak and low flows (Robinson et al., 2003). A 10% reduction in cover of a conifer forest increased water yield by some 20-25mm, whereas that for eucalyptus forest increased yield by only 6mm (Sahin et al., 1996). Runoff yield annually increased 30% due to the destruction of forest after a wildfire in Real Collobrier basin, France (Lavabre et al., 1993).

Andreassian (2004) notes that deforestation increases low flows. Recovery of the forest causes flows to cease. Reforestation in the harvested areas may cause water yield to return to pre-harvesting levels within 8 years, and storm peak flows, quickflows, and low flows back to original levels within 10 years (Fahey, 1997). Reforestation and soil conversion are able to reduce the increase of peak flow and storm flow associated with soil degradation (Bruijnzeel, 2004).

Changes in forest structure also cause changes in water yield. A catchment of less than 1km^2 may increase water yield after replacing tall vegetation with shorter plants (Bruijnzeel, 2004). A decrease in total basal area resulted in an increase in total stream flows, direct runoff, and ground water recharge for six dormant and growing seasons during 1968-1971 (Bent, 2001).

In Vietnam, forest coverage decreased from 43% in 1943 to approximately 28.8% in 1999 (EPA, 2000). Vietnam's deforestation is a consequence of high population growth, rapid industrialization and urbanization, and inappropriate management policies during this period (MARD, 2000). Between 1990 and 2005, Vietnam lost a staggering 77.8 percent of its primary forests, leaving only 85,000 hectares of old growth forest (FAO, 2005). However, forest is recovering. Since 1999, the area covered by plantations has expanded from 1.47 million hectares to 2.55 million hectares (FPD, 2007). Deforestation has simplified vegetative communities in terms of diversity and structure, leading to soil degradation (Lal, 1996). Figure 2.1 is a simple diagram representing degradation of primary forest by human impacts in the northern forests of Vietnam (Phuong, 1970).

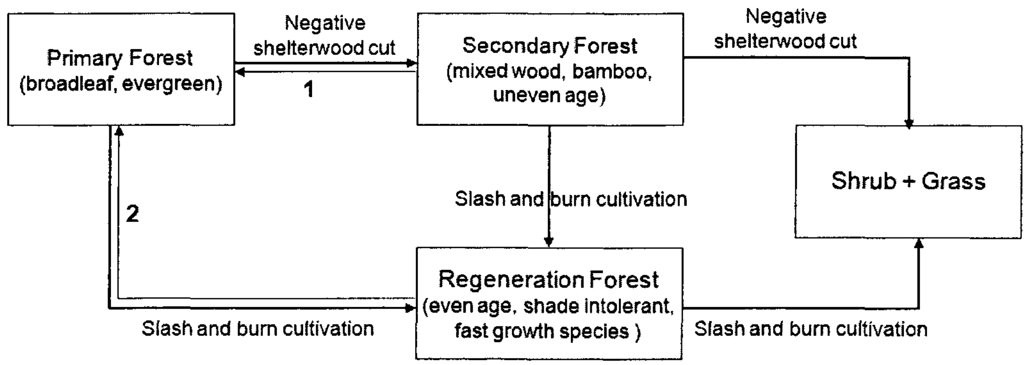


Figure 2.1. Natural forest degradation by human impacts in the northern forests of Vietnam. (1) a long life shade tolerant species (*Erythrophloeum fordii)* forest, if experiencing repeatedly negative selective cutting, will be, in turn, forest with complex mixed wood species (i.e., long and short life species, shade tolerant and intolerant species); mixed wood trees and bamboo forest; shrub and grass; (2) if primary forest experienced rotation of slash and burn cultivation, it will be, in turn, forest of even age, fast growth and shade intolerant of some dominant species; forest of shorter life wood species + bamboo; shrub and grass. Without human impacts, forest can rehabilitate to the first stage from mixed wood + bamboo stage (Phuong, 1970).

Vietnam's deforestation has been blamed for worsening soil erosion and floods (EPA, 2000). A few studies on forest hydrology indicate that the hydrological roles of forest are different from those of the other cover types. Phien and Toan (1998) demonstrated that runoff from forests was 2.5 - 27 times smaller than runoff from agricultural crops. Runoff measurements observed in natural forests were 3.5 to 7 times less than that in plantation forests (Nganh et al., 1984; Hai, 1996). The infiltration rate in a natural forest was measured at 16.8 mm per minute, while it was reported at 10.2 mm per minute in forests restored after shifting cultivation, and 2.1 mm per minute for shrub and grass land (Niem, 1994; Tuan, 2003). This study will contribute to a better understanding of hydrological processes in different types of forests for improved management of both water and forest resources.

2.2. METHODOLOGY

2.2.1. Study Sites

The study sites are located in a watershed of Thuong Tien river, Hoa Binh province, (roughly $105^0$20'-$105^0$40' E, $20^0$30'-$20^0$40' N), about 60km in the western of Ha Noi, Vietnam. The watershed lies between 200m and 1100m elevation; average slope and slope length are from 25^0 to 30^0, and from 1km to 1.5 km, respectively (Fig. 2.2). Soils are brown feralit with fined-textured and well-drain, derived from Bazich bedrock. Average soil depth is greater than 80cm.

The climate is monsoon tropical. The dynamic monsoon circulation patterns produce two main seasons, a dry, cool winter and a warm, wet summer. The rainy season begins in May and lasts until the end of September. Average annual rainfall is 2,263mm. Rainfall is highly seasonal, with approximately 80% of rain falling during the wet season. Average annual air temperature is 24^0C, mean monthly air temperature ranges from 5^0C in January to 39^0C in July. Average annual air humidity is 84%, with low variation. The highest monthly air humidity is 88% in September and the lowest one is 82% in May (HMDC, 2006).

Vegetation is mainly secondary evergreen broadleaf forests, interspersed with regeneration forests, shrub, grass, and slash and burn cultivation. These classifications are based on the forest structures that include cover types, composition, tree volume, and forest age (FIPI, 2005). For example, total tree volume is ranked from high to low, so called "rich forest", "moderate forest", and "poor forest", respectively; Young, even-age forest that is recovering from sifting cultivation or clear cutting is classified as "regeneration forest". The current cover type of the study sites are the result of human activities (i.e., selective or clear cutting) in the 20^{th} century. They are distributed throughout the entire research areas (FIPI, 2005).

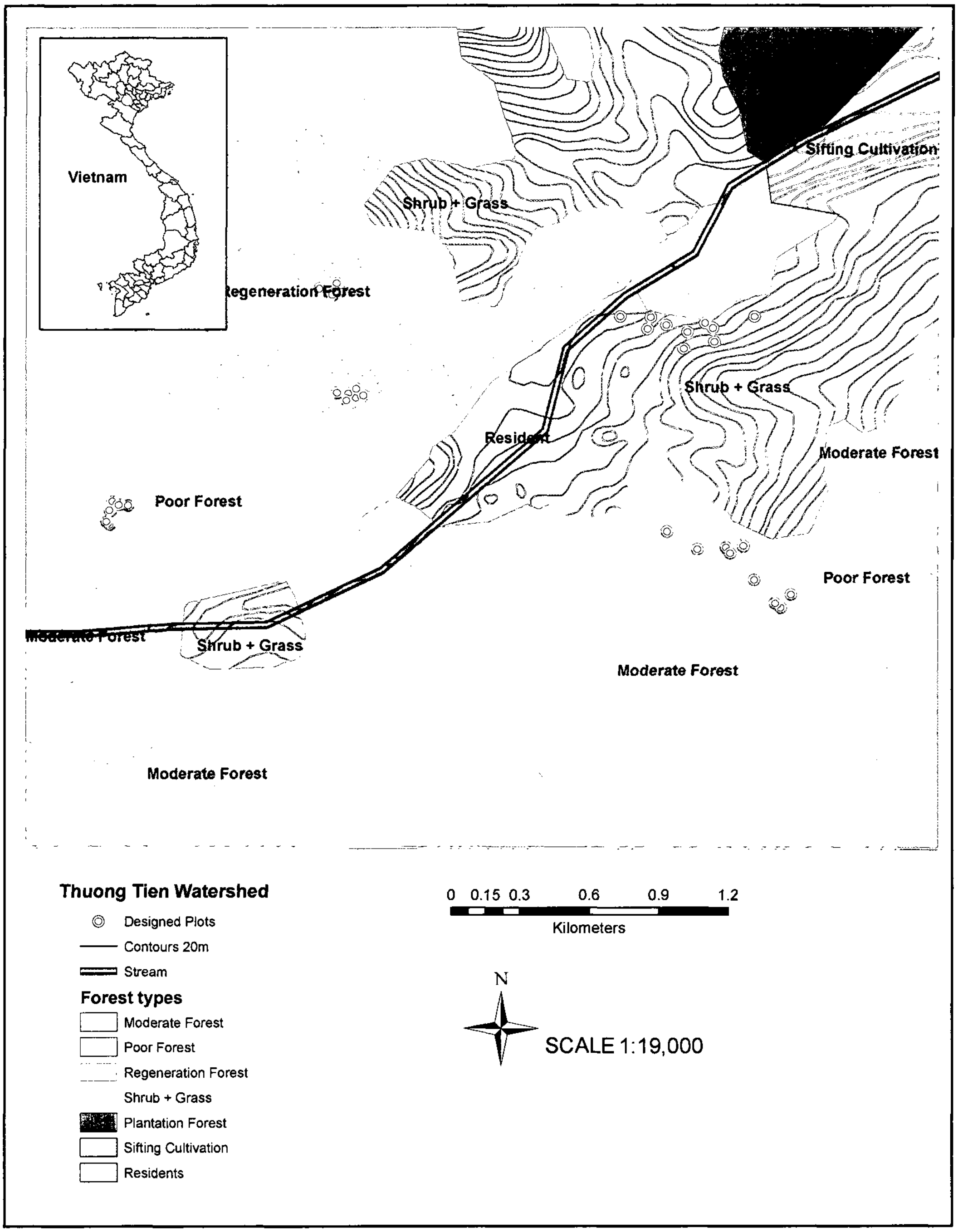


Figure 2.2. Map of the study site showing the location of study area in northern of Vietnam; cover types and the distribution of 40 plots in 4 main forest types (10 plots/type), UTM coordinates are given for scale.

2.2.2. Data Collection

Data were collected in 40 plots, 10 plots for each forest type. The plot size is 400m^2 (20m x 20m). The system of plots were predefined on a digital map and navigated to in the field by GPS (Fig. 2.2). The location of plots were judgmentally selected, they are evenly distributing on three types of topography (convex, concave, and plane), to account for variations of slope and elevation in watershed, and setting up far from top-ridge at least 50m. In each of the forest types, the distance between plots is about from 100m to 200m. Data measured and collected from each plot includes:

- *Forest structure:* DBH (cm); height (m); canopy closure (%); vegetation ground cover (%); dried litter cover (%); and density (trees/ha) was measured for all trees in the plot. Basal area (m^2/ha) and tree volume (m^3/ha) are calculated from DBH and height.

- *Soil moisture (%):* Daily soil samples were taken at different levels of soil depth (0-10cm; 20-30cm; 40-50cm; 80-100cm; and >100cm) during 8h30' to 9h30' for 60 consecutive days (from May 15 to July 15, 2006). Each sample was marked and stored in a plastic bag. Soil moisture was identified in the laboratory using equation (2.1).

$$W(\%) = \frac{(W_1 - W_2)}{W_2} * 100 \qquad (2.1)$$

Where: W = soil moisture (%); W_1 = weight of soil sample before oven drying; W_2 = weight of soil sample after oven drying.

- *Soil porosity (%):* A bulk density pipe was used to collect soil samples at different given soil horizons (0-10cm; 20-30cm; 50-60cm). The soil porosity is calculated from soil bulk density and soil particle density identified in laboratory using equation (2.2).

$$Porosity(\%) = \left(1 - \frac{BulkDensity}{ParticleDensity}\right) * 100 \qquad (2.2)$$

- *Soil water retention (mm):* The total amount of water retained in the soil is a function of soil depth, bulk density, and soil moisture using equation (2.3).

$$P_{Wr} = SoilDepth * BulkDensity * SoilMoisture \tag{2.3}$$

Where: P_{Wr} = soil water retention (g/cm^2); Soil depth (cm); bulk density (g/cm^3); soil moisture (%). Soil water retention (g/cm^2) is converted to "mm" by dividing with water density.

- *Soil water storage capacity (P_{Wc}; mm):* Similar to equation (3), soil water storage capacity uses the soil's maxmum saturation capacity rather than soil moisture using equation (2.4).

$$W_C(\%) = \frac{W_{SW} - W_T - W_S}{W_S} * 100 \tag{2.4}$$

Where: W_{SW} weight of tube and maximum saturated soil; W_T weight of tube; W_S weight of absolutely dried soil.

2.2.3. Data Analysis

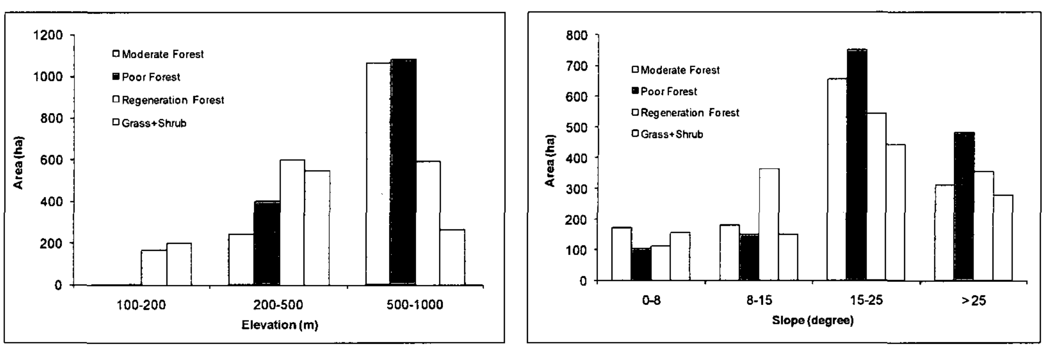
Forest soil moisture and soil water retention changes over time of four forest types were analyzed in relation to forest structures, topography and precipitation. Various techniques are available to quantify the relation between soil moisture and those independent variables, the multiple linear regressions were preferred for this study. Statistical significance (P value) of independent variables is used to determine the importance of the independent variable. The independent variables with significant slope coefficients in the regression equation are more important than those not. The higher the standardized coefficient (β), the more variation of the dependent variable is accounted for (Vasky, 2007). The best regression model was selected based on "stepwise" process in SPSS. The models were validated by comparing actual data and predictive data (i.e., root square mean error).

2.3. RESULTS AND ANALYSIS

2.3.1. Forests and Structures

2.3.1.1. Forest Distribution

Distributions of cover types on elevation, slope, and topography in research areas are summarized in Table 2.1. Total area of study sites are 5611 ha, including 10 cover types. Vegetation is classified based on their structure, age and magnitude of human impact (FIPI, 2005). The four main cover types are moderate forest, poor forest, regeneration forest, and grass+shrub. They account for 92.8% of the study site (5207ha), the largest cover type is poor forest (26.5%), the next largest cover types are regeneration forest (24.5%), moderate forest (23.5%), and shrub + grass (18.3%). They are selected to estimate the relationship between forest structure and soil moisture and soil water retention.



(a) (b)

Figure 2.3. Distribution of forest type on elevation (a) and on slope (b)

Moderate and poor forests are mostly found at elevations above 500m. The lower areas are regeneration forest and grass+shrub (Fig. 2.3a). These forests are mainly concentrated in the slopes greater than 15^0 (Fig. 2.3b). The figures reveal that when forests are spatially distributed on a higher elevation and steeper slope, they tend to have a diversified structure and a higher volume (moderate forest vs. poor forest). This can be explained by the magnitude of human impacts (i.e., shelterwood cutting, clearcutting) since the 1980s in the 20^{th} century, the lower elevation is easier accessibility for human to harvest than the higher elevation (MARD, 2000).

Table 2.1. Spatial distribution of forests on elevation, slope and topography in research area (ha)

Cover types[a]	Elevation (m)[b]				Slope[c]				Topography[c]			$\sum$	Percent (%)
	100-200	200-500	500-1000	> 1000	$0\text{-}8^0$	$8\text{-}15^0$	$15\text{-}25^0$	$> 25^0$	Convex	Plane	Concave		
Moderate Forest	0.4	243.0	1065.2	11.3	172.2	180.0	655.9	311.9	480.4	350.3	489.2	1320.0	23.5
Poor Forest	0.5	402.9	1083.5	0.9	104.9	149.0	751.1	482.9	513.5	457.4	517.1	1487.9	26.5
Regeneration Forest IIA	19.3	138.5	296.2	6.5	61.5	45.3	168.5	185.0	148.5	138.0	173.9	460.3	8.2
Regeneration Forest IIB	150.3	464.7	299.0	0.0	49.9	318.1	375.2	170.8	156.6	603.9	153.5	914.0	16.3
Bamboo Forest	0.0	23.3	12.6	3.8	4.0	2.3	16.2	17.2	13.1	13.4	13.1	39.7	0.7
Grass + Shrub	203.0	551.5	268.1	2.9	154.4	151.0	442.9	277.2	375.0	277.3	373.2	1025.5	18.3
Rockies Mountain	0.3	2.3	10.8	0.0	3.3	0.0	0.9	9.2	5.7	3.2	4.5	13.4	0.2
Paddy Field	47.0	5.6	0.0	0.0	20.1	21.8	8.1	2.6	20.3	8.5	23.8	52.6	0.9
Sifting Cultivation	38.6	205.7	11.9	0.0	28.0	31.8	97.9	98.6	87.6	74.6	94.1	256.3	4.6
Residents	0.0	42.2	0.0	0.0	9.5	14.1	16.7	1.8	18.7	6.0	17.5	42.2	0.8
$\sum$	459.4	2079.8	3047.3	25.4	607.8	913.4	2533.4	1557.1	1819.4	1932.7	1859.8	5611.9	100

Sources:

[a] Cover types were delineated from National Land Cover Data (2005) of Forest Inventory and Planning Institute

[b] Elevation were from Institute of Geography, Vietnam, 2004

[c] Slope and Topography were calculated from elevation (ArgGIS 9.2)

2.3.1.2. Forest Structures

Forest structure characteristics are averaged in Table 2.2. Each of the forest types has their own structure distinguishing it from the other forest types.

Table 2.2. Averaged forest's structure indices of 10 plots for the 4 forest types

Cover types	Plots	Density (trees/ha)	DBH (cm)	Height (m)	Volume (m^3/ ha)	CC (%)	GC (%)	LC (%)
Moderate forest	10	533	20.0	15.5	131.4	64.3	51.4	72.8
Poor forest	10	360	16.5	14.6	58.3	51.7	52.4	59.1
Regeneration forest	10	596	14.7	12.8	64.5	51.5	52.0	49.1
Grass+shrub	10			0.80			76.7	71.5

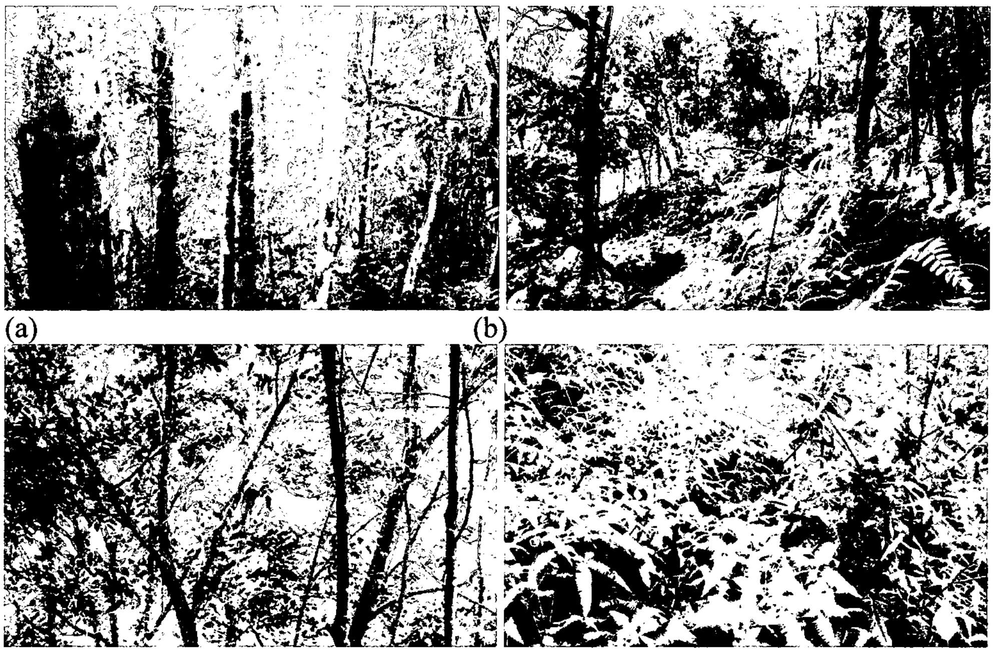
* *CC: canopy cover; GC: ground cover; LC: litter cover*

Moderate forest (moderate tree volume) is secondary natural forest with low human impact. Therefore, its tree volume, DBH, and height are the highest among the forest types. Density ranges from 425 to 693 trees/ha, canopy closure is approximately 65%; DBH and height range from 18cm to 24.3cm and from 14.8m to 17m, respectively. Grass and shrub ground cover is 51% (Table 2.2; Fig. 2.4a).

Poor forest (low tree volume) is also made up of secondary natural forest. It has been remained exposed to heavy selective cutting, compared to the low human impact in moderate forest. All poor forest's structure indices are smaller than those of moderate forest. Density ranges from 219 to 521 trees/ha, canopy closure is approximately 52%; DBH and height range from 12.3cm to 21.8cm and from 11.9m to 16.5m, respectively. Grass and shrub ground cover is 54% (Table 2.2; Fig. 2.4b).

Regeneration forest is areas that have regenerated from clear cutting or from slash and burn cultivation. Trees are young, density ranges from 412 to 773 trees/ha, higher than those of moderate forest and poor forest; canopy closure is about 51%; DBH and height range from 12.1cm to 17cm and from 10.9m to 14.9m, respectively. Grass and shrub ground cover is 51.7% (Table 2.2; Fig. 2.4c).

The mixed grass+shrub areas resulted from long term clear cutting or slash and burn cultivation. This type has no canopy which explains why? the ground cover is the highest among forest types (75% vs. 50%). The average height of grass + shrub is 0.8m (Table 2.2; Fig. 2.4d).



(a) (b) (c) (d)

Figure 2.4. Four selected forest types in Thuong Tien, (a) mixed species, uneven age, evergreen forest, total tree volume are moderate; (b) complex species, uneven age, forest, total tree volume are low (poor); (c) young regeneration forest with fairly even age of some shade intolerant species; (d) mixed shrub and grass.

2.3.2. Forest Soil Properties

2.3.2.1. Forest Soil Moisture

Forest soil moisture varies amongst forest types (Table 2.3). Moderate forest has the highest soil moisture (35.8%), followed by poor forest (32.2%), regeneration forest (30.4), and grass+shrub (25.3%). However, the differences in soil moisture between forest types are not considerable, the largest difference is between moderate forest and grass+shrub (10.5%), and the smallest ones is between poor forest and regeneration forest (1.8%).

Table 2.3. Averaged forest soil moisture (%) on depths of 4 forest types

Cover types	Plots	Soil depth (cm)					Average
		0-10	20-30	50-60	80 -100	> 100	
Moderate forest	10	39.0	34.9	33.4	36.0	35.8	35.8
Poor forest	10	33.9	30.7	31.1	33.1		32.2
Regeneration forest	10	32.7	27.2	29.4	32.3		30.4
Grass+shrub	10	27.9	23.2	24.3	26.0		25.3

*Average for a period of 60 consecutive days (May 15 - July 15, 2006)

For each forest type, average soil moisture is variable at different soil depths (Fig. 2.5). Generally, soil moisture is the highest in the topsoil (0-10cm), decreasing to the lowest moisture at depths of 20-30cm, and slightly increasing in depth of 50-60cm.

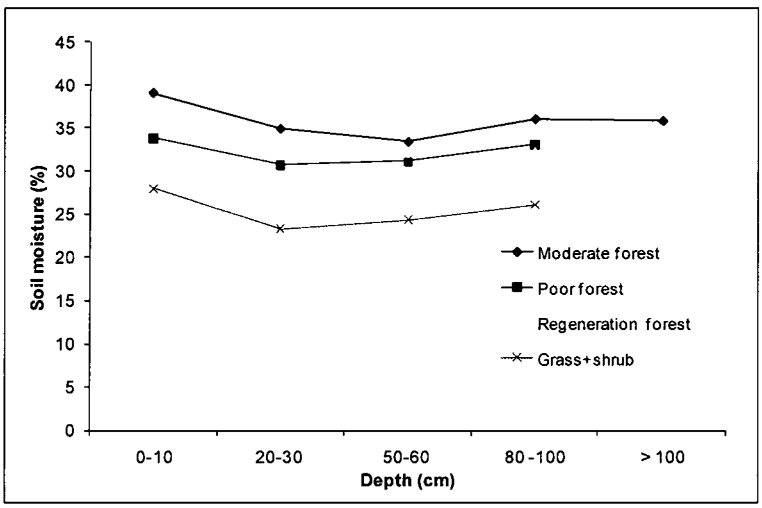


Figure 2.5. Changes in averaged soil moisture for 4 forest types during a period of 60 consecutive days

2.3.2.2. Relationship between Topsoil Moisture and Rainfall over time

Under the effect of rainfall, the changes of topsoil moisture in all forest types are fairly similar. Topsoil moisture increases after a precipitation event and decreases on consecutive days (Fig. 2.6). The rate of increase depends on the magnitude of antecedent topsoil moisture and rainfall. However, when topsoil moisture is at maximum saturation, it is unrelated to rainfall.

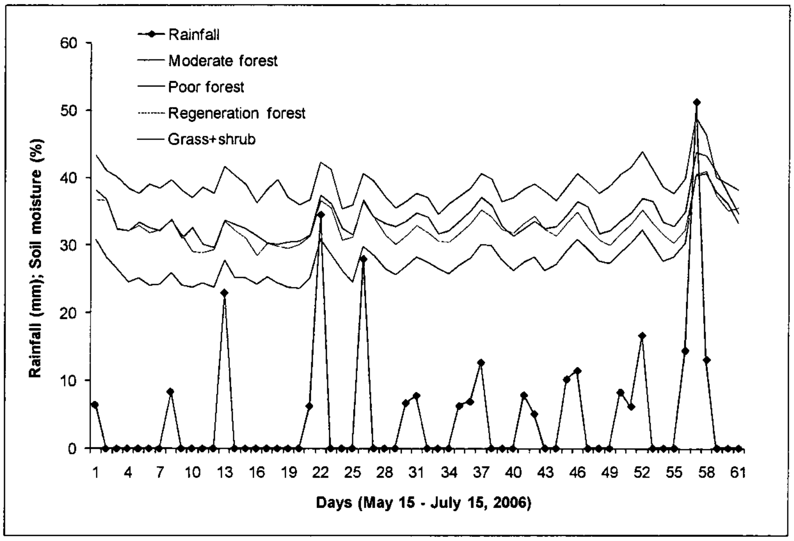


Figure 2.6. Changes of topsoil moisture and rainfall during a period of 60 consecutive days (May 15 – July 15, 2006).

The highest and the lowest values of topsoil moisture are in moderate forest and grass + shrub, the averaged value is 39% and 27.9%, respectively. Those of poor forest and regeneration forest are approximately equal to 33%. The variability in soil moisture is mainly caused by the variability of forest structures between forest types (Table 2.2).

2.3.2.3. Forest Soil Porosity

Porosity is a measure of the amount of pore space in the soil. It influences the movement of water and defines the amount of water stored in a soil (Kimmins, 2004). Averaged values of soil porosity of forests are summarized in Table 2.4 and Fig. 2.7.

Table 2.4. Averages for soil porosity (%) of 10 plots on soil depths of 4 forest types

Cover types	Plots	Soil depth (cm)		
		0-10	20-30	50-60
Moderate forest	10	57.1	49.7	46.1
Poor forest	10	46.6	43.6	40.9
Regeneration forest	10	45.3	42.1	40.6
Grass + shrub	10	40.5	39.0	37.2

Soil porosity varies among forest types. At any soil depth, soil porosities gradually decrease from moderate forest to grass + shrub. For each of forest type, soil porosity decreases from topsoil to the lower depth (Table 2.4; Fig. 2.7).

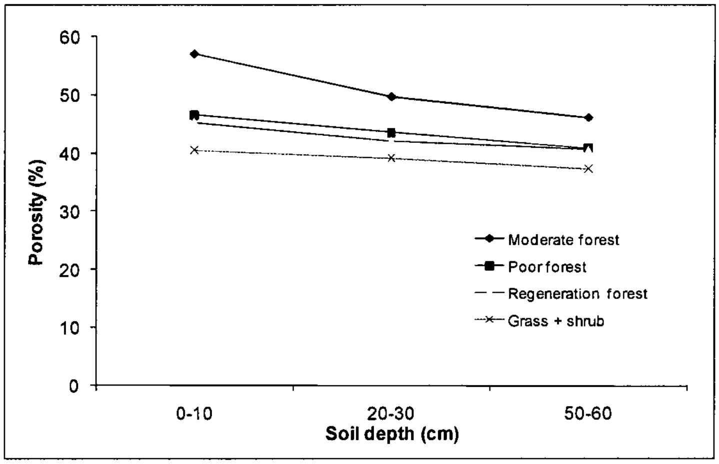


Figure 2.7. Changes in averaged soil porosity on depths for 4 forest types

2.3.3. Effects of Environmental Factors on Forest Soil Moisture

Forest soil moisture is varies spatially throughout the study sites. This is explained by changes in environmental factors among forests. From the data of 40 plots (Appendix 2.1), multiple linear regressions were used to inspect these relations.

Table 2.5. Regression equations of soil moisture and environmental factors

Equations		**R^2**	**Adj. R^2**	**P val.**
$W^a = 61.89 + 0.46*V - 3.98*LC$	(2.5)	0.78	0.72	0.005
$W^b = 39.85 - 0.131*GC - 0.188*LC + 0.223*Po$	(2.6)	0.78	0.68	0.019
$W^c = 19.93 + 0.282*Po$	(2.7)	0.85	0.83	0.001
$W^d = 41.01 - 0.214*SL - 0.297*GC + 0.305*Po$	(2.8)	0.78	0.67	0.020
$W^e = 26 - 0.084*GC - 0.072*LC + 0.355*Po$	(2.9)	0.67	0.64	0.001

* W: soil moisture (%); V: tree volume (m^3); LC: litter cover (%); GC: ground cover (%); SL: slope (%); Po: soil porosity (%)
* all independent variables are significant at $\alpha = 0.05$
[a] Eq. for moderate forest;
[b] Eq. for poor forest
[c] Eq. for regeneration forest
[d] Eq. for mixed grass+shrub
[e] Eq. for all cover types

As shown in Table 2.5, all regression models are significant (P val. <0.05), and represent a relationship (R^2 >0.70). The best goodness of fit model is in the regeneration forest (R^2=0.85). Those of moderate forest, poor forest, and grass + shrub are similar (R^2=0.78). The weakest model fit is in the general equation for all cover types (R^2=0.67).

Litter cover is only not significant in equation (2.8), and ground cover is not significant in equation (2.5), and (2.8), respectively. These variables are indirectly proportional to the soil moisture. It is contrary to other researcher's conclusions (Quynh, 1996) that litter cover and ground cover may reduce soil evaporation and retain more moisture in the soil. In this study, these inverse relations may be explained by small rainfall events during the study period where water was retained in the litter cover rather than being absorbed by the soil.

Porosity is significant in 4 of 5 equations. It is directly proportional to the soil moisture, because the higher porosity may be increasing water retentive capacity of the soil. Both tree volume and slope variables are found to be significant for an equation, tree volume directly related to the soil moisture in equation (2.5), and inversely to the slope in equation (2.8).

Standardized coefficients (β) of litter cover and porosity are usually higher than those of other variables in a same equation, indicating that litter cover and porosity are the most important variable affecting soil moisture.

Other independent variables (e.g., diameters, height, and canopy closure) are not present in all equations. It is probably explained by two reasons: They do not correlate with soil moisture, and are being removed in the model selection process (stepwise); There is colinearity among independent variables (Appendix 2.2). For example, diameter and height are highly correlated with tree volume. Their correlation coefficients (r) are 0.87 and 0.78, respectively.

2.3.4. Soil Moisture Prediction Models

Forest soil moisture is predicted by two models. The first model is the prediction of soil moisture for **rainy days**, and the second model is the prediction of soil moisture for **non rainy days**.

2.3.4.1. Prediction Models for rainy days (1)

The prediction model of soil moisture for a rainy day is a function of rainfall, antecedent soil moisture, forest structures, soil properties, and topography. The selective models for each of the forest types are summarized in Table 2.6.

Table 2.6. Soil moisture prediction models for rainy days of four forest types

Equations		R^2	P val.[e]
$W_{RD}{}^{a} = 43.96 + 0.288{*}P_m + 0.239{*}W_{BR} + 0.0036{*}CC + 0.0024{*}GC + 0.0014{*}LC + 0.012{*}Po - 0.01{*}SL$	(10)	0.61	0.001
$W_{RD}{}^{b} = 44.72 + 0.249{*}P_m + 0.0095{*}W_{BR} + 0.0017{*}CC + 0.0032{*}GC + 0.0024{*}LC + 0.02{*}Po - 0.013{*}SL$	(11)	0.55	0.001
$W_{RD}{}^{c} = 22.30 + 0.223{*}P_m + 0.501{*}W_{BR} + 0.0018{*}CC + 0.0041{*}GC + 0.0015{*}LC + 0.011{*}Po - 0.0062{*}SL$	(12)	0.83	0.001
$W_{RD}{}^{d} = 20.34 + 0.246{*}P_m + 0.404{*}W_{BR} + 0.0019{*}GC + 0.0023{*}LC + 0.0072{*}Po - 0.0071{*}SL$	(13)	0.81	0.001

W_{RD}: soil moisture after raining (%); W_{BR}: antecedent soil moisture - before raining (%); P_m: rainfall (mm); CC: canopy closure (%); LC: litter cover (%); GC: ground cover (%); SL: slope (%); Po: soil porosity (%)

[a] Eq. for moderate forest
[b] Eq. for poor forest
[c] Eq. for regeneration forest
[d] Eq. for mixed grasses, shrub
[e] P val. are significant at $\alpha < 0.001$

As shown in Table 2.6, all prediction models are highly significant and P val. <0.001, their coefficients of determination are substantial ($R^2 > 0.5$). The two best goodness of fit models are in regeneration forest (eq. (12), R^2=0.83), and grass + shrub (eq. (13); R^2=0.81), respectively. The weakest goodness of fit model is in poor forests (eq. (11); R^2=0.55).

In all regression equations, soil moisture after rainfall is directly proportional to rainfall, soil moisture before rainfall, canopy closure, ground cover, litter cover, and porosity ($\beta>0$). It is inversely related to slope ($\beta<0$).

Rainfall and soil moisture before rainfall are the two independent variables having the strongest effect on the dependent variable (W_{RD}), their standardized coefficients (β) are always higher than those of other independent variables in an equation. The effects of canopy closure, ground cover, litter cover, porosity, and slope on soil moisture after raining are minimal, in all equations their regression coefficients are less than < 0.01.

2.3.4.2. Prediction Models for no rainy days (2)

This model (2) is applied to predict soil moisture of non rainy days, when soil moisture of an antecedent rainy day is known, predicted by model (1). Model (2) is a multiple linear regression of soil moisture, interval time (days), forest structures, soil properties, and topography (Table 2.7).

Table 2.7. Soil moisture prediction models for no rainy days of four forest types

Equations		R^2	P val.[e]
$W_{AR}{}^{a} = 40.05 + 0.204*W_{RD} - 26.23*ND^{0.1} + 0.138*CC + 0.185*GC + 0.0056*LC + 0.101*Po - 0.044*SL$	(14)	0.52	0.001
$W_{AR}{}^{b} = 53.45 + 0.321*W_{RD} - 32.02*ND^{0.1} + 0.079*CC + 0.098*GC + 0.019*LC + 0.035*Po - 0.261*SL$	(15)	0.74	0.001
$W_{AR}{}^{c} = 26.36 + 0.535*W_{RD} - 25.66*ND^{0.1} + 0.154*CC + 0.161*GC + 0.036*LC + 0.038*Po - 0.061*SL$	(16)	0.79	0.001
$W_{AR}{}^{d} = 24.40 + 0.415*W_{RD} - 24.78*ND^{0.1} + 0.0064*GC + 0.034*LC + 0.121*Po - 0.295*SL$	(17)	0.83	0.001

W_{AR}: soil moisture of predicted day - a following day after raining (%); W_{RD}: antecedent soil moisture of a rainy day (%); ND: number of days from a rainy day to the predicted day; CC: canopy closure (%); LC: litter cover (%); GC: ground cover (%); SL: slope (%); Po: soil porosity (%)
[a] Eq. for moderate forest
[b] Eq. for poor forest
[c] Eq. for regeneration forest
[d] Eq. for mixed grass, shrub
[e] P val. are significant at $\alpha < 0.001$

As listed on the Table 2.7, all prediction models (2) are highly significant at α=0.05. The goodness of fit of model for each of forest type ranked, in turn, from grass+shrub (R^2=0.83), to the regeneration forest (R^2 = 0.79), poor forest (R^2 = 0.74), and moderate forest (R^2 = 0.52). The goodness of fit of models (2) are similar to that of those previous models (1).

In all models (2), the prediction soil moisture (W_{AR}) are directly proportional to the earlier soil moisture (W_{RD}), canopy closure, ground cover, litter cover, and porosity (β>0), whereas, it is inversely related to time and slope (β <0).

The most influential variables on the prediction is antecedent soil moisture and time interval. The standardized coefficient (β) is always higher than those of other independent variables. All independent variables, except time (days), are constants for a forest types (e.g., canopy closure, slope, etc.). Thus, the predicted soil moisture will gradually reduce over time and depends on the beginning soil moisture and predictive time interval. The reductive rate of soil moisture after rain mainly depends on standardized coefficient of time (β <0). Comparing these coefficients among four forest types reveals that the largest soil moisture reduction is in poor forest, where those of other forest types are similar.

2.3.4.3. Model Validation

The predicted soil moisture values are compared with actual data to determine which model might better represent prediction for the independent responses. The model verification and validation are based on root square mean error (RSME), equation (2.18). The RMSE is expected to be as small as possible.

$$RSME = \sqrt{\frac{(PredictedValue - ActualValue)^2}{\#Values}} \qquad (2.18)$$

In this study, due to lack of data for other forest types, only models for moderate forest are validated. 70 soil samples of moderate forest were daily collected from August 20 to October 31, 2006. These samples are independent and not used to establish the model. The corresponding predicted soil moisture values were also calculated. The results show that equation (2.10) and (2.14) are the two models giving the lowest RSME (3.03%). This indicates that the most statistically significant models (Table 2.6, 2.7) are also the most validation models.

2.3.4.4. Forest Soil Water Retention

Average soil water retention during the study period was estimated for each forest type (Table 2.8). The results show that it varies amongst forests, and depends on soil depth, bulk density, and soil moisture, respectively. The highest capabilities of soil water retention in moderate forest (401 mm), the lowest ones is in grass+shrub (350 mm). Those of poor forest and regeneration forest are approximately similar.

Table 2.8. Averaged forest soil water retention from May 15 to July 15, 2006

Cover types	Soil depth (m)	Bulk density (g/cm^3)	Soil moisture (%)	Soil water retention [a] (mm)
Moderate forest	0.85	1.32	35.8	401
Poor forest	0.78	1.38	32.2	346
Regeneration forest	0.80	1.44	30.4	350
Grass + shrub	0.67	1.47	25.3	249

[a] Soil water retention is calculated based on equation (2.3)

As show in Table 2.9, soil water retention is not only variable between forests, but also changes monthly. For a specific forest type, soil depth, bulk density are unchangeable, so the monthly variability of soil water retention strongly depends on the variability of soil moisture which is influenced by quantities and distribution of annual rainfall.

Table 2.9. Monthly averaged soil water retention for forest types

Months	Moderate forest		Poor forest		Regeneration forest		Grass + Shrub	
	W[a]	P_{Wr}[b]	W[a]	P_{Wr}[b]	W[a]	P_{Wr}[b]	W[a]	P_{Wr}[b]
1	28.4	319	21.9	236	21.4	247	15.1	151
2	27.6	310	21.2	228	20.7	239	14.3	143
3	30.1	338	23.6	254	23.1	266	16.8	168
4	31.2	350	25.0	269	24.5	282	17.9	179
5	34.3	385	30.0	323	29.7	342	25.1	251
6	36.8	413	32.4	349	32.1	370	27.6	276
7	38.1	428	33.7	363	33.4	385	28.9	289
8	39.7	445	35.4	381	35.1	404	30.5	305
9	37.3	419	32.1	346	31.1	358	28.1	281
10	33.6	377	27.1	292	25.5	294	21.8	218
11	30.7	345	25.4	273	23.8	274	19.4	194
12	28.9	324	23.5	253	21.9	252	17.6	176

*Rainfall and its distribution of 2005 was used to estimated monthly soil water retention
W[a]: soil moisture (%), estimated by applying the two corresponding prediction models in section (3.4). It is estimated as daily timescale, and monthly averaged as above.
P_{Wr}[b]: soil water retention (mm), calculated by equation (2.3).

Forest soil water retention varies both monthly and spatially among forest types (Fig. 2.8). Generally, soil water retention is the highest in moderate forest and the lowest in grass + shrub. At a monthly timescale, the trends of soil water retention of four forest types are similar. For a given forest type, soil water retention is lowest in February, gradually increasing to peak in August, and declining until January next year.

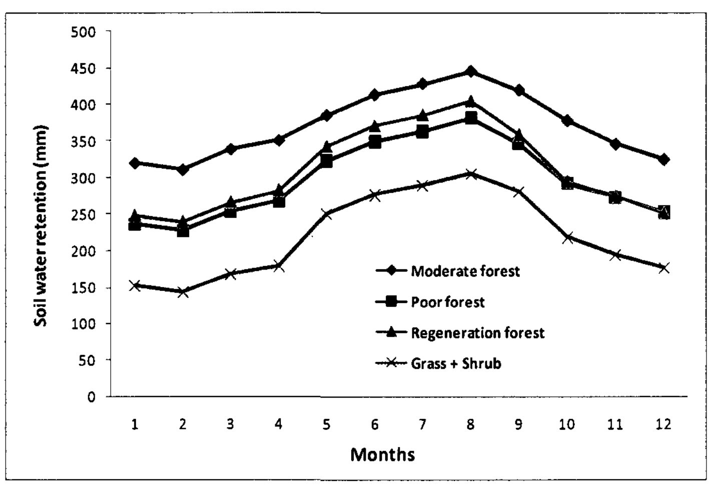


Figure 2.8. Monthly distribution of soil water retention of forests

2.3.5. Monthly Threshold of Rainfall

In general, when soil water storage is filled to capacity (soil's maximum saturation), the incremental rainfall will deliver runoff. The difference between maximum soil water storage capacity and current soil water retention is called the "threshold of rainfall". This study does not take into account the soil infiltration rate. It is assumed that the soil infiltration rate is equal or greater than rain intensity, and that the surface runoff will only occur on the ground when rainfall exceeds its threshold. The monthly threshold rainfalls for forest types are calculated as below.

$$P_{TR} = P_{Wc} - P_{Wr} \qquad (2.19)$$

Where: P_{Wc} soil water storage capability (mm)

P_{Wr} current soil water retention (mm)

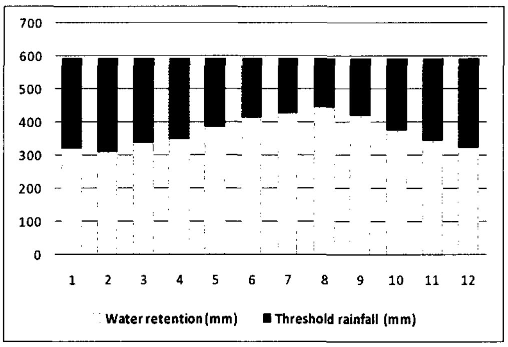
P_{TR} threshold rainfall (mm)

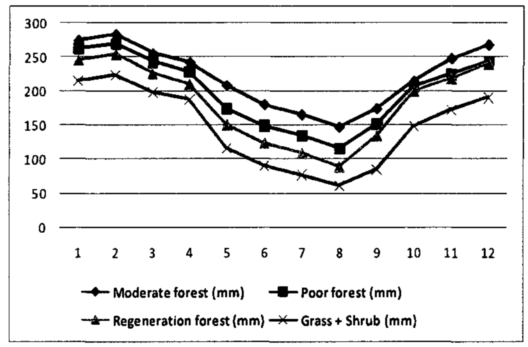
Table 2.10. Monthly soil water retention and threshold rainfall for forest types

Months	Moderate forest		Poor forest		Regeneration forest		Grass + Shrub	
	P_{Wr} [a]	P_{TR} [b]	P_{Wr} [a]	P_{TR} [b]	P_{Wr} [a]	P_{TR} [b]	P_{Wr} [a]	P_{TR} [b]
1	319	274	236	262	247	246	151	215
2[c]	310	283	228	269	239	254	143	223
3	338	255	254	243	266	226	168	198
4	350	242	269	228	282	210	179	187
5	385	208	323	174	342	150	251	115
6	413	180	349	149	370	123	276	90
7	428	165	363	135	385	108	289	77
8[d]	445	147	381	116	404	88	305	61
9	419	174	346	152	358	134	281	85
10	377	215	292	206	294	199	218	148
11	345	248	273	224	274	218	194	172
12	324	268	253	244	252	240	176	190

Soil water storage capacity (P_{Wc}), calculated by equation (2.3) when soil moisture is at maximum saturation (equation 2.4), P_{Wc} of moderate forest, poor forest, regeneration forest, and grass + shrub are 592.4mm, 497.3mm, 492.4mm, 365.9mm, respectively.
P_{Wr}[a]: soil water retention (mm), calculated similarly to the Table 2.9.
P_{TR}[b]: threshold rainfall (mm) is difference between P_{Wc} and P_{Wr}, calculated by equation 2.19.
[c] the highest threshold rainfall of the year.
[d] the lowest threshold rainfall of the year.

For a forest type, the threshold rainfall is inversely related to soil water retention and upper limited by its maximum soil water storage capacity. When soil water retention increases, threshold rainfall decreases (Fig. 2.9a). The results explain why floods usually occur in the rainy season (from May to September). During this time, the capability of soil to absorb water is low, whereas rainfall is high. Consequently, high unabsorbed water will become surface runoff.





(a) (b)

Figure 2.9. (a) soil water rentention vs. threshold rainfall for moderate forest; (b) monthly timescale for threshold rainfall of four forest types.

Variability of threshold rainfall at monthly timescale depends on forest types (Fig. 2.9b). Moderate forest can be the best forest type for preventing flood among four forest types. In August, threshold rainfall of moderate forest is 147mm, whereas, those of poor forest, regeneration forest, and grass + shrub are 116mm, 88mm, and 61mm, respectively (Table 2.10). Compared with those in February, moderate forest needs at least a rainfall of 283mm to have a surface runoff. Other forest types need rainfall greater than 220mm and that weather phenomenon rarely happens in this research area.

2.4. DISCUSSION

One of the interesting results obtained in this study is that soil moisture is decreasing, from moderate forest to poor forest, regeneration forest, and grass +

shrub. The lower level of forest degradation, the higher value of forest soil moisture. Forest soil moisture defines soil water storage which strongly influences storm flows (Scott et al., 2005). One may think that these results are contrary to historical scientific studies in North America and Australia that find deforestation (e.g., clear cutting, thinning, and conversion) increases water yield, stream flow, because of a reduction in interception and evapotranspiration (Beschta et al., 2000; Ruprecht at al., 1988, 1990; Borg et al., 1988). However, their results may not be similar to those of other places because of variation in forest management activities, climate, and physiography. As indicated by Robinson et al. (2003), in Europe changes in forest cover at a regional scale have a relatively small effect on peak and low flows.

The contrary results in this study can be explained as follow. First of all, the study did not quantify water yield or stream flows of corresponding forest types. It is generally accepted that soil water storage capacity affects lowflows or stormflows (Scott et al., 2005). The scientific results from this study are not conclusive enough to determine that moderate forest, having the highest soil water retention capacity, can enhance baseflows or lowflows better than those of the other forest types. Furthermore, more water infiltration into the soil (i.e., high soil moisture) may not relate to an increase in water yield, because the difference in interception loss and evapotranspiration among forest types. Secondly, this study did not apply a paired watershed experiment to evaluate effect of deforestation on hydrological responses of forest. All selected forest types are located in a small catchment, indicating that the variability of soil water retention may be caused by other factors, not forest type. In fact, soil moisture, soil depth and bulk density have strong influences on soil water retention (Table 2.8). Deforestation in association with soil degradation causes variations in soil water storage capacity among the forests in the study area.

Deforestation usually leads to a reduction in canopy and ground cover (Table 2.2), causing adverse changes in soil properties such as bulk density, infiltration rate, water storage capacity (Lal, 1996). In Vietnam, the positive hydrological role of canopies, vegetation – litter ground covering were proved by few studies. For example, rainfall interception loss by forest canopies is 10-20% in pine forest (Quynh, 1996), 2.91-18.55% in both natural forest and plantation (Dien, 2006). An integrated index from canopy, vegetation ground cover, and dried litter cover was used as criteria to evaluate the forest soil water storage capacity (Quynh, 1996). By comparing Table 2.2, 2.3, and 2.8, a general conclusion can be made that deforestation in Thuong Tien in associated with soil degradation significantly causes a reduction in forest soil water retention (moderate forest's vs. grass+shrub's). An important finding is that soil moisture and soil water retention of poor forest and regeneration forest are approximately equal. Regeneration forest was regenerated from grass+shrub, meaning that reforestation from degraded land can improve soil water retention capacity (regeneration forest's vs. grass+shrub's), more detail discussed by Scott et al. (2005), Bruijnzeel (1989).

2.5. CONCLUSIONS

In this study, forest soil moisture of 40 forest plots of four forest types (moderate forest; poor forest; regeneration forest; grass + shrub) were analyzed in relation to the environmental factors, including forest structures, rainfall, porosity, soil depth, and slope. The results from this study indicate there are effects of forest degradation on forest soil moisture.

The variation of forest's structure and soil porosity creates variation in soil moisture between forest types. Measured data show that average topsoil moisture decreases, in turn, from moderate forest to poor forest, regeneration forest, and mixed grass + shrub.

There is a strong multiple linear relationship between forest soil moisture and environmental factors for selected forest types ($R^2 = 0.64 - 0.83$). The most important factors affecting forest soil moisture are litter cover, ground cover, and porosity. These independent variables are at least significant in three of four regression equations for four forest types.

Forest soil moisture can be predicted by two models: (1) prediction model for a rainy day; (2) prediction model for a no rainy day. The determination coefficients (R^2) of the two models are 0.55 – 0.81, and 0.52 – 0.83, respectively. Rainfall and antecedent soil moisture are the two main predictors affecting the first model. Those of model 2 are time interval (days) and soil moisture of a rainy day (predicted by model 1). Forest's structure and soil porosity are positive relation to soil moisture prediction, whereas, slope (model 1) and time (model 2) are inversely proportional to soil moisture prediction. Models for moderate forest are validated by 70 independent soil samples (RSME = 3.03%).

Forest soil water retention also varies among forest types. The highest capability to retain water in soil is in moderate forest (401mm) and the lowest one is in grass + shrub (249mm). Those of poor forest and regeneration forest are approximately similar (350mm). At a monthly time scale, there is the same trend of soil moisture among forests. Annually, the highest water storage capacity in the soil is in August, and the lowest one in February, meaning that these months can store more or less rainy water than others respectively.

Monthly threshold rainfalls are defined for forests to identify the occurrence capability of runoff. Contrary to soil water retention, the threshold rainfall is the lowest in August, and the highest in February for all forest types. The values of each forest type are in decreasing ranking, moderate forest, poor forest, regeneration forest, and grass + shrub. This indicates that moderate forest and poor forest can prevent runoff or flood better than regeneration forest and grass + shrub in a same place.

LITERATURE CITED

Andreassian, V., 2004. Waters and forests: from historical and controversy to scientific debate. Journal of Hydrology 291, 1-27.

Bent, G.C., 2001. Effects of forest management activities on runoff components and ground water recharge to Quabbin Reservoir, central Massachusetts. Journal of Forest Ecology and Management 143, 115-129.

Beschta, R.L., M.R. Pyles, A.E. Skaugset, C.G. Surfleet, 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. Journal of Hydrology 233, 102-120.

Borg, H., Bell, R.W. and Loh, I.C., 1988. Streamflow and stream salinity in a small water supply catchment in southwest Western Australia after reforestation. J. Hydrol., 103, 323-333.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation change on water yield and evapotranspiration. Journal of Hydrology 55, 3-23.

Bruijnzeel, L.A., 2004. Hydrological function of tropical forests: not seeing the soil for the trees?. Journal of Agriculture, Ecosystems and Environment 104, 185-228.

Bruijnzeel, L.A., 1989. (De)forestation and dry season flow in the tropics: a closer look. Journal of Tropical Forest Science, 1, 229-243.

Dien, P.V., 2006. Water retention capability of some vegetation types in protection areas of Hoa Binh hydropower plant. Ph.D Dissertation, Forestry University, Vietnam.

Fahey, B., Jackson, R., 1997. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. Agricultural and Forest Meteorology 84, 69-82.

Fu, B.J., Chen, L.D., Ma, K.M., Zhou, H.F. and Wang, J. 2000. The relationships between land use and soil conditions in the hilly area of the Loess Plateau in northern Shaanxi, China. Catena, 36, 69–78.

Hai, V.D., 1996. Research on structural types of forest for rational watershed protection in Vietnam . Ph.D Thesis. Forest Science Institute of Vietnam , Hanoi , Vietnam.

Hornbeck, J. W., Pierce, R.S., Federer, C.A., 1970. Streamflow changes after forest clearing in New England. Water Resource Research 6, 1124–1132.

Kimmins, J.P., 2004. Forest Ecology – A foundation for sustainable forest management and environmental ethics in forestry. 3rd ed., Pearson Prentice Hall, pp. 284-323.

Lal, R., 1996. Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria .1. Soil physical and hydrological properties. Land Degradation and Development, 7, 19-45.

Lavabre, J., Torres, D.S., Cernesson, F., 1993. Changes in the hydrological response of a small Mediterranean basin a year after a wildfire. Journal of Hydrology 142, 273-299.

Nganh, B., Me, V.V., Mo., N.D., 1984. Research on erosion under different vegetation types in the North of Vietnam. Scientific report, Forest Science Institute of Vietnam, Hanoi.

Niem, H., 1994. Effects of forests on water run-off. Meteorology and Hydrological Newsletter, 7 (403).

Phien, T., Toan, T.D, 1998. Runoff and erosion on slope areas under different cultivation systems. Summary of scientific reports. Assessment of impacts of Hoa Binh reservoir on environment. Hanoi.

Phuong, T.N., 1970. Preliminary research on forest vegetation in northern of Vietnam. Agriculture Publishing House, Hanoi.

Quynh, V.V., 1996. Forest hydrology and erosion in Forestry University's experimental station. Scientific reports 1995-1999, Forestry University, Vietnam.

Robinson, M., A.L. Cognard Plancq, C. Cosandey, J. David, and 12 others, 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management 186, 85–97.

Ruprecht, J.K. and Schofield, N.J., 1989. Analysis of streamflow generation following deforestation in southwest Western Australia. J. Hydrol., 105, 1-17.

Ruprecht, J.K., N.J. Schofiel, D.S. Crombie, R.A, Vertessy and G.L. Stoneman., 1991. Early hydrological response to intense forest thinning in southwestern Australia. Journal of Hydrology, 127, 261-277.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology 178, 293-309.

Scott, D.F., L.A. Bruijnzeel, and J. Mackensen. 2005. The hydrologic and soil impacts of reforestation. In: Forests, Water and People in the Humid Tropics, M. Bonell and L.A. Bruijnzeel (Eds). Cambridge University Press, pp 622-651.

Shukla, M.K., Lal, R., Owens, L.B. and Unkefer, P. 2003. Land use and management impacts on structure and infiltration characteristics of soils in the North Appalachian region of Ohio. Soil Science, 168, 167–177.

Tuan, V.V., 2003. Using experimental method to evaluate impacts of forests on some hydrological features. In second workshop proceedings, Volume II: Hydrology and Environment, Institute of Meteorology and Hydrology, Hanoi, Vietnam.

Vaske, J. J., 2007. Survey Research and Analysis: Applications in Human Dimensions of Natural Resources (chapter 12), Venture Publishing, State College, Pennsylvania.

Yimer, F., Messing, I., Ledin, S., and Abdelkadir, A. 2008. Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia. Soil Use and Management, 24, 344–349.

Environment Protection Agency (EPA), Vietnam. http://www.nea.gov.vn/

FAO Forestry Country Profile, Vietnam. http://www.fao.org/forestry/32185/en/vnm/

Forest Inventory and Planning Institute (FIPI), Vietnam. http://fipivn.org.vn/

Forest Protection Department (FPD), Vietnam. http://www.kiemlam.org.vn/

HydroMeterological Data Center (HMDC), Vietnam. http://www.hymetdata.gov.vn/

Ministry of Agriculture and Rural Development (MARD), Vietnam. http://www.mard.gov.vn/

Chapter 3

THE EFFECTS OF WATERSHED CHARACTERISTICS ON STORM RUNOFF RELATIONSHIPS IN VIETNAM

Abstract

This chapter presents results of a study of watershed factors (e.g., slope, elevation difference, size, shape, forest cover, forest distribution) on storm runoff (lag time, increasing and decreasing flow rate) and daily variation of stream flow. Fifteen watersheds representing differ in ecological regions, climate regimes, and forest types in Vietnam are selected for this study. The basic hydrological data set corresponding to each watershed included rainfall and stream flow recorded hourly at the watershed outlet in 2005. There are a total 830 storm events in excess of 5 mm used to analyze the relationship between factors.

Peak discharge is influenced most by initial flow (m^3s^{-1}) and rainfall (mm), whereas intensity (mm hr^{-1}) is not significant at any watershed. The lag time to peak flow (hrs) is not significant related to any watershed factors. Forest cover (%) is indirectly significant with flow coefficient of variation (%), index of increasing and decreasing flow rates (m^3s^{-1}), respectively. Forest distribution (%) is directly significant with two flow rate indices. These two independent forest variables are associated with approximately 20 -30% of total variation in responding runoff variables. Watershed size (km^2) is not significantly related to any runoff indices, while shape index is directly significant with increasing and decreasing flow rate. Watershed shape explains about 27% of the total variation in the stream flow variation and increasing flow rate, respectively. Average slope (%) is not significant with any runoff variables at level 0.1. However, average elevation difference (m) is highly significant related to the two flow rate indices. In multiple regression analysis, only 4 watershed factors significantly presented in regression models are forest cover, shape index, average elevation difference, and forest integrated index.

3.1. INTRODUCTION

Watershed characteristics such as size, slope, shape, and vegetation are important factors affecting various aspects of runoff (e.g., water yield, peak flow, base flow, direct storm runoff, flow variation). A number of studies have been carried out worldwide to investigate these relationships (Hewlett et al., 1982; Wolock, 1995; Singh, 1997; Bruijnzeel, 2004; Andreassian, 2004).

Many physical variables of catchments have been found to correlate with runoff. A review of the effects of catchment size on hydrological relationships by Pilgrim et al. (1982) indicated that catchment size can be expected to influence runoff on not only the average runoff characteristics, but on their relative variabilities. When basin size is small, the variability of stream flow response to precipitation tends to increase (Wood et al., 1990). In Quebec, Lajoie et al. (2007) analyzed the monthly flow characteristics between natural rivers and regulated river. They concluded that watershed size significantly influences the extent of the hydrological changes induced by dams, and these changes are variable by seasons. For watershed shape, Tabios et al. (1988) found that an elongated watershed influences the storm movement more strongly than a delta-shaped watershed does. Storm water detention is more effective in a concentrated watershed than in an elongated watershed (Goff et al., 2006).

After reviewing literature on forest and water relationships, Sun et al. (2005) pointed out that increasing forest cover has the potential to decrease water yield and baseflow rate. The increases in runoff with clearing result from a rise in the groundwater table rather than from increases in storm runoff (Pilgrim et al., 1982). By summarizing results implemented by several other authors (e.g., Trendle and King, 1985; Fritsch, 1990; Robinson et al., 1991; Hornbeck et al., 1997), Andreassian (2004) concluded that deforestation generally increases flood peaks and flood volumes. Based on a comparison of 50 world wide basins, Guillemette et al. (2005) noted that peak flow originating from a rainfall event is significant increased when harvesting has reached about 30% of a watershed. Although there are scientific papers relating forest and water, very few papers have analyzed the effects forest distribution on responding storm runoff.

Rainfall and generated runoff relationships have long been a concern of hydrologists and watershed managers. Hewlett et al. (1977, 1984) analyzed a 30 year record of rainfall and storm flow in a 3 mi^2 forested watershed in the southern Appalachians. They concluded that hourly rainfall intensities do not have a significant effect on storm flow volumes at level 0.05. Storm rainfall, initial flow, season and storm duration are associated with 86.4% of the total variation in the log storm flow. Rainfall-runoff research in a catchment in Nepal (Merz et al., 2006) shows that runoff (mm) has the highest correlation with total rainfall volumes (mm) and maximum 60 minutes rainfall intensity. The magnitude changes in peak flow (%) tend to decrease with the increasing annual precipitation. The annual maximum daily flows are more frequent in spring compared to mid-winter (MacDonald et al., 1997).

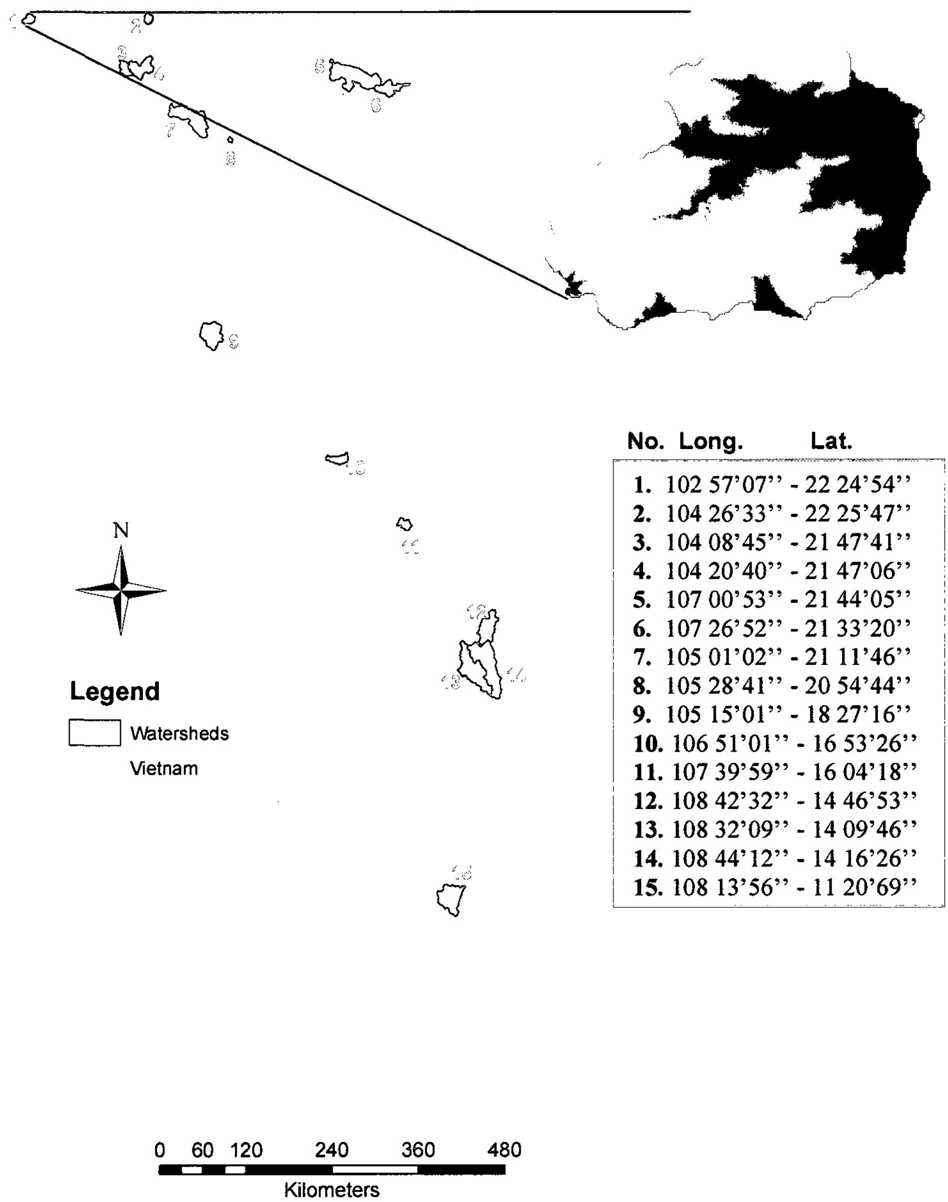
To date, no comprehensive studies on the relationship between watershed characteristics and storm precipitation dynamics and stream flow have been implemented in Vietnam. There are only some preliminary studies that address hydrological roles of forests on flow regulation and water retention (Pho, 1992; Niem, 1994; Hai, 1996; Quynh, 1996). The objectives of this study are: (1) to delineate and extract reference data for 15 watersheds in Vietnam; (2) to identify and calculate watershed and vegetation factors affecting storm runoff responses; (3) to analyze the relationship between watershed factors and runoff indices; and (4) to separately inspect rainfall dynamics and runoff relationships in 15 watersheds in Vietnam.

3.2. METHODOLOGY

3.2.1. Study Sites

The study was conducted in 15 watersheds in Vietnam. These selected watersheds are distributed throughout the Vietnam territory (Fig. 3.1). Watershed areas range from a small watershed (42.9 km^2) to a large watershed (2030.2 km^2). The climate varies among watersheds from north to south. The watersheds located in the northern areas (greater than 18^0 N) have a monsoon tropical climate. Temperature and rainfall are seasonal. Summers are hot, muggy, and rainy from May to October. Dry periods can vary from zero to six months depending on the location. In the south (to 16^0 N), temperatures are less seasonal, and the timing of the wet season varies, particularly between coastal and inland areas. Winters are cool, with rains extending from summer through autumn and into winter and a dry season of zero to three months. The central highlands have a similar climate to the south, but it is cooler and conditions wetter, with dry seasons lasting for only three months (Sterling et al., 2006). The average annual temperature is generally higher in the plains than in the mountains.

The selected watersheds consist of all main forest types in Vietnam (e.g., closed evergreen broadleaf forest, deciduous broadleaf forest, plantation forest). Evergreen forested watersheds are distributed in wet and humid condition, whereas deciduous forested watershed occurs in regions with long dry seasons. Shrub and grasslands are usually restricted to watersheds located in low lying areas (Sterling et al., 2006). The watersheds are also representative of various pedologic and topographic conditions in Vietnam (Fig. 3.1).



No.	Long.	Lat.
1.	102 57’07”	22 24’54”
2.	104 26’33”	22 25’47”
3.	104 08’45”	21 47’41”
4.	104 20’40”	21 47’06”
5.	107 00’53”	21 44’05”
6.	107 26’52”	21 33’20”
7.	105 01’02”	21 11’46”
8.	105 28’41”	20 54’44”
9.	105 15’01”	18 27’16”
10.	106 51’01”	16 53’26”
11.	107 39’59”	16 04’18”
12.	108 42’32”	14 46’53”
13.	108 32’09”	14 09’46”
14.	108 44’12”	14 16’26”
15.	108 13’56”	11 20’69”

Figure 3. 1. Map of the study sites showing the location of the 15 selected watersheds in Vietnam; an example of NaHu watershed delineated from National Elevation Dataset; and Outlet Geo-coordinates of 15 watersheds.

3.2.2. Sources of Data

The data used for this analysis include national elevation, national land cover, and hydrological data.

Elevation: Topographical characteristics used for this study, including slope and elevation (30 x 30m), were derived from a base contour map digitized from the topographical map (scale of 1:50000) by the Department of Land Survey and Mapping of Vietnam in 2004.

Forest cover types: The spatial distribution of forest and vegetation cover was defined from the National Land Cover Dataset which was made by the Forest Inventory and Planning Institute of Vietnam and published in 2005. Originally, the scale of the map was 1:10000. This map was established based on a national ground survey in 1997 and adjusted based on Landsat ETM+ data from 2002.

Rainfall and runoff data: Detailed rainfall-runoff data from 2005 for 15 watersheds were collected from 15 hydrological stations. During this period, all storm events and runoff were recorded hourly at the outlet of watershed.

3.2.3. Watershed Delineation

The watershed delineation process was based on Desktop GIS software 9.2 and the latest Hydrology Modeling Extension made by ESRI (2006). Watershed delineation was the most time consuming process of the data preparation summarized as follows: (Fig. 3.2): (1) the vector elevation map (contour 20m) was digitized and is converted to a raster map with a resolution of 30 x 30 m; (2) obtain the geo-coordinates of the 15 hydrological stations (outlets of corresponding 15 watersheds, Fig. 3.1); (3) delineate basin areas and watershed boundaries for 15 watersheds from elevation map and corresponding pour point; (4) delineate land cover for 15 watersheds from watershed boundaries and the corresponding national land cover data.

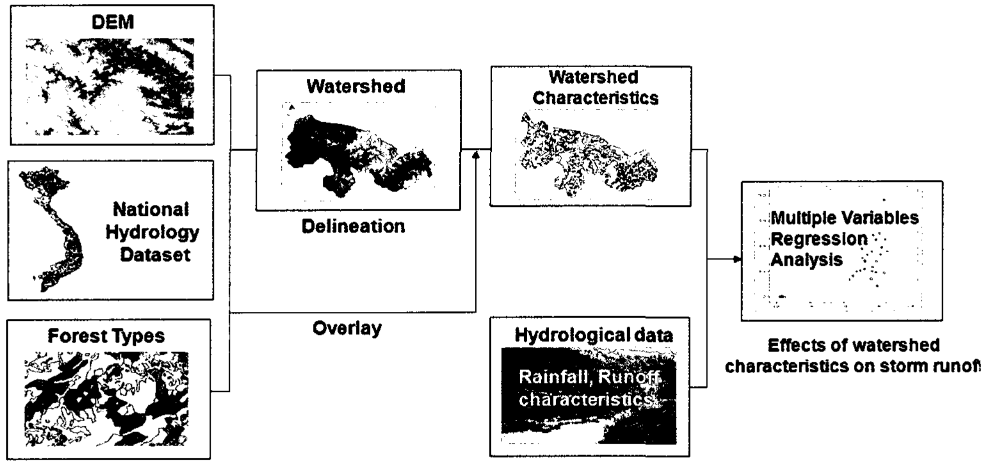


Figure 3.2. General methodology used for this study

3.2.4. Data Preparation and Analysis

▪ ***Recoded Land Cover Dataset and Calculated Forest Distribution Index***

Originally, Vietnam land cover data were divided into 20 categories/classes (FIPI, 2005). However, the study only focuses on estimating the effects of six main land cover types in 15 watersheds: rich forest; moderate forest; poor forest, young forest; plantation forest; and bare land. Other land cover types are grouped into six main land covers based on the relative similarity in their structures. For example, plantation forest is a combination of plantation forest, special forest, and gardening forest; or bare land is combination of bare land, shrub land, and grass land.

+ *Index of forest distribution (K_{CV}):* Randomly select 100 points within watershed and calculate the percentage of forest cover (K_i) (i.e., number of forested points), repeat the process n times. Forest distribution index (K_{CV}) is coefficient of variation of K_i. K_{CV} is grouped as follows: 0-10% is even distribution; 10-20% is relatively even distribution; 20-30% is uneven distribution; >30% is very uneven distribution. (Quynh et al., 2006)

+ *Integrated index of forest cover and its distribution (R_{CD}):*

$$R_{CD} = \frac{FC}{K_{CV}} \qquad (3.1)$$

Where: FC is forest cover (%); K_{CV} is forest even distribution index (%)

- ***Watershed's Factors***

+ *Shape factor:* Circularity ratio (R_{PA}) (McCuen, 2005)

$$R_{PA} = \frac{P}{(4\pi A)^{0.5}} \tag{3.2}$$

Where: P and A are perimeter (m) and area (m^2), respectively. A small number of R_{PA} (approximate 1) means a concentrated watershed shape, while a larger number of R_{PA} means an elongated watershed shape.

+ *Elevation difference (ΔE):* The elevation difference between the highest point and the lowest point within watershed.

+ *Average of elevation difference (ΔAE):* The average of elevation difference between the lowest point and all the other points within watershed.

$$\Delta AE = \frac{\sum_{i}^{n}(E_i - E_l)}{n} \tag{3.3}$$

Where E_i is the elevation of point i, E_l is the elevation of the lowest point, n is number of points (cells) within watershed.

- ***Flow's indices***

Flow indices used in this study were adapted from Hewlett et al. (1977) (Fig. 3.3.).

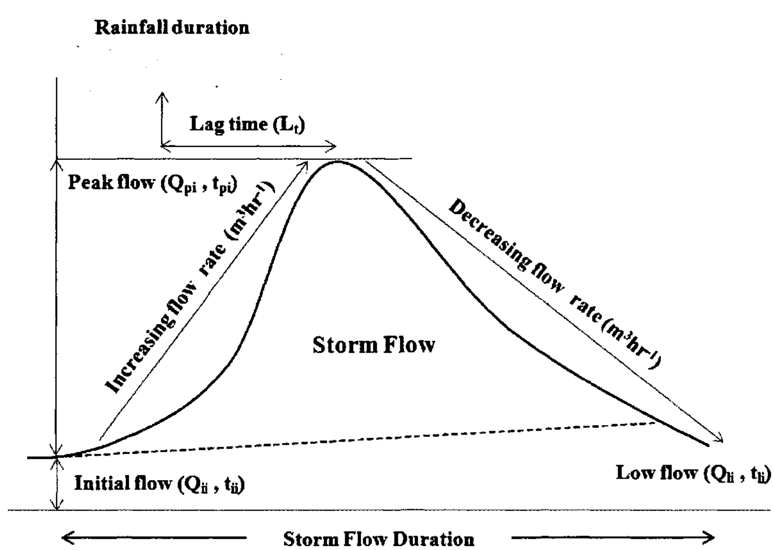


Figure 3.3. Definition diagram to show the relationship between hydrological variables

+ *Runoff coefficient of variation (Fcv)*

$$F_{CV} = \frac{s}{\mu} * 100 \tag{3.4}$$

Where, s and μ are standard deviation and mean of hourly stream flow of watersheds in 2005, respectively.

+ *Index of increasing flow (F_{in}):* increasing flow rate from initial flow to the peak flow ($m^3\ hr^{-1}$)

$$F_{in} = \frac{(Q_{pi} - Q_{ii})}{(t_{pi} - t_{ii})} \tag{3.5}$$

Where, Q_{pi} and t_{pi} are water yield and time of peak flow of rain i^{th}, respectively; Q_{ii} and t_{ii} are water yield and time when rain i^{th} starts, respectively.

+ *Index of decreasing flow (F_{de}):* decreasing flow rate from peak flow to the lowest flow ($m^3\ hr^{-1}$)

$$F_{de} = \frac{(Q_{pi} - Q_{li})}{(t_{pi} - t_{li})} \tag{3.6}$$

Where, Q_{pi} and t_{pi} are peak flow and time of rain i^{th}, respectively; Q_{li} and t_{li} are the lowest flow and time of rain i^{th} (on the same day with peak flow), respectively.

+ *Lag time (L_t):* the interval time (hours) from the center of rainfall excess to the peak flow (Bedient et al., 2002).

$$L_t = (t_{pi} - t_{li}) \tag{3.7}$$

Where, t_{pi} and t_{ri} are the time at the peak flow and at the center of rainfall of rain i^{th}, respectively.

- ***Data Analysis***

Multivariate regression techniques are available to analyze hydrological responses of the watersheds. First, linear regression is used to inspect the effect of a single watershed factor on different runoff indices. Second, multiple linear regression is used to test the statistical significance of different independent variables on a regression model. P value and standardized slope coefficient are used to compare the effects of different watershed factors on runoff indices (Ott et al., 2001).

3.3. RESULTS AND ANALYSIS

3.3.1. Watershed Characteristics

Characteristics of 15 watersheds are represented in Table 3.1. It can be noted that the watershed shapes are very diverse and irregular (Fig. 3.4). Shape index (R_{PA}) ranges from 1.13 (fairly concentrated, Lam Son) to 1.91 (irregular, Lang Son). The areas of those watersheds are also variable. They range from small (42.9 km2, Lam Son) to large (2030.2 km2, Binh Tuong). Elevation differences (ΔE), comparing the highest point to the lowest point in a watershed, vary among watersheds and range from 785m (Lam Son) to 2824 m (Ngoi Hut). Average elevation difference (ΔAE) which compares the highest point to the other points in a watershed is usually 2-4 times smaller than ΔE, ranging from 191m to 1008m.

Table 3.1. General characteristics of the 15 watersheds in this study

No.	Watersheds	Areas (km^2)	Perimeter (km)	ΔE [a] (m)	ΔAE [b] (m)	Slope (%)	FC [c] (%)	K_{CV} [d] (%)	R_{PA} [e]	R_{CD} [f] (%)
1	Lam Son	42.9	26.3	785	191	17.5	23.8	122	1.13	19.5
2	Lang Son	1847.5	290.3	1349	289	14.8	10.7	88	1.91	12.2
3	Na Hu	196.9	57.4	1832	1021	26.1	73.3	52	1.15	140.9
4	Mu C. Chai	295.7	80.1	2074	978	23.8	37.8	70	1.31	54.0
5	Ngoi Hut	664.8	141.7	2824	1008	24.5	40.7	91	1.55	44.8
6	Vinh Yen	158.7	56.2	1205	410	14.8	63.6	55	1.26	115.6
7	Binh Lieu	590.3	148.9	1389	478	20.9	17.2	140	1.73	12.3
8	Thanh Son	1497.2	227.1	1320	290	17.1	30.1	64	1.66	47.0
9	Son Diem	1002.2	143.4	1914	411	18.7	74.7	44	1.28	169.8
10	Gia Vong	347.0	91.5	1174	201	13.7	39.5	89	1.39	44.4
11	Thuong Nhat	248.6	69.2	1333	409	20.8	68.3	43	1.24	158.8
12	An Chi	954.8	175.6	1110	348	16.2	20.7	147	1.60	14.1
13	An Khe	1702.3	267.8	1531	617	9.3	45.6	67	1.83	68.0
14	Song Luy	1218.5	172.6	1750	422	13.5	80.2	53	1.39	151.3
15	Binh Tuong	2030.2	283.9	1377	597	13.2	50.6	51	1.78	99.2

The watersheds are listed from north to south.

[a] elevation difference.

[b] average elevation difference, calculated by equation (3.3).

[c] forest cover.

[d] index of forest even distribution.

[e] shape factor, calculated by equation (3.2).

[f] integrated index of forest cover and forest distribution, calculated by equation (3.1).

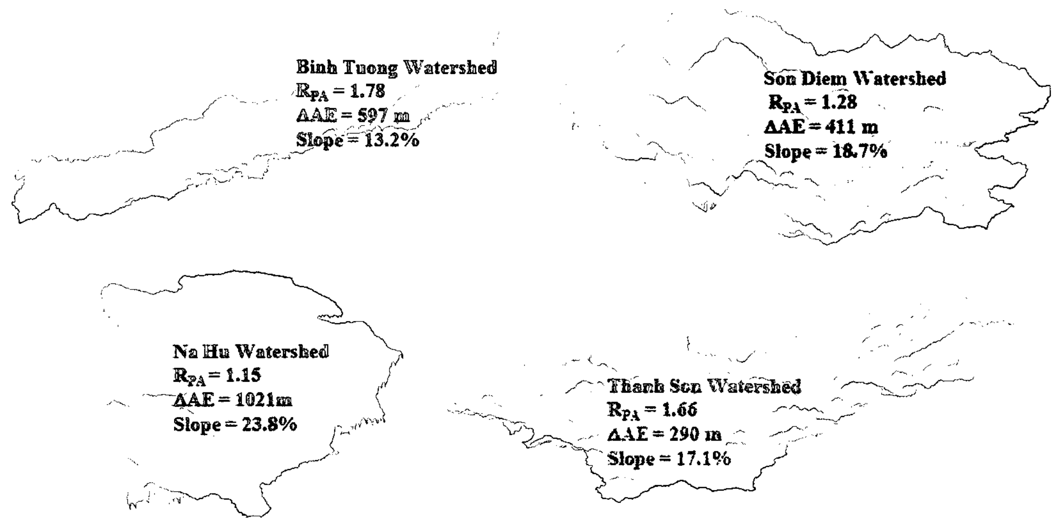
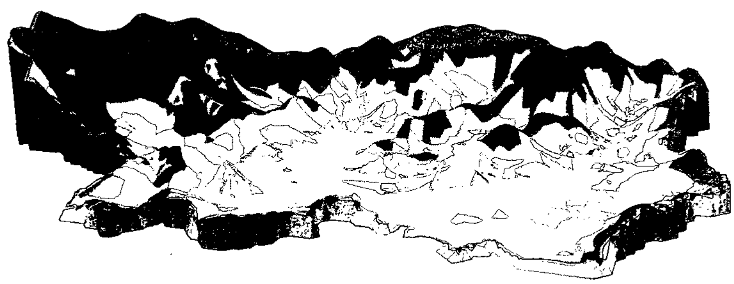


Figure 3.4. Elongated shape vs. concentrated shape of four watersheds

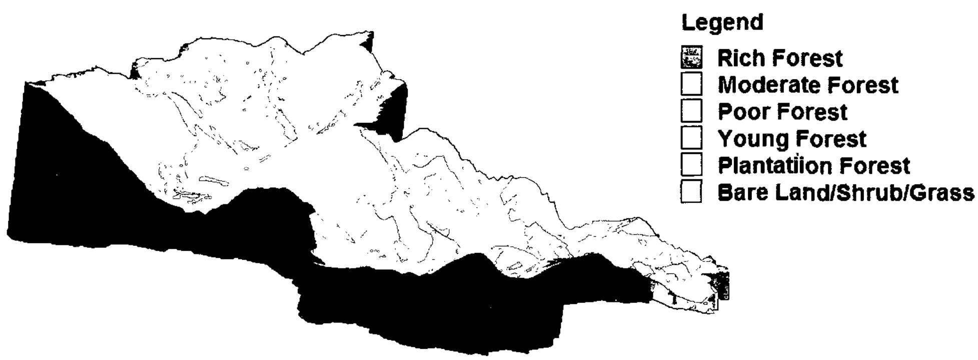
Average slope (%) in each watershed was relatively low, ranging from 9.3% (An Khe) to 26.1% (Na Hu). Generally, average slope has a positive relationship with average elevation difference ($R^2 = 0.39$).

Forest cover (%) ranges considerably from 10.7% (Lang Son) to 80.2% (Song Luy). Forest types (i.e., from high to low tree volume forests, young regeneration forest and plantation forest) are unevenly distributed among watersheds (Appendix 3.1, Fig. 3.5). Some watersheds have a large proportion of high and moderate tree volume compared to total forest areas (e.g., Son Diem, Na Hu), while some other watersheds are mainly plantation and young regeneration forest (e.g., Lam Son, Mu C. Chai). On average, forests are mostly located at an elevation from 500m to 1000m (accounting for 40%), and a slope from 15% to 25% (accounting for 36%). Natural forests (i.e., high and moderate tree volume forest, and regeneration forest) are usually distributed on slope greater than 15%, while plantation forests occur in areas where the slope is less than 8%.

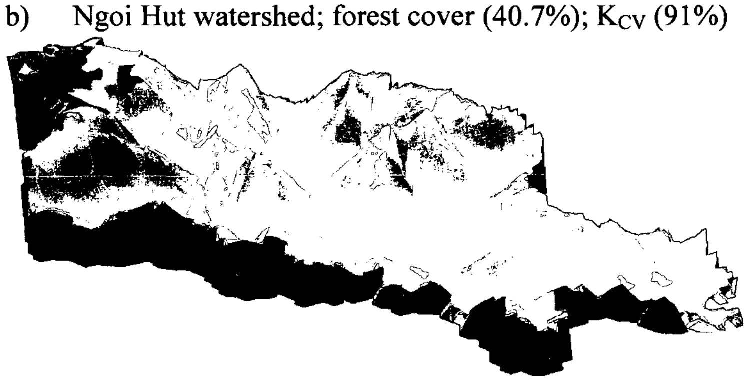
Forest distribution index (K_{CV}), representing how regularly forests are distributed within a watershed, varies dramatically among watersheds. The most aggregated distribution of forest is An Chi watershed (147%). Its distribution index is about three times larger than lowest in Thuong Nhat watershed (43%). An example of visual forest distribution and its corresponding index are demonstrated in Fig. 3.5. R_{CD} is an integrated index that combines forest cover (%) and forest distribution (%) in the watershed. A low value of R_{CD} (%) indicates that watershed has a high percentage of forest cover and even distribution, and vice versus.



a) Son Diem watershed; forest cover (74.7%); K_{CV} (44%)



b) Ngoi Hut watershed; forest cover (40.7%); K_{CV} (91%)



c) An Chi watershed; forest cover (20.7%); K_{CV} (147%)

Figure 3.5. Comparing and contrasting difference in Forest Cover (FC) and Forest Distribution Index (K_{CV}) in three watersheds

3.3.2. Runoff Characteristics

Storm runoff characteristics of 15 watersheds were calculated from 830 storm events in 2005 (Table 3.2). Numbers of storm events are relatively even among watersheds, about 50 storm events per watershed (Table 3.5). The lowest number (40 events) is in An Khe watershed located in the central highland, and the highest number (77 events) is in Mu C. Chai watershed located in northern of Vietnam.

Table 3.2. Averaging storm runoff characteristics of all storm events in 2005 of the 15 watersheds in this study

No.	Watersheds	$\sum P$ [a] (mm)	$\sum Q$ [b] (mil. m^3)	F_{in} [c] ($m^3\ hr^{-1}$)	F_{de} [d] ($m^3\ hr^{-1}$)	L_t [e] (hours)	F_{CV} [f] (%)
1	Lam Son	2136	45.76	10.53	7.68	6.10	193
2	Lang Son	1480	1181.74	9.90	5.97	7.44	205
3	Na Hu	2782	538.53	0.69	0.26	7.59	149
4	Mu C. Chai	1969	234.91	2.29	1.32	4.79	165
5	Ngoi Hut	1956	982.88	5.88	3.67	7.70	181
6	Vinh Yen	1740	211.22	7.95	1.59	6.52	103
7	Binh Lieu	2388	787.49	21.91	7.70	7.86	234
8	Thanh Son	1917	1297.38	17.83	7.99	8.46	227
9	Son Diem	2376	1360.58	13.47	7.72	11.56	196
10	Gia Vong	2669	680.68	12.46	9.28	6.24	211
11	Thuong Nhat	3457	431.07	6.61	5.44	8.12	161
12	An Chi	3494	2709.39	18.92	10.47	7.08	156
13	An Khe	1713	111.04	9.94	3.55	8.29	184
14	Song Luy	1033	337.43	2.47	3.07	7.87	157
15	Binh Tuong	2533	2778.72	16.43	7.29	7.84	176

Storm events are counted when its rainfall is greater than 5mm.
[a] total rainfall of watershed in 2005.
[b] water yield of watershed in 2005, gauged at the outlet.
[c] average index of increasing flow, calculated by equation (3.5).
[d] average index of decreasing flow, calculated by equation (3.6).
[e] average lag time, calculated by equation (3.7).
[f] coefficient of variation of stream flow, calculated by equation (3.4).

As described in section 3.2.1., the scattering distribution of watersheds and differences in climate regime in Vietnam causes a variation of total rainfall among watersheds. Average rainfall in 2005 is 2243mm, however the highest values of rainfall (An Chi, 3494mm) are about 3.4 times larger than the lowest one (Song Luy, 1033mm). Because of differences in rainfall and watershed areas, water yield also changes dramatically among watersheds, ranging from a very small number 45.76 million m^3 (Lam Son) to a very large number 2778.73 million m^3 (Binh Tuong).

As shown in Table 3.2, index of increasing flow rate (F_{in}) varies considerably among watersheds, ranging from a small value of 0.69 m^3hr^{-1} (Na Hu) to a large value of 21.91 m^3hr^{-1} (Binh Lieu). Average increasing flow rate of 15 watersheds is 10.49 m^3hr^{-1} with coefficient of variation is 61%, the most variable index in comparison with that of other runoff indices (i.e., F_{de}, L_t, F_{CV}). The second highest fluctuation of runoff indices is index of decreasing flow rate (F_{de}), its mean and coefficient of variation are 5.53 m^3hr^{-1} and 56%, respectively. The highest decreasing flow rate is in An Chi watershed (10.45 m^3hr^{-1}), and the lowest ones is in Na Hu watershed (0.26 m^3hr^{-1}). It is interesting to note that both the lowest increasing and decreasing flow rate appear in the same watershed (Na Hu). In general, when comparing the two flow rate indices among 15 watersheds, there appears to be a similar trend of 'high –high or low-low' of increasing and decreasing. The F_{in} is directly related to F_{de} in a regression equation with R^2=0.71.

Lag time (L_t), the interval time from center of rainfall excess to peak flow, has the lowest variation among watersheds when compared to those of F_{in} and F_{de}. The average L_t of 15 watersheds is 7.56 hrs with coefficient of variation is 19.6%. The highest and the lowest L_t appear in Son Diem (15.56 hrs) and Mu C. Chai (4.79 hrs).

Runoff coefficient of variation (F_{CV}) of a given watershed was calculated from the mean and the standard deviation of stream flow data recorded hourly in 2005. F_{CV} slightly varies among watersheds, the average runoff variation of 15 watersheds is 179%, the lowest variation is in Vinh Yen (103%) and the highest one is in Binh Lieu (234%).

3.3.3. Effects of Watershed's Factors on Runoff Characteristics

3.3.3.1. Effects of Forest Cover

Forest cover (FC) is significantly related to runoff coefficient of variation (Fcv) and index of increasing flow rate (F_{in}) at level 0.05 (Fig. 3.6a, 3.6b), and with index of decreasing flow rate (F_{de}) at level 0.1 (Fig. 3.6d). On average, about 30% of the total variation of Fcv or F_{in} is associated with forest cover ($R^2 \approx 0.3$), that of F_{de} is 25%. Forest cover is inversely related to F_{cv}, F_{in}, and F_{de}, respectively, meaning that when watershed forest cover increases, these runoff's indices decrease (i.e., reducing annual variation of stream flow, and a lower value of both increasing and decreasing flow rate). Although, it is not statistically significant with lag time (L_t), P value=0.164 (Fig. 3.6c), generally forest cover is directly proportional to L_t. This indicates that it takes a longer of time to attain peak flow if forest cover of watershed increases.

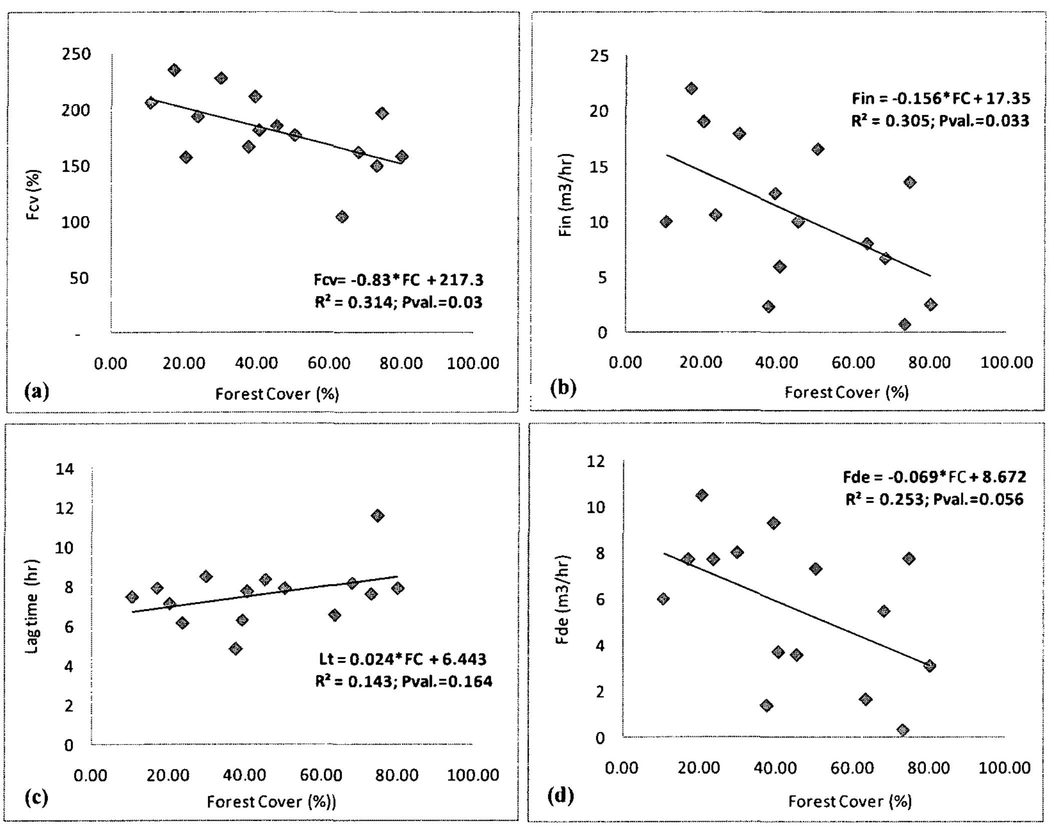


Figure 3. 6. Bivariate plots of forest cover (%) and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.2. Effects of Forest Distribution

As mentioned in section 3.3.1, a large value of forest distribution index (K_{CV}) indicates that forests are unevenly distributed within watershed. As a consequence, runoff coefficient of variation (F_{cv}), index of increasing flow rate (F_{in}), and index of decreasing flow rate (F_{de}) are directly related to forest distribution index, indicating that an aggregated distribution of forest within the watershed will cause a high rate of increasing or decreasing flow, and high fluctuation of interannual stream flow at the outlet of watershed. Two indices of flow rate (i.e., F_{in}, F_{de}) are significant related to forest distribution index at level 0.05 (Fig. 3.7b, 3.7d). This index explains for about 27% of total variation of increasing or decreasing flow rate ($R^2 \approx 0.27$). Forest distribution index is inversely proportional to lag time (L_t), it is not statistically in relation to both L_t and F_{CV} ($P>0.1$; Fig. 3.7a, 3.7c).

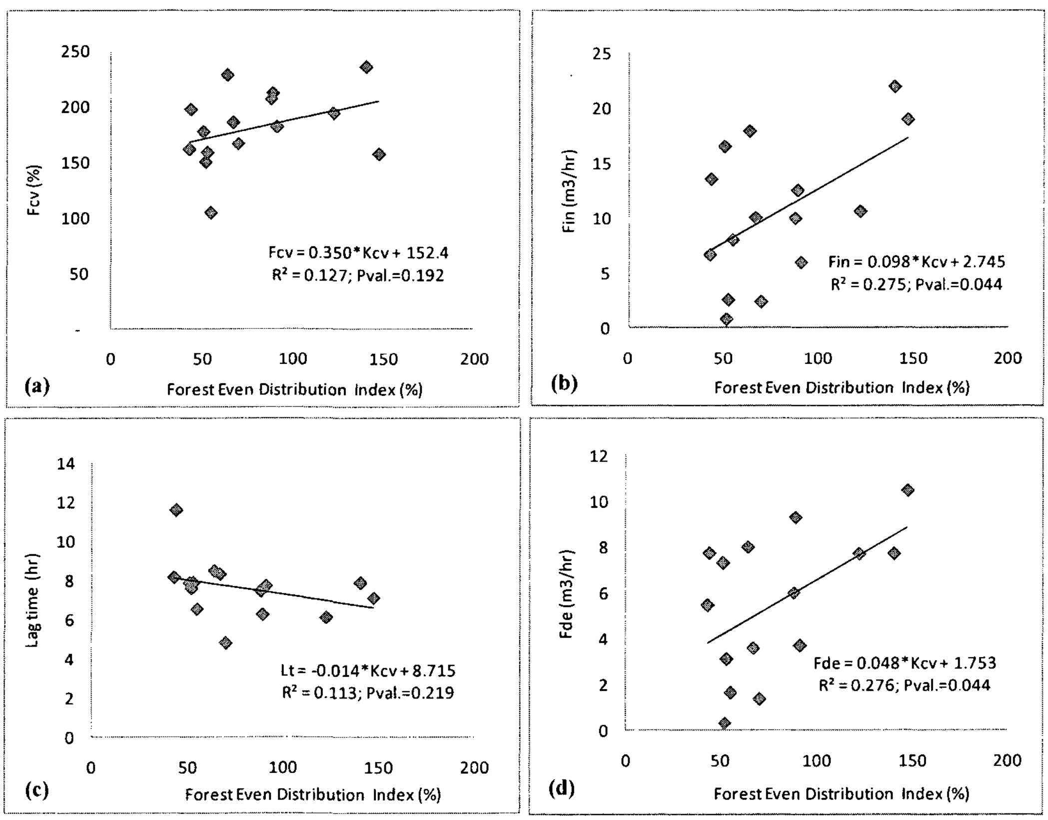


Figure 3. 7. Bivariate plots of index of forest even distribution (%) and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.3. Effects of Watershed Sizes

As shown in Fig. 3.8, watershed size (Ws) is not significantly related to any runoff's indices (i.e., F_{CV}, F_{in}, L_t, F_{de}) at level 0.1. R^2 of these linear equations are all less than 0.2. The most significant equation is the relationship of watershed size to lag time (Fig. 3.8c, P=0.127). When dependent variable (watershed size) increases, the interval time from center of rainfall to peak flow (lag time) will last longer. Although these relationships are not statistically significant, general trends of the effect of watershed size on runoff coefficient of variation and flow rate indices are also directly proportional (Fig. 3.8a, 3.8b, 3.8d). It probably suggests that a larger watershed size will cause a higher variation of stream flow (F_{CV}) and a faster rate of increasing or decreasing flow rate.

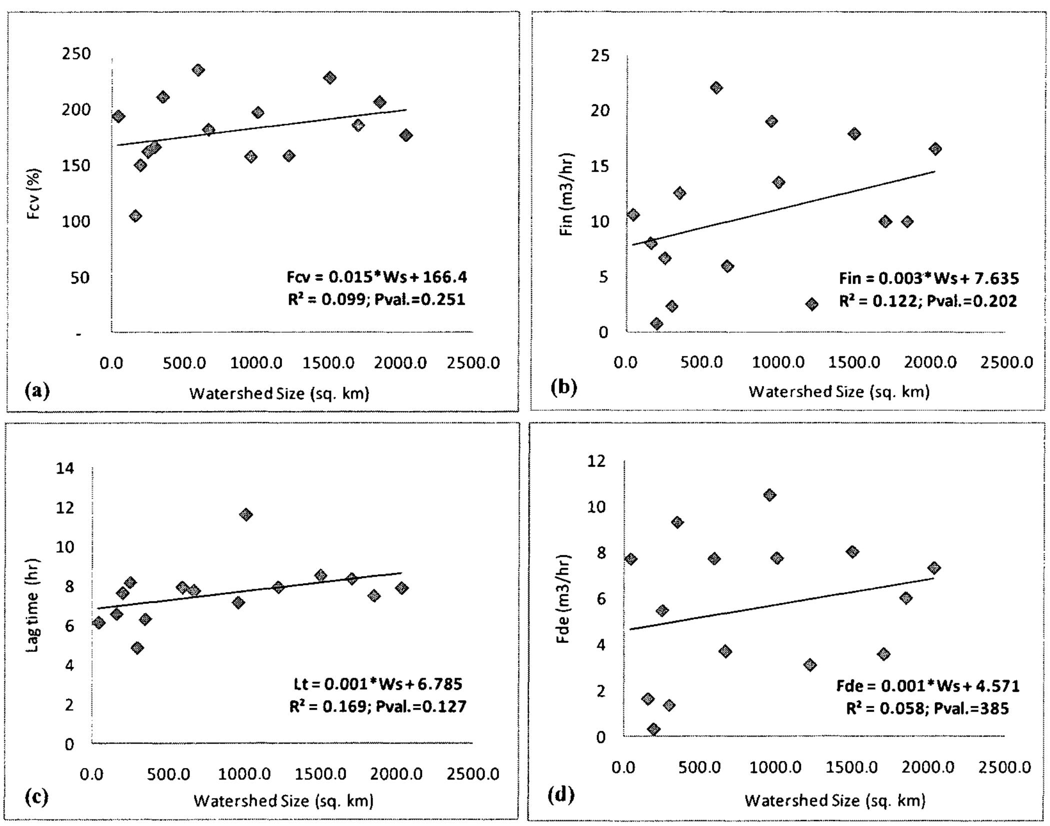


Figure 3. 8. Bivariate plots of watershed size (km^2) and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.4. Effects of Watershed Shapes

As shown in Fig. 3.4, a large value of shape index means an irregular shape of watershed. Shape index (Ws) is significantly related to the index of increasing flow rate at level 0.05 and to flow coefficient of variation (F_{CV}) at level 0.1 (Fig. 3.9a, 3.9b). Shape index accounts for about 21% of total interannual stream flow variation (F_{CV}) and 27% of total rate of increasing flow (F_{in}). The direct relationships of shape index to F_{CV} and F_{in} indicate that the more irregular shape of a watershed, the higher variation of stream flow and rate of increasing flow. Shape index is not significantly related tolag time (L_t) and index of decreasing flow (F_{de}) (P>0.2, Fig. 3.9c, 3.9d). However, their scatter plots simply show that these are positive relationships similar to those of flow coefficient of variation and index of increasing flow rate.

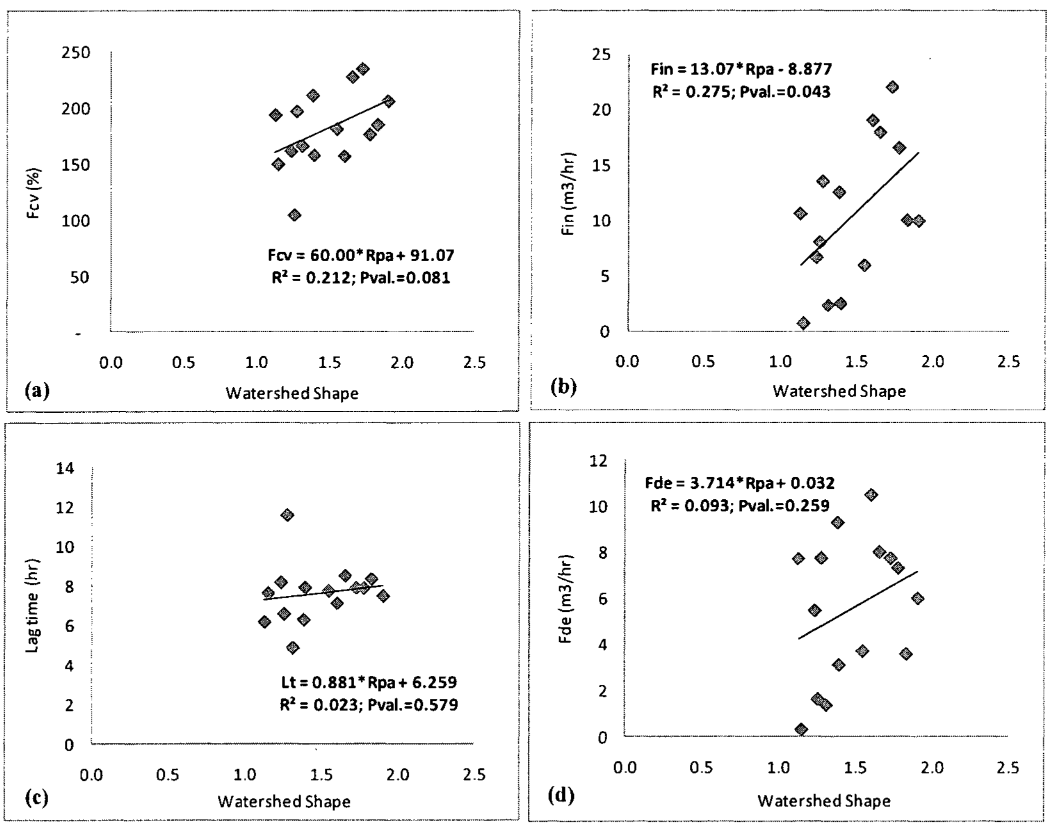


Figure 3. 9. Bivariate plots of watershed shape and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.5. Effects of Watershed Slope

Average watershed slope (S) is the variable having the least effects on runoff indices compared to those of other watershed factors. All regression equations are not statistically significant at level 0.2 (Fig. 3.10). The bivariate plots (Fig. 3.10a, 3.10c) show that there is no relationship between watershed slope and flow coefficient variation (F_{CV}) or lag time (L_t). Fitted lines on these scatter plots are almost parallel with the X- axis (R^2<0.01; P>0.7). However, watershed slope shows a trend in relation to both flow rate indices (F_{in}, F_{de}). Their two regression equations are significant at level 0.25. Watershed slope accounts for about 10% of total variation in both flow rate indices ($R^2 \approx 0.1$). If average slope of watershed increases, both flow rate indices decreases. This controversial result will be discussed in section 3.4.

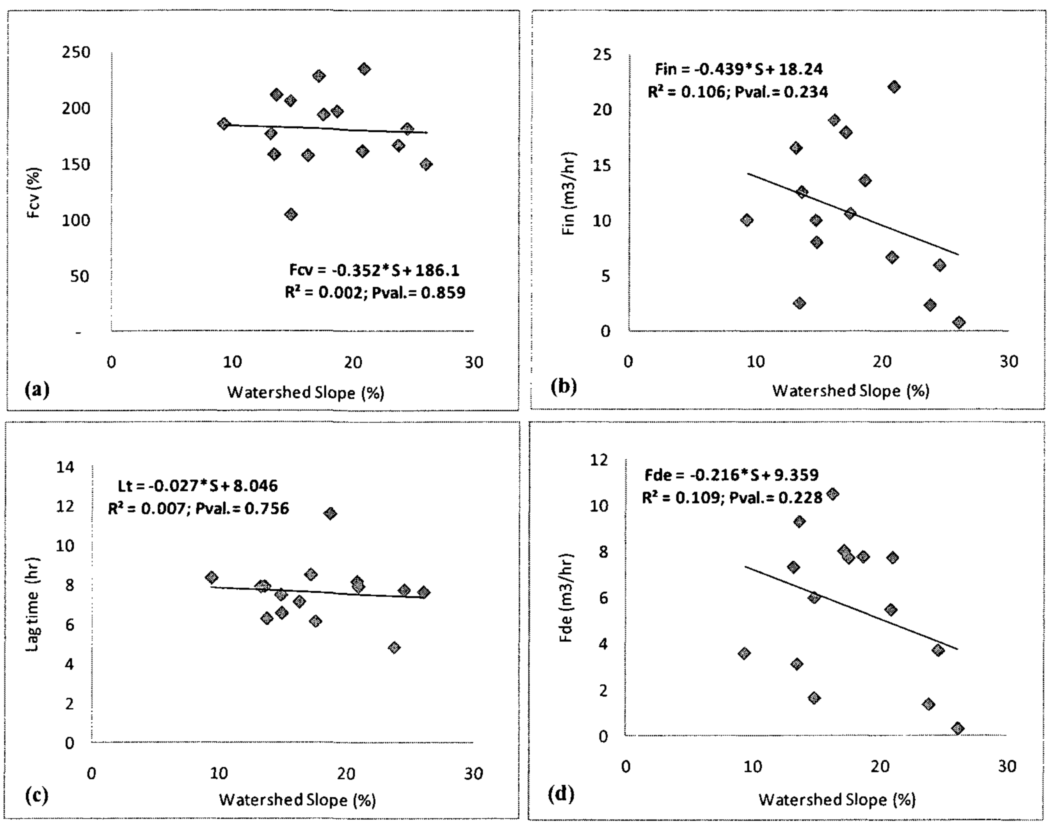


Figure 3. 10. Bivariate plots of watershed slope (%) and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.6. Effects of Watershed Elevation Differences

Average elevation difference (ΔAE) is highly statistically significant at level 0.05 in regression equations with increasing and decreasing flow rate (F_{in}, F_{de}). On average, about 28% of total variation of increasing flow rate (R^2=0.285) and 50% of total variation of decreasing flow rate (R^2=0.49) are associated with average elevation difference (Fig. 3.11b, 3.11d). The inverse relationships among these variable suggest that if average elevation difference increases, the flow rate indices decreases which is also a controversial result (section 3.4). Flow coefficient of variation (F_{CV}) is not statistically significant related to average elevation difference at level 0.2. However, the scatter plot (Fig. 3.11a) shows an indirect trend similar to those of flow rate indices. A very small value of R^2 (0.015) and high value of P value (0.63) show a no relationship between lag time and average elevation difference (Fig. 3.11c).

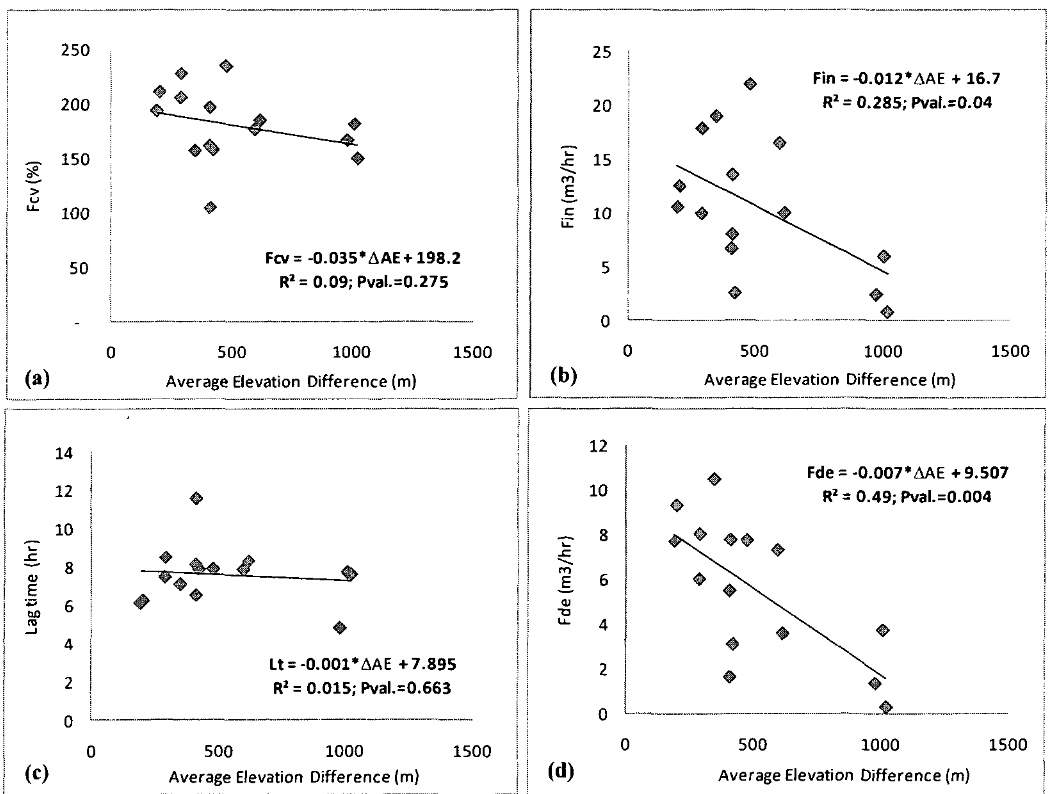


Figure 3. 11. Bivariate plots of average of elevation differences (m) and storm runoff characteristics in 15 watersheds in Vietnam, relation to (a) runoff coefficient of variation (%), (b) index of increasing flow rate (m^3hr^{-1}), (c) Lag time (hrs), (d) index of decreasing flow rate (m^3hr^{-1}).

3.3.3.7. Multivariate Analysis Effects of Watershed's Factors on Runoff

Multiple linear regressions are applied to inspect the effects of watershed's factors on storm runoff indices. Eight independent variables (i.e., area, shape, slope, elevation difference, forest cover, forest even distribution, integrated index of forest) in relation to storm runoff are analyzed. The best fit of the models are based on a "stepwise" model selection in which only independent variables statistically significant effect on response variables ($P<0.05$) are kept in the models (Table 3.3).

Table 3.3. The presence of significant slope coefficients of watershed's factors in regression equations with storm runoff characteristics ($P<0.05$)

Equations		R^2	Adj. R^2	P val.
$F_{in} = -1.52 + 11.94{*}R_{PA} - 0.011{*}\Delta AE$	(3.8)	0.51	0.43	0.013
$F_{de} = 11.13 - 0.07{*}\Delta AE - 0.047{*}FC$	(3.9)	0.60	0.53	0.004
$L_t = 1.85 + 2.86{*}R_{PA} + 2.01{*}R_{CD}$	(3.10)	0.49	0.41	0.017
$F_{CV} = 241 - 2.57{*}FC + 74.99{*}R_{CD}$	(3.11)	0.53	0.46	0.010

<u>Dependent variables</u>: F_{in}- index of increasing flow rate ($m^3\ hr^{-1}$); F_{de} - index of decreasing flow rate ($m^3\ hr^{-1}$); L_t - lag time from the center mass of rainfall to the peak flow (hours); **Predictors:* F_{CV} - runoff coefficient of variation (%); R_{LW} - shape index; FC - forest cover (%); R_{CD} - integrated index of forest cover and forest distribution; ΔAE - average of elevation differences (m).

Only 4 out of 8 independent variables used for a model selection process are found to be statistically significant in four models (Table 3.3). They are watershed shape (R_{PA}), average elevation difference (ΔAE), forest cover (FC), and integrated index of forest cover and forest distribution (R_{CD}). Each of the models has only two significant variables. All regression models are significant at level 0.05 (F test).

In equation (3.8), shape index (R_{PA}) and average elevation difference (ΔAE) significantly affect index of increasing flow rate (F_{in}). As analyzed in above, R_{PA} is in direct relationship to F_{in}, while ΔAE is in indirect. These two factors represent 51% of the total variation in increasing flow rate (R^2=0.51). Their standardized coefficients are approximately equal (β_{Rpa}=0.481; $\beta_{\Delta AE}$=-0.487, Appendix 3.2) indicating that the magnitude effect of R_{PA} and ΔAE on F_{in} are similar.

Forest cover (FC) and ΔAE are statistically significant in equation 3.9. Two factors have an inverse relationship with the index of decreasing flow rate (F_{de}). They explain for 60% of the total variation in F_{de} (R^2=0.60). The standardized coefficient of ΔAE ($\beta_{\Delta AE}$=-0.61) is higher than that of FC (β_{FC}=-0.34), indicating that ΔAE is a more important predictor than FC for prediction F_{de} in the model 8 (Appendix 3.2).

In equation 3.10, two significant variables are shape index (R_{PA}) and integrated index of forest cover and forest distribution (R_{CD}). On average, about 49% of the total variation in lag time (L_t) is associated with R_{PA} and R_{CD} (R^2=0.49). Both predictors are positive in relation to lag time. The standardized coefficient of R_{PA} (β_{Rpa}=0.49) is about 1.5 times higher than that of R_{CD} (β_{Rcd}=0.76), this means that R_{PA} is less important predictor than R_{CD} (Appendix 3.2).

Stream flow coefficient of variation (F_{CV}) has an indirect relation to FC and direct relation to R_{CD} (equation 3.11). The two independent variables are associated with 53% of the total variation in F_{CV} (R^2=0.53). The absolute standardized coefficients of FC (β_{FC}=-1.73) is higher than that of R_{CD} (β_{Rcd}=1.26). This indicates that forest cover has stronger effect on flow coefficient of variation in comparison with that of integrated index of forest cover and forest distribution (Appendix 3.2).

Other independent variables, such as watershed size, slope, elevation differences, and forest distribution index, are found to be no significance in 4 models (Table 3.3). They were removed in the 'stepwise' model selection process. This result can be explained by two reasons. These variables have no relationship (or have a weak relationship) to runoff indices. There are multi-collinearities among independent variables (Table 3.4), where any two variables that have correlation coefficient (r) less than 0.8 may suggest a problem of collinearity (Vaske, 2007).

Table 3.4. Coefficient Correlations among Independent Variables

	R_{CD}	Ws	ΔEA	Slope	ΔE	K_{CV}	R_{PA}	FC
R_{CD}	1.00							
Ws	**-0.59**	1.00						
ΔEA	0.40	-0.10	1.00					
Slope	**-0.71**	**0.53**	**-0.53**	1.00				
ΔE	0.27	-0.25	-0.35	-0.44	1.00			
K_{CV}	0.00	0.32	0.10	0.05	-0.06	1.00		
R_{PA}	0.11	**-0.69**	-0.20	0.12	-0.12	-0.16	1.00	
FC	**-0.88**	0.48	-0.42	**0.76**	-0.37	0.28	0.15	1.00

3.3.4. Effects of Rainfall on Peak flow

The model (equation 3.12), developed by Hewlett at al. (1984), is applied to test the effects of rainfall on peak flow rate (Q_p) for 15 watersheds in Vietnam. The basic data set used to test the model included a total 830 storm events in excess of 5mm in 2005 of 15 watersheds, 249 storms in dried season and 581 storms in rainy season in which rainfall and runoff are recorded hourly.

$$Q_p = e^{(a_1+a_2S)} P^{(b_1+b_2S)} I^{(b_3+b_4S)} P_t^{(b_5+b_6S)} e^{\varepsilon} \qquad (3.12)$$

Where

Q_p peak flow ($m^3\ s^{-1}$);
e base of natural log;
a_1, a_2 regression intercept and differential intercept due to season, respectively;
S dummy variable for season (1 for rainy season from May to October, 0 for dried season from November to April);
P gross storm rainfall (mm);
I initial flow rate ($m^3\ s^{-1}$);
P_t rainfall intensity ($mm\ hr^{-1}$);
$b_1 \div b_2$ average and differential response for season of Q_p to P, respectively;
$b_3 \div b_4$ average and differential response for season of Q_p to I, respectively;
$b_5 \div b_6$ average and differential response for season of Q_p to P_t, respectively;
ε random error term.

The model was linearlized by taking logs to base e of the equation. The F statistics test was used to test the main effects (i.e., rainfall, initial flow rate, and rainfall intensity) and their interaction with season (S) on peak flow rate. The statistically significant levels (P values) of these effects are listed in Table 3.5.

Table 3.5. Analysis of Peak flow (ln Q_p) by watersheds, showing P values of three independent variables in Equation (3.12) and their interactions with season (S)

No.	Watersheds		Independence variables in regression					
			ln(P)	ln(P_t)	ln(I)	S*ln(P)	S*ln(P_t)	S*ln(I)
1	Lam Son	45 events	<.001*	0.93	<.001*	0.90	0.48	0.84
2	Lang Son	45 events	0.31	0.15	<.001*	0.86	0.88	0.30
3	Na Hu	68 events	<.001*	0.42	<.001*	0.60	0.43	0.77
4	Mu C. Chai	77 events	<.001*	0.25	<.001*	0.02*	0.60	<.001*
5	Ngoi Hut	60 events	0.39	0.08	<.001*	0.05*	0.01*	0.26
6	Vinh Yen	60 events	0.04*	0.49	<.001*	0.47	0.09	0.02*
7	Binh Lieu	45 events	0.45	0.10	<.001*	0.53	0.28	0.02*
8	Thanh Son	53 events	0.02*	0.34	<.001*	0.24	0.59	0.87
9	Son Diem	48 events	0.33	0.36	<.001*	0.40	0.54	0.78
10	Gia Vong	57 events	<.001*	0.77	<.001*	0.68	0.66	0.42
11	Thuong Nhat	74 events	0.02*	0.44	<.001*	0.86	0.47	0.70
12	An Chi	55 events	0.01*	0.68	<.001*	0.08	0.58	0.31
13	An Khe	40 events	0.04*	0.14	<.001*	0.14	0.24	0.11
14	Song Luy	39 events	0.39	0.90	<.001*	0.49	0.79	0.55
15	Binh Tuong	49 events	0.23	0.26	<.001*	0.72	0.72	0.65

P values of F test with the hypothesis that regression coefficient (b_i) is equal 0
* Significantly different from 0 of main effects or their interactions by season at the 0.05 level

Rainfall contributes significantly in 9 out of 15 watersheds at the 0.05 level. Initial flow affects peak flow significantly, 15 watersheds have P values less than 0.001, whereas none of the watersheds are significantly affected by rainfall intensity. Season has a negligible effect on peak flow. Coefficients for differential effects of P, I, and P_t by season are not significantly different from 0 at 0.05 level in most of watersheds. However, three watersheds have significant interaction with initial flow (e.g., Mu C. Chai, Vinh Yen, and Binh Lieu); two watersheds have significant interaction with rainfall (e.g., Mu C. Chai and Ngoi Hut); and one has significant interaction with rainfall intensity (e.g., Ngoi Hut).

Due to low effect (not significant) of season and intensity on peak flow in the full model (equation 3.12), we tested a reduced model omitting intensity (ln P_t) and interactions between season and rainfall (ln S*P), initial flow (ln S*I), and intensity (ln $S*P_t$) from the full model. F test was calculated to test the null hypothesis that the full model is significantly different from reduced models (Ott et al., 2001).

Table 3.6. Analysis of peak flow (ln Q_p) by watersheds, showing coefficient of determination (R^2) and P values of full and reduced models in equation (3.12)

No.	Watersheds	Full model		Reduced model		ΔR^2	F Cal.	Standard
		R^2	P val.	R^2	P val.	Full-Reduced		Error
1	Lam Son	0.84	<.0001	0.83	<.0001	0.01	0.17 *	0.68
2	Lang Son	0.77	<.0001	0.71	<.0001	0.06	1.67 *	0.84
3	Na Hu	0.95	<.0001	0.95	<.0001	0.002	0.47 *	0.14
4	Mu C. Chai	0.83	<.0001	0.71	<.0001	0.12	9.73	0.71
5	Ngoi Hut	0.77	<.0001	0.71	<.0001	0.06	2.63	0.74
6	Vinh Yen	0.74	<.0001	0.65	<.0001	0.09	3.19	0.61
7	Binh Lieu	0.86	<.0001	0.83	<.0001	0.03	1.86 *	0.79
8	Thanh Son	0.83	<.0001	0.82	<.0001	0.01	0.51 *	0.63
9	Son Diem	0.87	<.0001	0.86	<.0001	0.01	0.32 *	0.52
10	Gia Vong	0.88	<.0001	0.87	<.0001	0.01	0.51 *	0.75
11	Thuong Nhat	0.78	<.0001	0.76	<.0001	0.02	1.31 *	0.72
12	An Chi	0.90	<.0001	0.89	<.0001	0.01	1.15 *	0.75
13	An Khe	0.88	<.0001	0.86	<.0001	0.02	1.05 *	0.52
14	Song Luy	0.81	<.0001	0.80	<.0001	0.01	0.57 *	0.66
15	Binh Tuong	0.87	<.0001	0.86	<.0001	0.01	0.67 *	0.81

The full model in equation (3.12), the reduced model omits ln(S), ln(P_t), ln(S*P), ln($S*P_t$), ln(S*I). Calculated F test a2=b2=b4=b5=b6=0 at the 0.05 level. Standard error of reduced model is in m^3hr^{-1}.
* Full and reduced models are not significantly different at 0.05 level.

Both full and reduced models are significant at 0.001 level in all 15 watersheds. Omitting intensity variable and season interaction with main effects in the full model decreases R^2 from 0.002 to 0.12 in reduced model in these 15 watersheds (i.e., reducing variation of ln Q_p explained by omitting variables). On average, about 3.1% of the total variation in peak flow is associated with intensity and season interaction with rainfall, initial flow, and intensity. Based on F calculated, the full and reduced models are not significantly different in 12 out of 15 watersheds.

3.4. DISCUSSION

Forest hydrological research has shown that forestation is capable of decreasing water yield, baseflow, but have limited effects on peakflow rates and flooding events (Bruijnzeel, 2004; Adreassian, 2004; Sun, 2006). In this study, the similar trend in relation of forest cover and peakflow rates (Fig. 3.6) may not match with the conclusions above, because of differences in response variables (i.e., runoff indices) used for the analysis. Instead of using absolute values of peakflow rate as other previous studies, we calculated increasing rate from initial flow to peak flow (F_{in}), and decreasing rate from peak flow to low flow (F_{de}) of any rainfall event. Under the effects of forest, direct rainfall is redistributed into different components such as canopy interception, throughfall, stemflow, etc. (Lee, 1980; Dien, 2006). The decrease in total basal area resulted in an increase in total streamflow and direct runoff (Bent, 2001). This may explain for the conclusion (Fig. 3.6) that forest cover is inversely relation to increasing or decreasing flow rate, streamflow variation (F_{CV}), and delay time to peak flow (L_t).

Little literature exists about the relationship between forest distribution and runoff responses. Fig. 3.7 shows that the more evenly distributed a forest within a watershed (i.e., low K_{CV}), the less rate of increasing or decreasing flow, and streamflow variation. Although, the study did not apply a paired watershed experiment for comparison or run a stimulated model with different forest distribution scenarios. It is probably presumed that for a given percentage of forest cover of a watershed, scattering forest distribution better intercepts rainfall, direct runoff than aggregated forest distribution does. Consequently, it takes a longer time to excess peak flow (L_t), reduces flow rate to peak (F_{in}) and base flow ((F_{de}) as well.

Based on results of literature research and review, there are relatively few scientific papers directly addressing the relationship between hydrological characteristics and catchment size in which catchment size was treated as independent variables in regression analysis. There is a large body of knowledge that addresses the significant effect of catchment size on hydrological variables. However, there are many studies of poor or non existent relations among these variables (Pilgrim, 1982). In this study, due to variation of other uncontrollable variables (i.e., forest, slope), watershed size is not statistically significance at level of 0.05. However, the study shows that watershed size is directly relation to runoff indices (Fig. 3.8). These results are supported by previous studies (Minikou, 1984; Lajoie, 2007). The maximum floodflow and lag time are highly correlated with basin size in a power function (Mimikou, 1984). Drainage area is highly correlated with mean monthly discharge (m^3s^{-1}), and it does not show obvious trends in relation to coefficient of variation of monthly maximum and minimum flow (Lajoie, 2007). Watershed shape is found to be significantly related to stream flow variation and indices of flow rate (Fig. 3.9). Irregular shapes create a higher value of daily flow variation (F_{CV}), of increasing rate to peak low (F_{in}), and of decreasing to low flow (F_{de}) than regular shapes do (e.g., concentrated vs. elongated). These results match with previous studies (Tabios et al., 1988; Goff et al., 2006). These can be generally assumed that for a similar storm event, the variation in geophysical and morphological conditions among watersheds will cause differences in 'commutative effects' on runoff (e.g., runoff volume, storm velocity).

Effect of watershed slope on runoff is a controversial issue (Fang et al., 2008) dependent upon the kind of slope indices used. In this study, average watershed slope does not have a significant effect on any runoff indices (Fig. 3.10). This suggests that this may be not a good topological index representative for watershed in relation to runoff responses. Previous studies have given some other indices better representative for average slope, such as density (km km^{-2}), length, and slope of stream (Gray, 1961, Singh, 1997, Dutta et al., 2001). Another alternative found in this study is average elevation difference (ΔAE). It is significant in relation to two flow rate indices (Fig. 3.11), and correlates with average slope (Table 3.4). Slope and elevation differences are directly related to increasing or decreasing storm speed. Inverse relations (Fig. 3.10, 11) in this study are may also be controversial. As mentioned before, the study did not apply 'paired watershed' experiment to inspect the relationship (control vs. treatment). The results possibly caused by impacts of other variables and their interaction (e.g., watershed size, forest).

In term of rainfall – runoff relationship, as reviewed by Singh (1997) rainfall intensity greatly influences overland flow and its time of occurrence. The response of peak discharge to rainfall volume, initial flow and duration of storm varies from summer to winter (Hewlett, 1977). However, in this study these two variables (i.e., season, intensity) are not significantly related to peak flow. This can be explained by two broad causes: First, rainfall is less seasonal in 2005, average rainfall per storm event in dry and rainy seasons are 21mm and 36mm, respectively. Second, due to lack of gauging rainfall in Vietnam, the study used average rainfall intensity rather than maximum intensity of rainfall in an interval of time as in previous studies (e.g., 0.5 hour, 1 hour), it may be not a good predictor of peak discharge. Therefore, reduced models removing rainfall intensity and season are not statistically different from the full model at $p<0.05$.

3.5. CONCLUSIONS

In this chapter, 8 watershed's factors (*watershed areas, shape index, elevation difference, average elevation difference, average slope, forest cover, forest distribution index, integrated index of forest cover and forest distribution*) of 15 watersheds in Vietnam were analyzed in relation to storm runoff characteristics (*flow coefficient of variation, index of increasing flow rate, index of decreasing flow rate, lag time*). The study also applies an exponential model (Hewlett et al., 1984) to investigate the effects of rainfall, intensity, and initial flow on peak flow by season for all 15 watersheds.

It has been demonstrated that watershed factors affect runoff characteristics at the different level of significant. Forest cover is inversely significant effect with index of increasing and decreasing flow rate at 0.05 level, and flow coefficient of variation at 0.1 level. Forest cover is associated with about 30% of the total variation in response variables. Forest even distribution is positively significant in relation to both index of increasing and decreasing flow rate at 0.05 level. It explains for about 27% of the total variation in flow rate indices.

Watershed size is found to have no significance to any runoff indices at 0.1 level. Generally, watershed size shows a direct relation to runoff responding variables. Watershed shape is positively significant relation to index of increasing flow rate at 0.05 level and flow coefficient of variation at 0.1 level. This index accounts for about 27% of total variation in increasing flow rate, and 21% of total variation in annual flow variation, respectively. Average slope of watershed is not related to any response variables at 0.1 level of significance. This reveals only a slight indirect relation to the index of increasing and deceasing flow rate. Average elevation difference within a watershed is inversely significant with increasing and decreasing flow rate. It explains about 28% of the total variation in increasing flow rate, and about 49% of the total variation in decreasing flow rate, respectively. There are no watershed factors found to have a significant effect with lag time at level of 0.05.

For the 'stepwise' multiple regressions between watershed factors and runoff indices shows that there are only 4 out of 8 independent variables presented in four regression equations. Each of selected models has 2 independent variables significant at level of 0.05. These watershed variables are associated with about 50% - 60% of the total variation in runoff indices.

The exponential full models relationship between rainfall, intensity, and initial flow and peak flow by season are significant in all 15 watersheds ($P < 0.001$). However, none of the watersheds has significant effect of intensity and very few watersheds (2-3) found to have significant effect of season (interaction). Reduced models, removing intensity and season interaction from the full model, are not significantly different from full model in 12 out of 15 watersheds.

LITERATURE CITED

Andreassian, V., 2004. Waters and forests: from historical and controversy to scientific debate. Journal of Hydrology, 291, 1-27.

Baxla, A.K., Kumar, R., and Wadood, A., 2001. Infiltration Characteristics of Soils Under Different Soil Series of Jumar Nala Sub-watershed. Annals of Arid Zone, 40 (1), 29-33.

Bedient, B.P., and Huber, C.W., 2002. Hydrology and Floodplain Analysis, Third Edition, Prentice Hall, pp. 98-99.

Bent, G.C., 2001. Effects of forest-management activities on runoff components and ground-water recharge to Quabbin Reservoir, central Massachusetts. Forest Ecology and Management, 143 (1-3), 115-129.

Bruijnzeel, L.A., 2004. Hydrological function of tropical forests: not seeing the soil for the trees?. Journal of Agriculture, Ecosystems and Environment, 104, 185-228.

Dien, P.V., 2006. Water retention capability of some vegetation types in protection areas of Hoa Binh hydropower plant. Ph.D Dissertation, Forestry University, Vietnam.

Fang, H.Y., Cai, Q.G., Chen, H., and Li, Q.Y., 2008. Effect of Rainfall Regime and Slope on Runoff in a Gullied Loess Region on the Loess Plateau in China. Environmental Management, 42, 402-411.

Forest Inventory and Planning Institute (FIPI), Vietnam. http://fipivn.org.vn/

Goff, K. M., and Gentry, R. W., 2006. The Influence of Watershed and Development Characteristics on the Cumulative Impacts of Stormwater Detention Ponds. Water Resources Management, 20, 829-860.

Gray, D.M., 1961. Interrelationships of Watershed Characteristics. Journal of Geophysical Research, 66 (4), 1215-1223.

Guillemette, F., Plamondon, A.P., Prévost, M., Lévesque, D., 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. Journal of Hydrology, 302, 137-153.

Hai, V.D., 1996. Research on structural types of forest for rational watershed protection in Vietnam . Ph.D Thesis. Forest Science Institute of Vietnam , Hanoi , Vietnam.

Hewlett, J. D., J. C. Fortson, and G. B. Cunningham, 1977. The effect of rainfall intensity on storm flow and peak discharge from forest land, Water Resource Research, 13(2), 259-266.

Hewlett, J. D., J. C. Fortson, and G. B. Cunningham, 1984. Additional test on the effect of rainfall intensity on storm flow and peak flow from wild-land basins, Water Resource Research, 20 (7), pp. 985-989.

Lajoie, F., Assani, A.A., André, R.G., and Mesfioui, M., 2007. Impacts of dams on monthly flow characteristics. The influence of watershed size and seasons. Journal of Hydrology, 334, 423-439.

Lee, R., 1980. Forest Hydrology. Columbia University Press, New York, pp. 111-126.

MacDonald, L.H., Wohl, E.E., Madsen, S.W., 1997. Validation of Water Yield Thresholds on the Kootenai National Forest (Chapter 2). Department of Earth Resources, Colorado State University, Fort Collins, CO. 197 p.

McCuen, H.R., 2005. Hydrologic Analysis and Design, Third Edition, Pearson, pp. 113-114.

Mimikou, M., 1984. Regional relationships between basin size and runoff characteristics. Journal of Hydrological Sciences, 29 (1), 63-73.

Niem, H., 1994. Effects of forests on water run-off. Meteorology and Hydrological Newsletter, 7 (403).

Ott, R. L., and M. Longnecker, 2001. An Introduction to Statistical Methods and Data Analysis, Fifth Edition, Duxbury, pp. 531-783.

Pho, N.V., 1992. Hydrological Issues and Tropical Forest. Journal of Forestry, 92 (11), 5-9.

Pilgrim, D. H., Cordery, I., and Baron, B. C., 1982. Effects of catchment size on runoff relationships. Journal of Hydrology, 58, 205-221.

Quynh, V.V., 1996. Forest hydrology and erosion in Forestry University's experimental station. Scientific Reports 1995-1999, Forestry University, Vietnam.

Quynh, V.V., and Bao, T.Q., 2006. Final Report: Defining minimum forest areas for provinces in Vietnam. Ministry of Agriculture and Rural Development, Vietnam.

Singh, P.V., 1997. Effect of Spatial Variability in Rainfall and Watershed Characteristics on Stream flow Hydrograph, Hydrological Processes, 11, 1649-1669.

Sterling, J. E., Hurley, M.M., and Minh, D.L., 2006. Vietnam: A Natural History, Yale University Press, pp. 7-10.

Sun, G,.Zhou, G., Zhang, Z., Wei, X., McNulty, S.G., and James, V., 2005. Forest and water relationships: hydrologic implications of forestation campaigns in China Nanchang, Jiangxi Province, China. Southern Research Station, US Forest Service, USA.

Tabios, G.G., Obyesekera, J.B., and Shen, H.S., 1988. The influence of storm movement on stream flow hydrograph through space time and rainfall generation and hydraulic routing. Unpublished paper. Colorado State University, Fort Collins, CO.

Vaske, J. J., 2007. Survey Research and Analysis: Applications in Human Dimensions of Natural Resources (chapter 16), Venture Publishing, State College, Pennsylvania.

Wolock, D. M., 1995. Effects of subbasin size on topographic characteristics and simulated flow paths in Sleepers River watershed, Vermont. Water Resources Research, 31 (8), 1989-1997.

Wood, E.F., Sivapalan, M., Beven, K., and Band, L., 1988. Effects of Spatial Variability and Scale with Implications to Hydrologic Modeling. Journal of Hydrology, 102, 29-47.

Chapter 4

DEFINING AREAS UNSUITABLE FOR AGRICULTURE IN VIETNAM WITH A GIS-BASED MODEL OF SOIL EROSION

Abstract

Forests play an important role in reducing erosion. In Vietnam, clearing of natural forests has caused serious environmental problems for sustainable development, such as destruction of wildlife habitat, upland soil degradation, hydropower dam longevity reduction, unsustainable aquaculture (Lung et al, 1995; Quynh, 1996). Areas unsuitable for agriculture in Vietnam defined in this study.

An algorithm to define area where forest is needed for soil erosion prevention is based on a comparison of soil loss prediction and its threshold of 10 ton $ha^{-1}yr^{-1}$ (soil loss tolerance) within the GIS environment. Soil loss is predicted from a rainfall erosivity index, slope, soil porosity and vegetation structure in which rainfall index is calculated from 30 year monthly rainfall data from 158 weather stations. A map of erosion risk for Vietnam illustrating soil erosion potential was generated from slope, rainfall index and soil porosity by using spatial interpolation and map algebra techniques in ArcGIS. Vegetation index, a function of canopy closure, height, ground cover and litter cover, is classified into four groups. Land requiring forest cover for protection of soil from erosion is defined from an erosion risk map in comparison with categories of vegetation index. An area (a raster cell) is suitable for forest (natural forest or the others) when its erosion risk is higher than the vegetation index.

4.1. INTRODUCTION

Soil erosion by water is one of the most serious environmental problems in the world. It causes adverse effects on soils, agricultural production, and water quality

(Lal, 2001). Worldwide, soil erosion rates are highest in Asia, Africa, and South America, averaging 30 to 40 tons $ha^{-1}yr^{-1}$, and they are lowest in Europe and the United States, averaging about 17 tons $ha^{-1}yr^{-1}$ (Pimentel et al., 1995). However, erosion rates are low on land with natural vegetation cover, about 2 tons $ha^{-1}yr^{-1}$ in relatively flat land and about 5 $ha^{-1}yr^{-1}$ in mountainous areas (Pimentel et al., 1998).

In tropical regions, where mean annual sediment yield is greater than 250 tons km^{-2} (Walling at al., 1983), upland areas are usually protected from erosion by a dense vegetation cover. Forest clearing has caused an increase in runoff and erosion (Morgan, 2005). Sidle et al. (2006) has summarized some key note papers about soil erosion in Southeast Asia and concludes that forest conversion to agriculture and exotic plantation (e.g., shifting cultivation) have significant effects on both surface and landslide erosion. The rates of surface erosion depend on the extent that dynamic management practices disturb and compact soil, alter ground cover, and modify soil properties. Therefore, accurate estimation of soil loss or evaluation of erosion risk has become an urgent task. Erosion prediction can help to address long range land management planning under natural and agricultural conditions (Angima et al., 2003).

Efforts to mathematically predict soil erosion by water have occurred only since the 1930s. Several models have been developed for estimating soil loss (e.g., Wischmeier and Smith, 1965; Morgan et al., 1984, 2001; Woolhiser, 1990; Quynh, 1996). The initial parameters in these models include susceptibility of soil to erosion, potential erosivity of rainfall and runoff, and soil protection afforded by plant cover (Renard et al., 1997). In practice, the Revised Universal Soil Loss Equation (RUSLE) model initially developed by Wishchmeier and Smith (1965) has been most widely used. It was originally developed for use on cropland. The RUSLE has been applied in different land uses (Renard et al., 1997). However, due to the complexity of defining factors of RUSLE for a given region, the application of the RUSLE in Vietnam has been challenging in terms of prediction accuracy and its validation (Quynh, 1996).

Traditionally, soil loss was predicted at the local scale based on the factors usually calculated from field measurement. Soil erosion prediction at large scale is often difficult due to spatial and temporal variability of model's factors (Lu et al., 2004). In recent decades, the development of GIS techniques has facilitated the estimation of soil erosion and its spatial distribution over large areas. For example, Yukel et al. (2008) applied the CORINE model integrated with remote sensing and GIS to generate an accurate and inexpensive erosion risk map in Turkey. Wang et al. (2003) estimated soil loss by integrating a sample ground data set, TM images, and a slope map and showed that the geostatistical method performed significantly better than traditional stratification in terms of overall and spatially explicit estimate. Several studies have applied GIS to interpolate independent factor maps in RUSLE model (or CORINE), then to overlay these maps to generate a regional erosion risk map (Bissonnais et al., 2001; Lufafa et al., 2003; Kheir et al., 2006; Qing et al., 2008).

In Vietnam, forests have long been recognized as important to environmental protection (Lung et al., 1995; Quynh, 1996; Dien, 2006). However, under pressure of economic development, the demand land for agricultural and other sectors has increased, creating conflicts between land managers. Natural forests, mostly distributed in mountainous areas have experienced high deforestation rates since the 1980s (FPD, 2008). Consequently, soil erosion in these uplands has caused serious environmental problems (Lung et al., 1995). There is an essential need to maintain forest cover on land prone to soil erosion. This study applies an empirical model for predicting soil loss to produce an erosion risk map and defines lands that require forest cover to protect soil from erosion for Vietnam. Spatial analyses and interpolation techniques in GIS are used for this study. The input data layers for mapping include DEM, rainfall and vegetative cover.

4.2. METHODOLOGY

4.2.1. Study Sites and Data Sources

Lands that are not unsuitable for agriculture because of erosion risk are identified for Vietnam, an S-shaped country located in the tropical monsoon area in the southeast of Asia with a great variety of deltas, mountains, forest mosaics, and climates. It has a rather high temperature and humidity, average annual temperature and humidity are above 20^0C and 80%, respectively. Average total annual rainfall is about 1940 mm. Total land area is about 330.000 km^2, three fourths of Vietnam is covered by mountains, causing differences in climate regime between regions (VNEA, 2006). Forest cover is about 38.2 %, of which natural forests is account for 80 % and plantation forests account for 20% (FPD, 2007). Data sources used for spatial analysis include: the National Elevation Dataset (90m x 90m); 30 years monthly rainfall data gauged in 158 weather stations of Vietnam; Archive data of vegetation structures and soil loss measurement on 63 research plots. These plots are from different vegetation types in Vietnam (Quynh et al., 1996).

4.2.2. Criteria for Defining Required Forest Area

The amount of soil erosion by water is an integration of the effects of vegetation cover, topographic features, climatic variables, and soil characteristics (Renard et al., 1997). In this study, to areas that require forest for protection from soil erosion, average soil loss per unit areas was spatially predicted for Vietnam by applying an equation to predict soil loss developed for Vietnam (Quynh et al., 1996).

The relationship between soil loss and rainfall, slope, vegetation structures and soil porosity is expressed expression in the following equation.

$$A = \frac{\left(2.31 * 10^{-6} * K * \alpha^{2}\right)}{\left(\frac{CC}{H} + GC + LC\right)^{2} * P} \tag{4.1}$$

Where:

A = estimate average soil loss (mm yr^{-1})

α = slope (degree)

CC = canopy closure (%)

H = forest height (m)

GC = ground cover (%)

LC = dried litter cover (%)

P = soil porosity (%)

K = rainfall erosivity factor, calculated based on monthly rainfall (equation 4.2)

$$K = \sum_{i=1}^{12} \left(\frac{R_i}{25.4}\right) * \left\{\frac{16 + 331 * \lg[(-5.8263 + 2.481 * \ln(R_i))/25.4]}{100}\right\} \tag{4.2}$$

Where: R_i is rainfall of the i^{th} month.

The acceptance limit of erosion is 10 ton ha^{-1} yr^{-1}, this is the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically (Hudson, 1977; Renard et al., 1997). It is about equal 0.8mm yr^{-1}. To prevent soil degradation, annual soil loss (A) is required of less than the sustainably replacement rate (0.8 mm yr^{-1}).

Then, $$A = \frac{\left(2.31 * 10^{-6} * K * \alpha^{2}\right)}{\left(\frac{CC}{H} + GC + LC\right)^{2} * P} \leq 0.8 \text{ mm yr}^{-1} \tag{4.3}$$

Let $C_1 = \left[\frac{CC}{H} + GC + LC\right]$ (4.4) is index of vegetation for soil protection. An area has potential soil erosion less than the replacement rate when its C_1 meets the inequality equation (4.5) derived from inequality (4.3).

$$C_1 \geq \sqrt{(2.31*10^{-6}*K*\alpha^2)/(0.8*P)} \quad (4.5)$$

Let $C_2 = \sqrt{(2.31*10^{-6}*K*\alpha^2)/(0.8*P)}$ (4.6)

be an index of erosion risk. C_2 does not depend on vegetation cover structure or other changeable factors. It is only affected by stable factors (i.e., slope, rainfall factor, and soil porosity). Based on value of C_2 for a specific area, we can identify the corresponding vegetation cover structure (C_1) to protect soil from erosion.

4.2.3. Spatial Analysis to Define Areas Requiring Forest Cover

The digital maps of elevation and rainfall of Vietnam are developed in GIS, using Spatial Analyst in ArcGIS 9.2 software (ESRI, 2008). We used these maps to produce a map that spatially identified erosion risk (C_2) of Vietnam. This was compared with the threshold of vegetation index (C_1) to generate a map of required forest area for erosion protection. Figure 4.1 indicates the methodology used in the model.

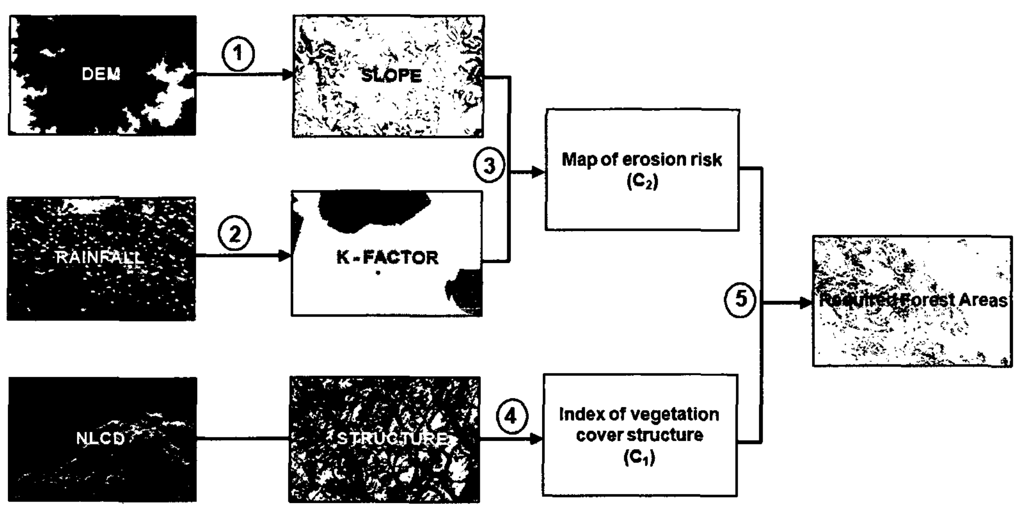


Figure 4.1. Analytical methodology for defining required forest area

The explanations of each procedure in the model will be followed:

(1) Slope data layer was derived from National Elevation Dataset (DEM)

(2) Calculated average monthly rainfall for 158 meteorological stations in Vietnam, then spatially interpolated 12 monthly rainfall maps from these point data. A map of rainfall erosivity factor (K) for Vietnam was generated by overlaying 12 monthly rainfall maps based on a raster calculation in equation (4.2).

(3) An erosion risk map (C_2) for Vietnam was produced from three input layers (i.e., porosity, slope, and rainfall erosivity maps), in which P was assumed to equal 0.4, this is equivalent to the average porosity of fallow land following one year of traditional swidden cultivation (Quynh at al., 1996). The raster calculation for the erosion risk map was based on equation (4.6).

(4) From the data of vegetation cover structures (i.e., canopy closure, ground cover, litter cover, and height) of previous study (Quynh et al., 1996), calculate C_1 for different main cover types in Vietnam (equation 4.4). Index of vegetation covers (C_1) are classified into five classes based on their relationship with soil loss (Table 4.1).

Table 4.1. Classes of vegetation cover structure index in Vietnam

Cover types	C_1
Natural Forests	>1.7
Plantation forest, agro-forests	1.3 - 1.7
Industrial plants, fruits	0.9 - 1.3
Agriculture	0.6 - 0.9

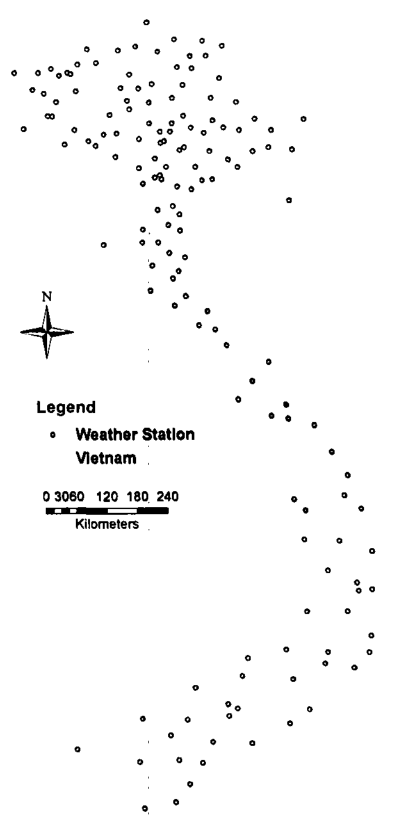
(5) Defining required protective forest area

Algorithm of this step is based on a comparison between actual value of erosion risk (C_2) and threshold of vegetation index (C_1) in Table 4.1. An area (a raster cell) is required natural forest when its C_2 is greater than 1.7 (i.e., C_1 of natural forest). It is required natural forest, or plantation forest, or agro-forest, when its C_2 is less than 1.7, but greater than 1.3 (i.e., C_1 of plantation forest, agro-forest). These conditional statements were executed by Map Algebra functions (i.e., If Then Else) in Spatial

Analyst Tool of ArcGIS 9.2 (Theobald, 2003). Total areas of forested cells are required forest areas for protection soil from erosion in Vietnam.

4.2.4. Rainfall Interpolation

Monthly rainfall maps are interpolated from 30-year averaging rainfall data of 158 weather stations relative evenly distributed in Vietnam (Fig. 4.2). The interpolation method used is Inverse Distance Weighted (IDW), in which an unknown point is interpolated from usually scattered set of known points (Bartier et al., 1996).



$$\hat{Z}(s_0) = \frac{\sum_{i=1}^{n} Z(s_i)\lambda_i}{\sum_{i=1}^{n} \lambda_i} \qquad (4.7)$$

Where:

$Z(s_i)$ is rainfall of station i^{th}

$\hat{Z}(s_0)$ is interpolated rainfall for location s_o

n is number of the nearest stations used for interpolation, n is chosen equal 3.

λ_i is weighted value for station i^{th}, $\lambda_i = 1/d_i^2$, where d_i is distance from location s_i to location s_o.

Figure 4.2. Map of Vietnam showing the locations of 158 weather stations in Vietnam

4.3. RESULTS AND ANALYSIS

4.3.1. Rainfall Interpolation and Rainfall Erosivity Factor

The temporal and spatial distributions of monthly rainfall in Vietnam are illustrated in Figure 4.3 from January to December.

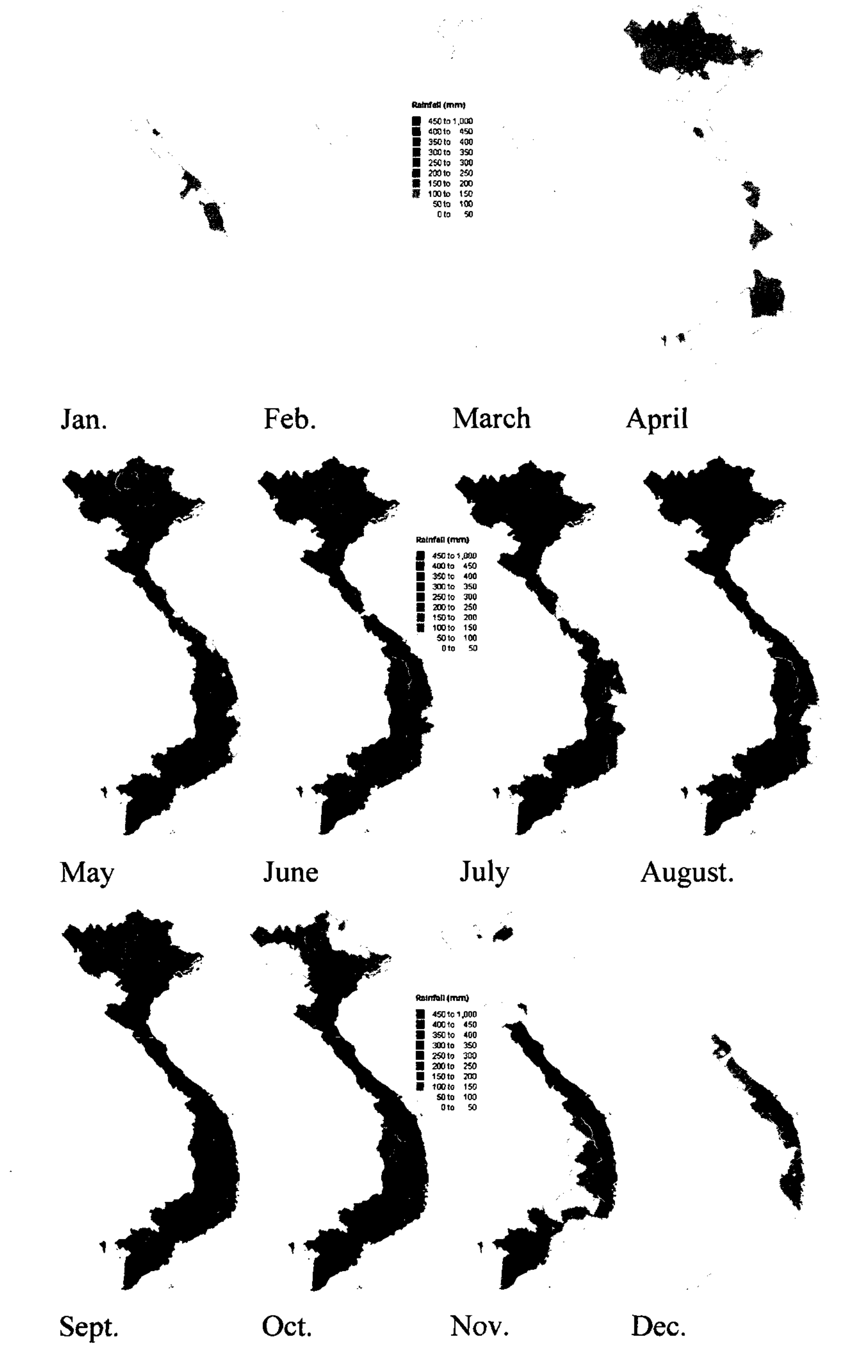
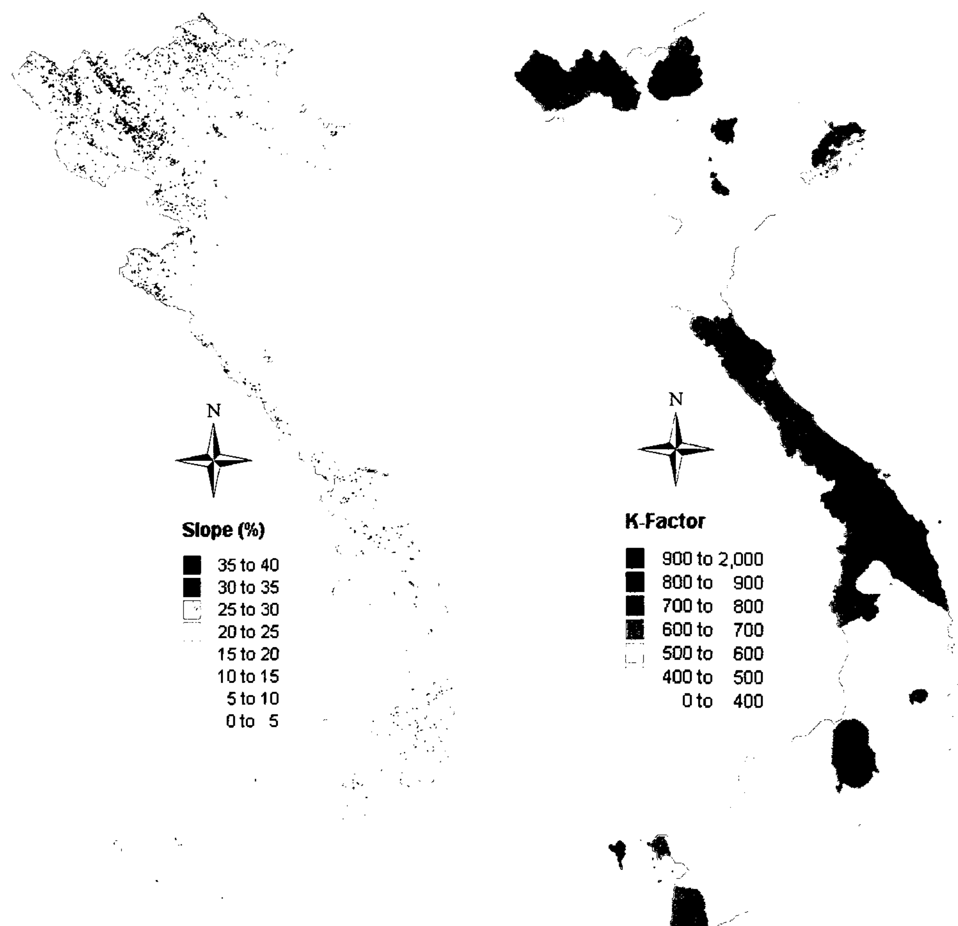


Figure 4.3. Interpolated average monthly rainfall for Vietnam

As shown in Figure 4.3 and indicated in Appendix 4.1, average annual rainfall varies dramatically ranging approximately from 1000mm in Nha Ho to 4000mm in Bac Quang. The rainfall is unevenly spatio-temporally distributed. The variation of rainfall is the main cause of droughts in the dry season and floods in the rainy season. In some areas like Ham Tan, Phan Thiet there is either no rain for 2-3 months or very little rainfall. The highest monthly rainfall occurring in August and September is 900 – 1000mm (e.g., Bac Quang, Nam Dong). The rain season starts from April to October, particularly from July to December in the central coastal area. The rainfall in rainy season accounts for 80% of the total annual rainfall.



(a) **(b)**

Figure 4.4. Map of slope (a) and rainfall erosivity factor (b)

4.3.2. Erosion Risk and Areas Requiring Forest Cover

As indicated above, about three fourths of the total natural land area of Vietnam is covered by hills and mountains, with a general downward slope from west to east (Fig. 4.4a). A high gradient of slope, together with unevenly distribution of rainfall erosivity (Fig. 4.4b), consequently created a great variability within erosion risk map of Vietnam (Fig. 4.5a). The northwest and central west areas of Vietnam (red color) have the highest potential to erode soil. The two large areas having the lowest erosion risk (blue color) are located in Red River Delta (northern) and Mekong River Delta (southern).

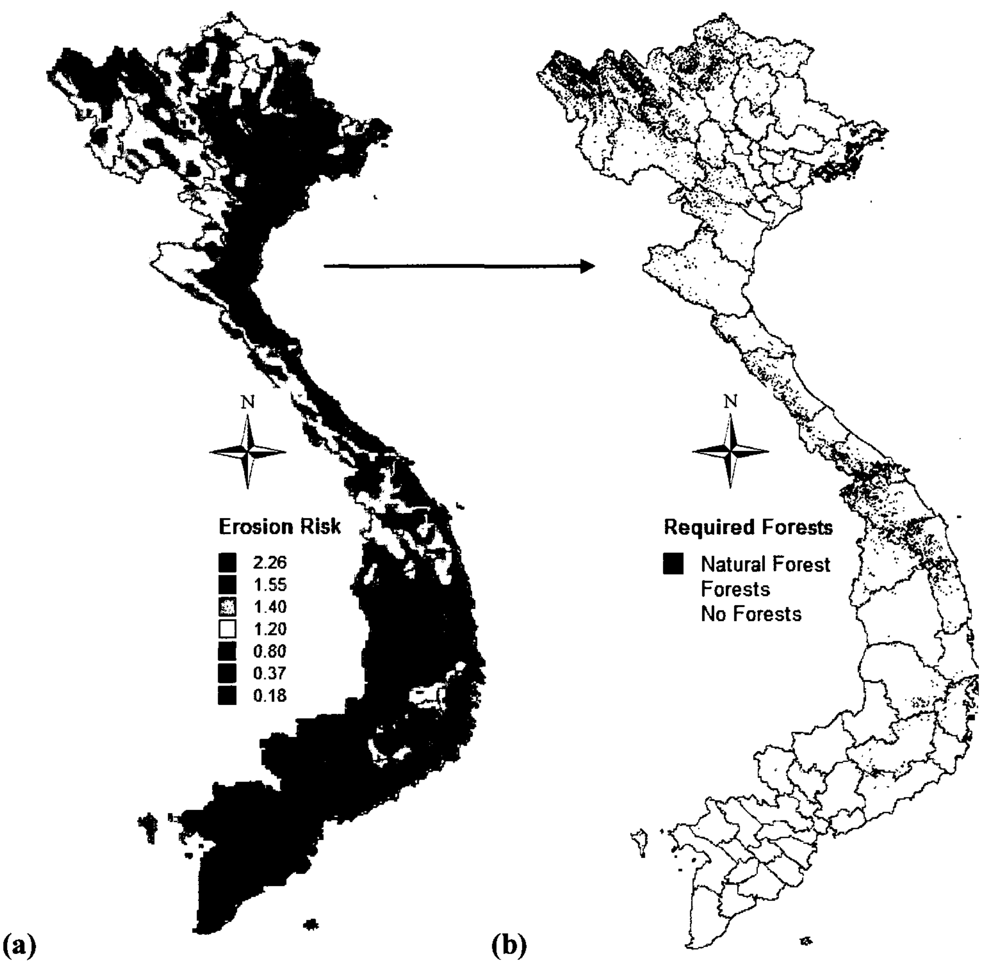


Figure 4.5. Maps of Vietnam showing (a) erosion risk and (b) Areas requiring forest cover

The map of areas suitable only for a forested land use for Vietnam (Fig. 4.5b) was generated from erosion risk map in comparison with vegetation index (inequality 4.5). Total required forest areas for protection of soil from erosion for Vietnam are 7,191,436 ha, of which 2,469,497 ha is natural forest. The study has calculated the required forest areas for different provinces of Vietnam (Appendix 4.2). Fifteen out of 64 provinces do not require forests for erosion prevention, most are distributed in the Red and Mekong river deltas. Provinces requiring high percentages of forest cover are mainly located in the northwest and south central of Vietnam.

4.4. DISSCUSSION

The revised universal soil loss equation (RUSLE) is an erosion model predicting longtime average annual soil loss, it is a powerful tool that is widely used in the United States and many foreign countries (Renard et al., 1997). The RUSLE was developed initially by Wischmeier and Smith (1965, 1978) for original use on cropland. It has been being applied to different land uses (e.g., rangeland, forestland). The RUSLE is expressed as:

$$A = R * K * L*S * C * P \tag{4.8}$$

Where: A = estimated spatial average soil loss per unit area

R = rainfall-runoff erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover-management factor

P = support practice factor

The essence of universal soil loss equation is to isolate each variable and reduce its effect to a number. Soil loss is predicted by multiplying the numbers. For a given situation (e.g., soil type, cover, slope and length) the value of each factor in the equation is fixed, which only can be established after it has been measured (Hudson, 1977). In Vietnam, there are limited applications of the RUSLE to predict erosion from land surface due to a lack of references to qualitatively assess the factors for given circumstances. Lung et al. (1995) has defined factors in the equation (4.8) for the Central Highlands, and also identified C factor for different forest covers in this area (Table 4.2). However, there are some disadvantages when applying this equation to predict soil erosion; these include: (1) there is no verification for method used to define factors; (2) vegetation classifications are not detailed enough; (3) and experimental plots were designed in a small range of the factors.

Table 4. 2. An example of USLE factors calculated for the central highland of Vietnam

Locations	R	K[a]	LS	C	P
Konhanung	872.5	0.021	2.37 (10^0)	0.0083[b]	1.0
Pleiku	943.3	0.024	4.38 (15^0)	0.0076[c]	1.0

Sources: Lung et al. (1995)

[a] K factor for Bazan soil; [b] C factor for bamboo forest; [c] C factor for grass

These disadvantages are resolved by applying the erosion prediction equation (4.1) used in this study. This equation was established based on observations of 63 field plots of different cover types, including natural forests, plantation forests, orchards, abandoned land, grazing land and paddy field (Quynh et al., 1996). Soil erosion in each plot is measured and estimated by using the triangle of three steel poles. In the middle of each pilot plot, place three steel poles in a triangle form. The length of each side of the triangle (the distance from each pole) is 3 m. Each pole is placed deeply into the soil and left about 20 cm higher than the surface of the land. Use a long plastic durable string to connect the three poles at the height of 10 cm from the surface, then measure the distance at 9 points (3 points in each side of the triangle) from the string to the surface before and after each rain event to estimate the thickness of soil layer eroded by each rain (mm). Soil loss depth was analyzed in relation to vegetation structures (e.g., height, canopy closure, ground cover, and litter cover), slope, and rainfall. The authors have found a close relationship among these variables (Fig. 4.8a). They used monthly rainfall as a replacement of rainfall intensity (Fig. 4.8b) for calculation of rainfall erosivity factor. The root mean squared error (RMSE) of soil loss prediction by using the equation (4.1) is about 16%. Recently, the equation has been widely applied in Vietnam (Quynh et al., 2006).

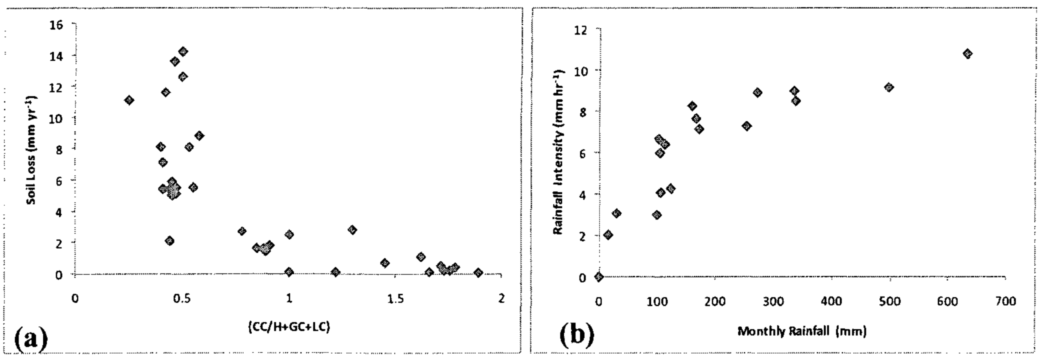


Figure 4.6. Bivariate plots of (a) vegetation cover structure (i.e., canopy closure, height, ground cover, and litter cover) and soil loss (mm yr^{-1}), R^2 =0.73; and (b) monthly rainfall (mm) and rainfall intensity (mm hr^{-1}), R^2=0.78, (Quynh at al., 1999).

4.5. CONCLUSIONS

Soil erosion by water continues to be serious environmental problems in Vietnam. The primary objectives of this study were applying GIS techniques to define required forest areas for protection soil from erosion in Vietnam.

Due to difficulties in identifying factors for Revised Universal Soil Loss Equation (RUSLE) in Vietnam, the spatially potential soil loss was predicted by an equation developed by Vietnam itself, in which soil erosion prediction is a function of vegetation cover structures, slope, erosivity rainfall index, and soil porosity. Based on the selected soil loss equation and the threshold for soil loss in tropical regions (10 ton ha^{-1} yr^{-1}), we have established two criteria to define required forest area, one is index of erosion risk (C_2), the other one is index of vegetation (C_1). The map of erosion risk was interpolated from mean 30-year monthly rainfall data, slope, and porosity. The index of vegetation was calculated for main cover types in Vietnam from available data (i.e., height, canopy closure, ground cover, and litter cover). Applying raster analysis techniques in ArcGIS, the map of required forest areas for soil erosion prevention was generated from erosion risk map in comparison with vegetation index.

LITTERATURE CITED

Angima, S.D., Stott, D.E., O'Neill, M.K., Ong, C.K., Weesies, G.A.., 2003. Soil erosion prediction using RUSLE for central Kenyan highland conditions. Agriculture Ecosystems and Environment, 97, 295-308.

Bartier, P.M., and Keller, C.P., 1996. Multivariate interpolation to incorporate thematic surface data using inverse distance weighting (IDW). Computers and Geosciences, 22 (7), 795-799.

Bissonnais, Y.L., Montier, C., Jamagne, M., Daroussin, J., and King, D., 2001. Mapping Erosion Risk for Cultivated Soil in France. Catena, 46, 207-220.

Dien, P.V., 2006. Water retention capability of some vegetation types in protection areas of Hoa Binh hydropower plant. Ph.D Dissertation, Forestry University, Vietnam.

ESRI, 2008. ArcGIS Spatial Analysis, www.esri.com/spatialanalyst.

FPD, 2008. Vietnam Annual Forest Cover, 2007. Forest Protection Department (FPD), Ministry of Agriculture and Rural Development, http://www.kiemlam.org.vn/

Hudson, N.W., 1977. Soil Conservation. Cornell University Press, Ithaca, New York.

Kheir, R.B., Cerdan, O., Abdallah, C., 2006. Regional Soil Erosion Risk Mapping in Lebanon. Geomophology, 82, 347-359.

Lal, R., 2001. Soil degradation by erosion. Land Degradation & Development, 12 (4), pp. 519-539.

Lung, N.N., Hai, V.D., 1995. Research on scientific foundation of technical economic solutions for planning and designing watershed, upstream protective forests, and coastal mitigating storm forests. Report for National Project No. K03-09, Ha Noi.

Lu, D., Li, G., Valladares, G.S., and Batistella, M., 2004. Mapping soil erosion risk in Rondônia, Brazilian Amazonia: using RUSLE, remote sensing and GIS. Land Degradation and Development, 15, 499-512.

Lufafa, A., Tenywa, M.M., Isabirye, M., Majaliwa, M.J.G., and Woomer, P.L., 2002. Prediction of Soil Erosion in a Lake Victoria Basin Catchment using a GIS-based Universal Soil Loss Model. Agricultural Systems, 76, 883-894.

Morgan, R.P.C., Morgan, D.D.V., and Finney, H.J., 1984. A predictive model for the assessment of soil erosion risk. Journal of Agricultural Engineering Research, 30, 245-253.

Morgan, R.P.C., 2001. A Simple Approach to Soil Loss Prediction: A Revised Morgan-Morgan-Finney Model. Catena, 44, 305-322.

Morgan, R.P.C., 2005. Soil Erosion and Conservation. Third Edition, Blackwell Publishing.

Pimentel, D., and Kounang, N., 1998. Ecology of Soil Erosion in Ecosystems. Ecosystems, 1 (5), pp. 416-426.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., and Blair, R., 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. Science, 267, 1117-1123.

Qing, X.Y., Mei, S.X., Bin, K.X., Jian, P., and Long, C.Y., 2008. Adapting the RUSLE and GIS to Model Soil Erosion Risk in a Mountains Karst Watershed, Gouzhou Province, China. Environmental Monitoring and Assessement, 141, 275-286.

Quynh, V.V., Tuat, N.H., Khai, H.Q., 1999. Forest Criteria for Soil Conservation. Report for Project Funded by Ministry of Agriculture and Rural Development.

Quynh V.V., Lan, N.N., 1996. Capability to protect soil of different vegetation covers in Ham Yen, Tuyen Quang. Report for Vietnam – Swedish Cooperation Program, SIDA.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. Prediction soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA, Agriculture HandBook, No. 703.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., and Turkelboom, F., 2006. Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecology and Management, 224, 199-225.

Sterling, J. E., Hurley, M.M., and Minh, D.L., 2006. Vietnam: A Natural History, Yale University Press, pp. 1-21 and pp. 91-92.

Theobald, D.M., 2003. GIS Concepts and ArcGIS Methods. 1st Edition, Conservation and Planning Technologies Publisher, USA. pp. 238-266.

VEPA, 2006. Environmental Report of Vietnam, 2006. Vietnam Environment Protection Agency.

Walling, D.E., and Webb, B.W., 1983. Patterns of Sediment Yield. In Morgan, R.P.C. (3rd ed.), Soil Erosion and Conservation, Blackwell Publishing, pp. 1-10.

Wang, G., Goerge, G., Fang, S., and Alan, A., 2003. Mapping multiple variables for predicting soil loss by geostatistical methods with TM images and a slope map. Photogrammetric engineering and remote sensing, 69 (8), 889-898.

Wischmeier, W.H., and D.D. Smith, 1965. Predicting rainfall erosion soil losses from cropland east of the Rocky Mountain: A guide for selection of practices for soil and water conservation. USDA, Agriculture Handbook, No. 282.

Wischmeier, W.H., and D.D. Smith, 1978. Predicting rainfall erosion soil losses: A guide to conservation planning. USDA, Agriculture Handbook, No. 537.

Woolhiser, D.A., Smith, R.E., Goodrich, D.C., 1990. KINEROS: a kinematic runoff and erosion model: documentation and user manual. USDA Agricultural Research Service ARS-77.

Yuksel, A., Gundogan, R., and Akay, A.E., 2008. Using the Remote Sensing and GIS Technology for Erosion Risk Mapping of Kartalkaya Dam Watershed in Kahramanmaras, Turkey. Sensors, 8, 4851-4865.

Chapter 5

THE RELATIONSHIP BETWEEN MANGROVE STRUCTURE AND WAVE ATTENUATION IN COASTAL VIETNAM

Abstract

Mangrove forests are located in upper intertidal zones of the tropics. They play a vital role in coastline protection, mitigation of wave and storm impacts and mudflats stabilization, and protection of near shore water quality. Mangrove forest also provide critical habitat for fish and wildlife. Many species new to sciences have recently been document in mangrove forest areas in Vietnam (Thompson et al., 2008). This chapter analyzes wave attenuation in coastal mangroves in Vietnam. Data from 32 mangrove plots of six species located in 2 coastal regions are used for this study. In each plot, mangrove forest structure (e.g., height, density, and canopy closure) and wave height at different cross-shore distances are measured. Multivariate analysis was used to inspect the relationship between mangrove structures and wave height reduction.

Wave height closely relates to cross-shore distances. Ninety one exponential regression equations are highly significant with $R^2 > 0.95$ and P val. <0.001. Wave height reduction depends on initial wave height, cross-shore distances, and mangrove forest structures. This relationship is used to define minimum mangrove band width for coastal protection from waves in Vietnam. For specific assumptions of maximum initial wave height of 300 cm and safe wave height behind mangrove band of 30 cm, the minimum mangrove band width depends only on its structures. It ranges from less than 40 m to greater than 240 m. The minimum mangrove band width decreases from north to south because of the spatial variation in mangrove structure.

5.1. INTRODUCTION

Mangrove forests span the interface between marine and terrestrial environments, growing in the mouths of rivers, in tidal swamps, and along coastlines where they are regularly inundated by salty or brackish water (Sterling et al., 2006).

The trunks and roots above the ground of mangrove forests have a considerable influence on the hydrodynamics and sediment transport within forests (Quartel at al., 2007). In 2002, Vietnam has approximately 155,290 ha of mangrove forests. More than 200,000 ha of mangrove forests have been destroyed over the last two decades by conversion to agriculture and aquaculture (e.g., shrimp farming) as well as by development for recreation (VNEA, 2005). Mangrove forests are thought to play an important role in flood defense by dissipating incoming wave energy and reducing the erosion rates (Hong et al., 1993; Wu et al., 2000). However, physical processes of wave attenuation in mangroves are not widely studied, especially in Vietnam, because of difficulties in analyzing the flow field in the vegetation field and the lack of comprehensive data (Kobayashi et al., 1993).

Coastal mangrove forests can mitigate high waves, even tsunamis. By observing causalities of the tsunami of December 26, 2004, Kathiresan et al., (2005) highlighted the effectiveness of mangrove forest in reducing the impact of waves. Human death and loss of wealth decreased with areas of dense mangrove forests. A review by Alongi (2008) concluded that significant reduction in tsunami wave flow pressure when mangrove forest was 100 m in width. The energy of wave height and wave spectrum is dissipated within mangrove forest even at small distance (Luong et al., 2008). The magnitude of energy absorption strongly depends on mangrove structures (e.g., density, stem and root diameter, shore slope) and spectral characteristics of incident waves (Massel et al., 1999; Alongi, 2008). The dissipation of wave energy inside mangrove forests is mostly caused by wave-trunk interactions and wave breaking (Luong et al., 2006).

Mazda et al. (1997a) on their study in Red River Delta, Vietnam showed that the wave reduction due to drag force on the trees is significant on high density, six-year-old mangrove forests. Hydrodynamics in mangrove swamps changes in wide range with their species, density and tidal condition (Mazda et al., 1997b). High tree density and above ground roots of mangrove forest causes a much higher drag force of incoming waves than the bare sandy surface of the mudflat does. The wave drag force can be expressed in an exponential function (Quartel et al., 2007).

The general objective of this study is to analyze the relationship between wave height and mangrove forest structures, and then to define minimum mangrove forest band width for coastal protection from waves for coastline of Vietnam.

5.2. METHODOLOGY

5.2.1. Study Sites

The study was made in two coastal region of Vietnam, coastal mangrove forests in the Red River delta in the north and Can Gio mangrove forest in the south (Fig. 5.1).

The northern study site is located in the Red River delta, which is the second largest delta in Vietnam and flows into the Bay of Tonkin (Fig. 5.1). The tides in the Bay of Tonkin are diurnal with a range of 2.6-3.2 m. Active intertidal mudflats, mangrove swamps and supratidal marshes in estuaries and along open coastlines characterize the coastal areas (Mather et al., 1999; Quartel et al., 2007). Mangrove in the Red river delta is one of the main remaining large tracts of mangrove forest in Vietnam, which are important sites for breeding/stop-over along the East-Asian or the Australia flyways. In this northern region, four mangrove locations were selected for the research, including Tien Lang and Cat ba– Hai Phong; Hoang Tan – Quang Ninh; Tien Hai – Thai Binh. In each of location, four mangrove forest plots were set up to measure mangrove structure and wave height at different cross-shore distances.

The southern study site is Can Gio mangrove forest, it is the first Biosphere Reserve in Vietnam located 40 km southeast of Ho Chi Minh City and has a total of

75,740 ha (Fig. 5.1). Can Gio lies in a recently formed, soft, silty delta with an irregular, semi-diurnal tidal regime (Luong et al., 2006). The major habitat types in Can Gio are plantation mangrove, of which there is about 20,000 ha, and naturally regenerating mangrove. The site is an important wildlife sanctuary in Vietnam as it is characterized by a wetland biosystem dominated by mangrove. The intertidal mudflats and sandbanks at Can Gio are an important habitat for migratory shorebirds. Eighteen mangrove forest plots were set up in Can Gio to collect data of mangrove structures and wave height. These plots are selected representative for difference in mangrove structures in the region (e.g., age, species, height, tree density).

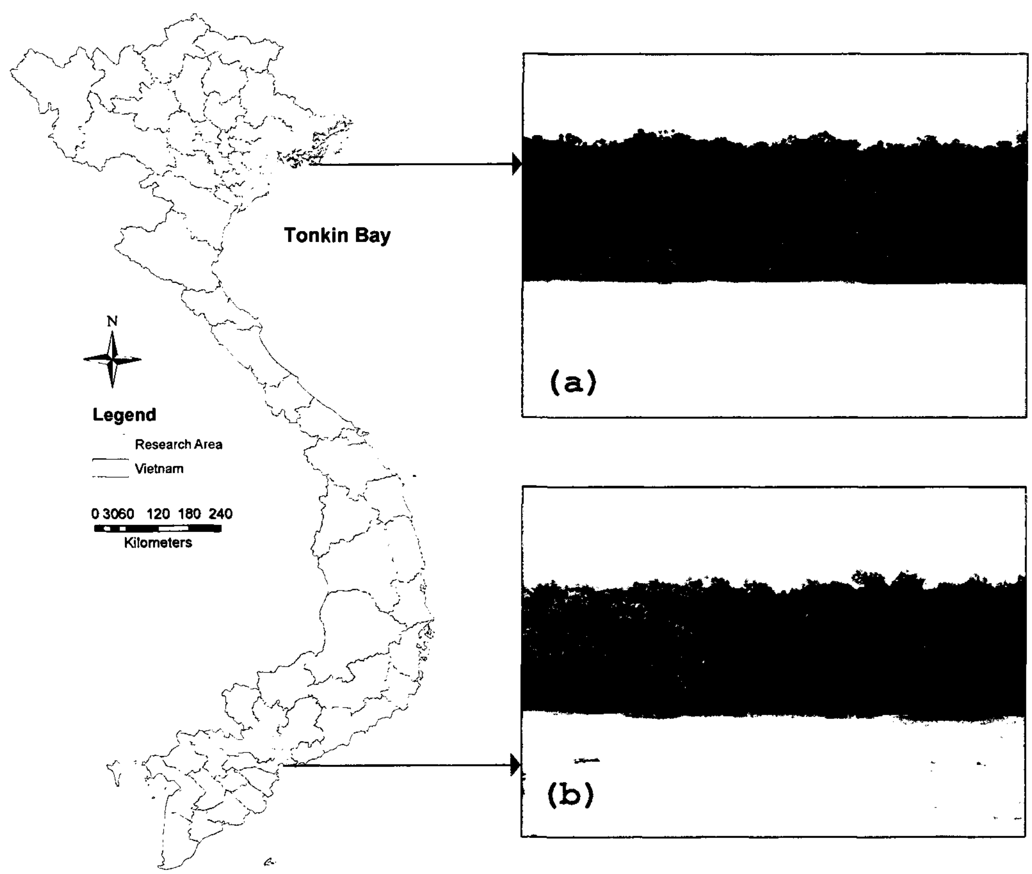


Figure 5.1. Map of Vietnam showing the location of study areas; (a) *Sonneratia caseolaris* forest in Hai Phong, and (b) *Rhizophora mucronata* forest in Ho Chi Minh City.

5.2.2. Data Collection

A total 32 mangrove forest plots of 400 m^2 (20 m x 20 m) were set up in five locations of two regions along coastal Vietnam (Fig. 5.1). In each plot, about 2-5 routes are designed to measure wave height at different cross-shore distances (i.e., 0m, 20m, 40m, 60m, 100m, and 120m) from the edge to the center of the mangrove stand (Fig. 5.2). Numbers of measurable replications in each route are from 2 to 10. Mangrove forest structures, such as DBH, height, tree density, canopy closure and species are collected in each plot. Wave attenuation is analyzed in relation to distances, initial wave height and mangrove forest structures.

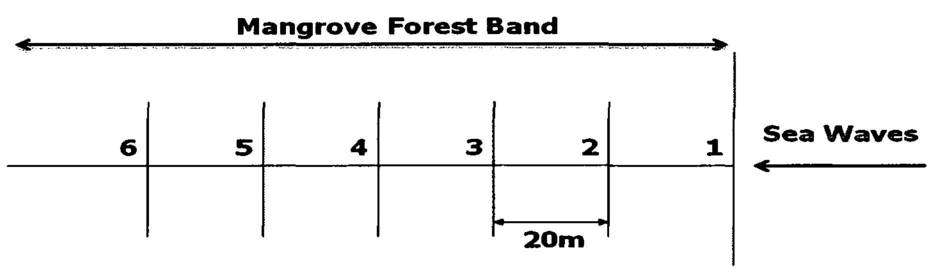


Figure 5.2. A diagram designed to measure wave height on a cross shore transect

5.3. RESULTS AND DISCUSSION

5.3.1. Effects of Mangrove Structures on Wave Height

The structures of 32 mangrove forest plots in five coastal research areas are relatively simple (Appendix 5.1). There are only six dominant species (i.e., *Rhizophora mucronata; Sonneratia caseolaris; Sonneratia griffithii; Aegiceras corniculatum; Avicennia marina; Kandelia candel*) with high tree density (2000 ÷ 13000 trees ha^{-1}) and canopy closure averaging above 80%. Diameter and height ranges from 7.5 to 12 (cm) and 1.6 to 11.3 (m), respectively. Generally, DBH and height of mangrove forests increases toward the south. It may be explained by the differences in resources supply (i.e., more mudflats, and warmer climate in the south). Average wave height observed in all plots ranges from 20 to 70 (cm).

From the data on wave height (cm) measured at different distances (m) from the edge to the center of the mangrove stand (Appendix 5.2), we applied regression models to inspect the relationship between wave height and cross-shore distances to the forest. The results (Appendix 5.3) show that wave height decays exponentially and is significantly related to distances. All 92 exponential regression equations of five research areas with different mangrove forest species are highly significant with P values of <0.001 and R^2 > 0.95. The exponential reduction of wave height in mangroves can be explained by dense network of trucks, branches and above ground roots of the mangrove trees increasing bed roughness and causing more friction and dissipating more wave energy (Quartel et al., 2007).

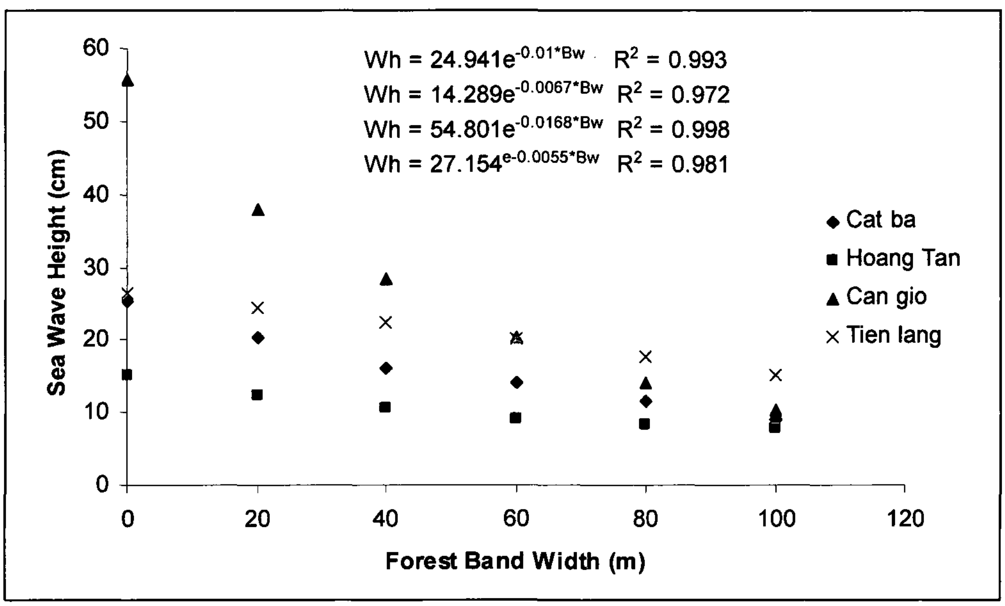


Figure 5.3. The reduction of wave height by cross shore distances. Examples from measured data of route 1 and the first replication of plots in Cat ba, Hoang tan, Can gio, Tien lang, respectively.

The effect of mangrove forest band width on wave height can be generalized in an exponential equation (5.1)

$$W_h = a * e^{b*B_w} \quad (5.1)$$

Where: W_h is the sea wave height behind forest band (cm)

B_w is the forest band width (m)

a is intercept coefficent in log base e of equation (5.1)

b is slope coefficient in log base e of equation (5.1)

To establish a general equation for all measurements in five locations, from the data in Appendix 5.3 listing all 92 regression coefficients of equation (5.1) we analyze the relation of these coefficients (i.e., intercept and slope) with different independent variables. We have found interesting results of relationship of regression coefficients to initial wave height and mangrove forest structures:

1) Intercept coefficient (a) is highly correlated to initial wave height (i.e., wave height at the edge of mangrove forest, distance = 0), $R^2 = 0.989$, $P < .0001$. It is a linear equation, in which a coefficient is directly proportional to initial wave height.

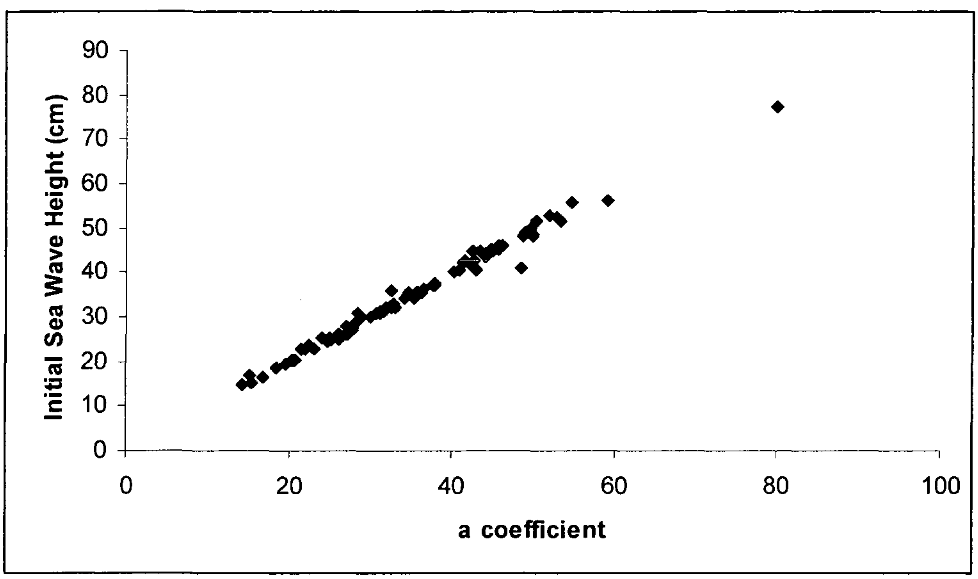


Figure 5.4. Bivariate plots of coefficient **a** in equation (5.1) and initial wave height (cm)

$$a = 0.9899*I_{wh} + 0.3526 \quad (5.2)$$

Where: a is coefficience in the exponential equation (5.1)

I_{wh} is the initial sea wave height (cm)

2) Slope coefficient (b) is in regression with mangrove forest structures, about 71% of total variations of b coefficient is in associated with height, density, and canopy closure ($R^2 = 0.713$, $P<.0001$). These independent variables are inversely relation to exponential coefficient of equation (5.1).

$$b=0.048-0.0016*H-0.00178*Ln(N)-0.0077*Ln(CC) \quad (5.3)$$

Where: b is exponential coefficient in the equation (5.1)

H is average tree height (m)

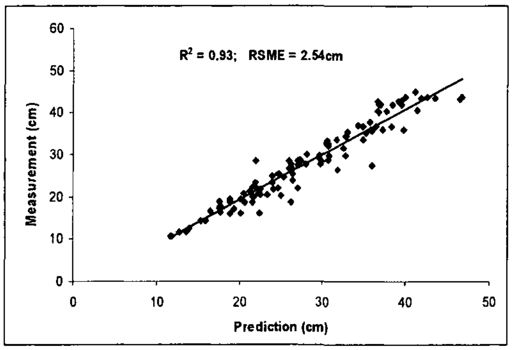
N is tree density (tree ha^{-1})

CC is canopy closure (%)

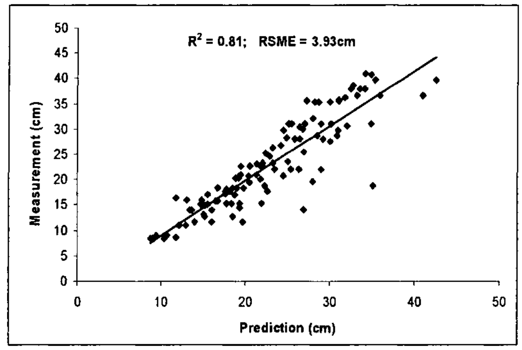
By plugging two equations (5.2) and (5.3) into the equation (5.1), we have an integrated equation (5.4) demonstrating the relationship of wave height reduction to initial wave height and mangrove forest structure.

$$W_h = \left(0.9899 * \mathrm{I}_{\mathrm{wh}} + 0.3526\right) * e^{(0.048-0.0016*H-0.00178*Ln(N)-0.0077*Ln(CC))*Bw} \quad (5.4)$$

To validate accuracy of the model (5.4), the predicted values are compared with actual data. Fig. 5.5 (a, b) shows a high correlation between predicted wave height and observed wave height at two cross-shore distances of 40m and 80m ($R^2>0.8$). The root squared mean errors (RSME) of the predictions are 2.54cm and 3.93cm, respectively.



(a)



(b)

Figure 5.5. Bivariate plots of predictive and actual values of wave height (cm) at two distances from the edge to the center of forest, (a) distance = 40m; (b) distance = 80m.

5.3.2. Minimum Mangrove Band Width for Coastal Protection from Waves

5.3.2.1. Defining Mangrove Band Width

The integrated equation (5.4) is the prediction of wave height from cross-shore distance (i.e., mangrove band width), mangrove structures, and initial wave height. Mangrove band width is identified by equation (5.5) derived from equation (5.4). In the equation (5.5), for given predicted wave height (i.e., safe wave height) and initial wave height, mangrove band width depends on mangrove forest structures.

$$B_w = \frac{\ln(W_h) - \ln(a)}{b} \tag{5.5}$$

Where: B_w is forest band width (m)

W_h is safe wave height behind forest band (cm)

a is a function of initial wave height (equation 5.2)

b is a function of forest structure (equation 5.3)

To identify average initial wave height for equation (5.5), we have collected maximum wave height at different typical regions along coastline of Vietnam (Table 5.1). In two years from 2004 to 2005, the maximum wave height approximately ranges from 1.25m to 5.0m. In reality, wave height depends on characteristics of storm events. Wave height is caused by strong wind and heavy rain, whereas in normal weather wave height is usually low in Vietnam. We selected a threshold of 3m of maximum wave height to calculated minimum mangrove band width for coastal protection.

Table 5.1. Maximum Sea Wave Height in coastal Vietnam

Regions	Maximum sea wave height (m)		
	6^h30	12^h 30	17^h 00
Hai Phong	2.97	3.69	3.60
Quang Ninh	1.25	1.25	1.50
Vung Tau	1.25	125	1.50
Thanh Hoa	0.75	1.35	1.50
Da Nang	3.50	5.00	3.50

* Sources: Department of Hydrometeorology, observed from Jan 01, 2004 to Dec. 31, 2005

Safe wave height behind forest band in equation (5.5) is 30cm, it is averaging value of wave height by interviewing 50 people (e.g., farmer, peasant, manager) working in aquaculture and agriculture in research areas.

By plugging the values of initial wave height (300cm), and safe wave height (30cm) into equation (5.5), as a result, required mangrove band width (B_w) is only a function of forest structure index depending on height, density, and canopy closure (equation 5.3).

Let V = - b = [- 0.048 + 0.0016*H + 0.00178*ln(N) + 0.0077*ln(CC)] (5.6)

is an index of mangrove forest structure. A theoretical line of minimum forest band width in relation to vegetation index is demonstrated in Fig. 5.6.

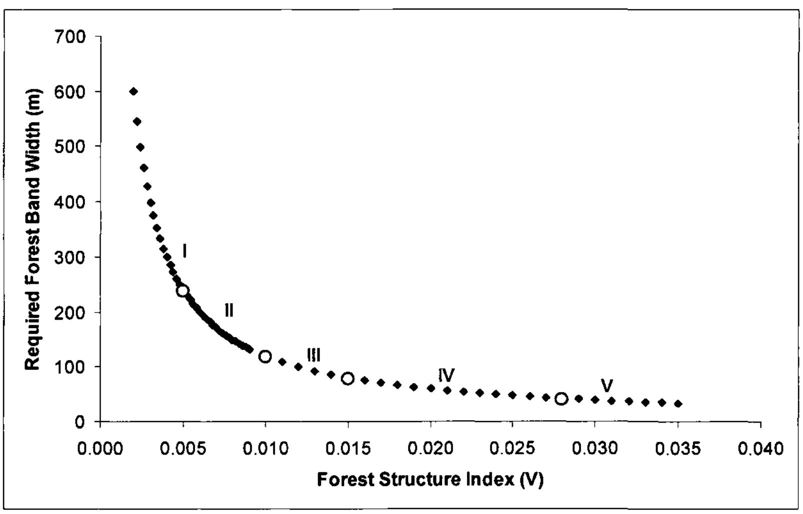


Figure 5.6. Theoretical curve showing relationship between mangrove structure index (V) and mangrove band width (m).

Index of mangrove structure is classified into 5 levels of wave prevention based on its relation to wave height (Fig. 5.6; Table 5.2). Required mangrove band width decays exponentially by vegetation index (V). When mangrove forest is tall, dense, and high canopy closure (i.e., high V index), a narrower forest band is required. When mangrove forest is short, low tree density and canopy closure (i.e., low V index), a wider mangrove band is required.

Table 5.2. Classification of mangrove forests for preventing sea waves

Levels	V index	Required Band Width (m)	Name of levels
I	< 0.005	> 240	very weak prevention
II	0.005 – 0.010	120 - 240	weak prevention
III	0.010 – 0.015	80 - 120	moderate prevention
IV	0.015 – 0.028	40 - 80	strong prevention
V	> 0.0280	< 40	very strong prevention

* Maximum wave height is assumed 300cm

- Level 1: V index is less than 0.005, in this level when V index is increasing. The minimum mangrove band width is decreasing quickly from 600m to 240m.

- Level 2: V index is ranging from 0.005 to 0.015. In this level the increasing of V index causes the minimum band width fairly quickly decreasing from 240m to 120m.

- Level 3: V index is ranging from 0.010 to 0.015. In this level, the increasing of V index results in a gradually decreasing of minimum band width from 120m to 80m.

- Level 4: V index is ranging from 0.015 – 0.028. The increasing of V index in this level results in a slowly decreasing of minimum band width from 40m to 80m.

- Level 5: V index is greater than 0.028. The increasing of V index causes a minimal decreasing of minimum band width always less than 40m.

Applying the threshold of V index in Table 5.3, we have identified the levels of wave prevention for 32 mangrove forest plots (Appendix 5.4). The results show that the levels of wave prevention of southern plots about 3÷4 are higher than those of northern plots about 1÷2. This indicates that the southern mangrove forest can protect coastline better than the northern mangrove forest does.

5.3.2.2. Minimum Mangrove Band Width for Coastal Vietnam

Naturally, structures of mangrove forests change from north to south along coastal Vietnam due to the variations in nutrient supply and climate (Hong et al., 1983). Therefore, required mangrove band width for a given coastal area is depending on its structures (V index). From the data in Appendix 5.1, we analyze the changes of vegetation index by Latitude (degree). The results show that Latitude is inversely related to V index (equation 5.6) indicating that mangrove forests grow better to the south coast.

$$V = -0.0008*Lat + 0.21 \qquad R^2=0.694,\ P<0.0001 \qquad (5.7)$$

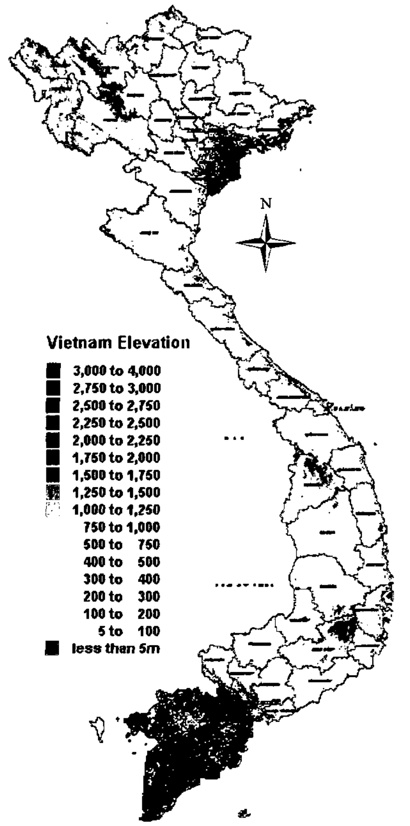
Where: V is forest structure index (equation 4.11)

Lat is the latitude (degree)

Required mangrove forest areas for different coastal provinces of Vietnam are defined by following steps.

1. Plugging geo-coordinates of different coastal provinces into equation (5.7) to predict corresponding V index.
2. Plugging predicted V index (step 1) into equation (5.5) to identify required mangrove band width for different coastal provinces with the assumptions that initial and safe wave height are 300cm and 30cm, respectively.
3. Using spatial analysis in GIS to identify required mangrove band length (i.e., coastal length having elevation less than 5m) for each province. The product of mangrove band width (step 2) and length is required mangrove forest areas for different provinces of Vietnam (Table 5.3).

Table 5.3. Mangrove structure index (V), required band width, length, and areas for coastal provinces; Map of Vietnam showing areas having elevation less than 5m



Provinces	V Index	Widths (m)	Lengths (km)	Areas (ha)
Quang Ninh	0.0057577	400	220	8798
Hai Phong	0.0062634	368	37	1360
Thai Binh	0.006619	348	43	1496
Nam Dinh	0.0069398	332	69	2289
Ninh Binh	0.0069837	330	15	495
Thanh Hoa	0.0072341	318	38	1210
Nghe An	0.0080583	286	43	1229
Ha Tinh	0.0091554	252	38	956
Quang Binh	0.0101276	227	23	523
Quang Tri	0.0110317	209	30	626
Hue	0.0114572	201	32	643
Da Nang	0.0118131	195	4	78
Quang Nam	0.012464	185	15	277
Quang Ngai	0.0130819	176	18	317
Binh Dinh	0.0140979	163	10	163
Phu Yen	0.0151644	152	15	228
Khanh Khoa	0.0161735	142	40	569
Ninh Thuan	0.0168845	136	20	273
Binh Thuan	0.0176622	130	35	456
Vung Tau	0.0182507	126	27	341
Ho Chi Minh City	0.0180121	128	41	524
Tien Giang	0.0184426	125	40	499
Ben Tre	0.0188193	122	83	1016
Tra Vinh	0.0191366	120	68	818
Soc Trang	0.0193371	119	71	845
Bac Lieu	0.0196994	117	70	818
Ca Mau	0.0200049	115	211	2429
Kien Giang	0.0189446	122	140	1702

- Assumptions for calculations: initial wave height is 300cm; safe wave height behind forest band is 30cm; coastal lengths are identified with elevation less than 5m.
- Provinces are listed from north to south.

As shown in Table 5.3, the required mangrove band widths for provinces reduce from north to south. With the assumption of wave height of 300cm, minimum mangrove band widths for northern, central and southern provinces are 300-400m, 150-300m, and 150-300m, respectively. The total required mangrove forest areas for wave protection of Vietnam are about 38000 ha. The calculation with assumption of initial wave height of 500cm is listed in Appendix 5.5.

5.4. CONCLUSIONS

Mangrove forests are very important ecosystems located in the upper intertidal zones of the tropics. They are the primary source of energy and nutrients in these environments. They have a special role in stabilizing shorelines, minimizing wave damage, and trapping sediments. However, in recent decades mangrove forests in Vietnam are threatened by conversion to agriculture and aquaculture. The primary objectives of this study were to define minimum mangrove band width for coastal protection from waves in Vietnam.

We have set up 32 plots in 2 coastal regions of Vietnam to measure wave attenuation from the edge to the center of forest (distances). The results show that wave height closely relates to cross-shore distances in an exponential equation. All single equations are highly significant with $P < 0.001$ and $R^2 > 0.95$.

We have established an integrated exponential equation applied for all cases, in which a coefficient (i.e., intercept in log transformation of exponential equation) is a function of initial wave height, and b coefficient (i.e., slope in log transformation of exponential equation) is a function of canopy closure, height, and density. The integrated equation was used to define appropriated mangrove band width. With the assumption that the average maximum wave height is 300cm and safe wave height behind forest band is 30cm, required mangrove forest band width in associated with its structures was defined.

Mangrove structure index (V) is classified into 5 levels of protection waves. The southern mangrove forests of Vietnam protect waves better than the northern mangrove forests do (i.e., higher V index). Required mangrove band width and length for wave attenuation are calculated for different coastal provinces of Vietnam based on the relationship between index of mangrove structures and latitude. The total required mangrove forest areas for coastal protection from wave are about 38,000 ha.

LITTERATURE CITED

Alongi, D. M., 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine Coastal and Shelf Science. 76, 1-13.

FPD, 2008. Vietnam Annual Forest Cover, 2007. Forest Protection Department (FPD), Ministry of Agriculture and Rural Development, http://www.kiemlam.org.vn/

Hong, P.N., and San, H.T., 1993. Mangroves of Vietnam. IUCN, Wetland Programme, Bangkoc, Thailand, 158pp.

Kathiresan, K., and Rajendran, N., 2005. Coastal mangrove forests mitigated tsunami. Estuarine Coastal and Shelf Science. 65, 601-606.

Kobayashi, N., Raichle, A. W., and Asano, T., 1993. Wave Attenuation by Vegetation. Journal of Waterway, Port, Coastal, and Ocean Engineering. 119 (1), 30-48.

Luong, V. H. P., and Massel, S. R., 2008. Energy disspation in non-uniform mangrove forests of arbitrary depth. Journal of Marine Systems. 74, 603-622.

Luong, V. H. P., and Massel, S. R., 2006. Experiments on wave motion and suspended sediment concentration at Nang Hai, Can Gio mangrove forest, Southern Vietnam. Oceanlogia, 48 (1), 23-40.

Massel, S.R., Furukawa, K., and Brinkman, R.M., 1999. Surface wave propagation in mangrove forests. Fluid Dynamics Research. 24, 219-249.

Mathers, S., and Zalasiewicz, J., 1999. Holosence sedimentary architechture of the Red River Delta, Vietnam. Journal of Coastal Research, 15 (2), 314-325.

Mazda, Y., Magi, M., Kogo, M., and Hong, P.N., 1997a. Mangroves as a Coastal Protection from Waves in the Tong King Delta, Vietnam. Mangroves and Salt Marshes, 1, 127-135.

Mazda, Y., Wolanski, E., King, B., Sase, A., Ohtsuka, D., and Magi, M., 1997b. Drag Force due to Vegetation in Mangrove Swamps. Mangroves and Salt Marshes, 1, 193-199.

Quartel, S., Kroon, A., Augustinus, P.G.E.F., Van Santen, P., and Tri, N.H., 2007. Wave Attenuation in Coastal Mangroves in the Red River Delta, Vietnam. Journal of Asian Earth Sciences. 29, 576-584.

Sterling, J. E., Hurley, M.M., and Minh, D.L., 2006. Vietnam: A Natural History, Yale University Press, pp. 1-21 and pp. 91-92.

Theobald, D.M., 2003. GIS Concepts and ArcGIS Methods. 1st Edition, Conservation and Planning Technologies Publisher, USA. pp. 238-266.

Thompson, C., and Thompson, T., 2008. First Contact in the Greater Mekong: new species discoveries. www.panda.org/greatermekong.

VEPA, 2005. Overview of Wetlands Status in Vietnam Following 15 Years of Ramsar Convention Implementation. Vietnam Environment Protection Agency.

VEPA, 2006. Environmental Report of Vietnam, 2006. Vietnam Environment Protection Agency.

Wu, Y., Falconer, R.A., and Struve, J., 2001. Mathematical Modelling of Tidal Currents in Mangrove Forests. Environmental Modelling Software. 16, 19-29.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary and Conclusions

The main objective of the study was to investigate the impacts of forest and topography on soil water retention, storm runoff, erosion, and wave attenuation in Vietnam. The dissertation addresses the objective through four chapters. The following summarizes the major components of each chapter.

Chapter 2 explores effects of forest degradation on soil water retention. Forest degradation is a human-caused transition from a primitive natural forest to a poorer quality, secondary forest and shrubland. Forty forest plots were set up in four forest types in Thuong Tien Natural Reserve located in northern Vietnam, including moderate tree volume forest, low tree volume forest, young regeneration forest, and mixed shrub and grass. The information measured in each plot includes forest structure, topography, and soil properties. Rainfall amounts and soil samples, taken at different depths were collected on 60 consecutive days. Soil porosity and soil moisture were analyzed in the laboratory.

The results from this study show that forest degradation in Vietnam has affected soil water retention. Soil water retention, a function of soil moisture, bulk density and soil depth, spatially and temporally varies among forest types. It decreases, in turn, from moderate forest to poor forest, regeneration forest, and mixed grass and shrub, meaning that the lower the human impacts, the higher the soil water retention. Litter cover, ground cover, and porosity mostly cause the variations among forests. Temporarily, the two models with the Root Square Mean Error (RSME) about 3% predict forest soil moisture. Model 1, prediction for a rainy day, is most influenced by rainfall and antecedent soil moisture. Those of model 2, prediction for a no-rain day, are influenced by time interval and soil moisture after the last rain event.

Chapter 3 analyzed the relationships between watershed characteristics and rainfall on storm runoff responses. Fifteen watersheds representing different ecological regions, climates and forest covers in Vietnam were selected for this study. Hydrological data include both rainfall amounts and hourly streamflow rates gauged at watershed outlets in 2005. There were a total 830 storm events during the time frame. Six watersheds factors (e.g., watershed slope (%), elevation difference (m), watershed size (km^2), watershed shape, forest cover (%), and forest distribution index (%)) are analyzed in relation to four runoff indices. They are indices of increasing initial flow to peak flow (m^3hr^{-1}), decreasing peak flow to low flow (m^3hr^{-1}), lag time from center of rainfall to peak flow (hr), and variation of daily streamflow (%). Additionally, this study tests effects of rainfall amounts, rainfall intensity, initial flow and season of peak flow for the different watersheds by adapting an exponential equation.

In this chapter it is shown that the watershed factors influence runoff indices at different levels of statistical significance. Forest cover and forest cover distribution were more highly correlated with runoff when compared to other watershed factors. They amount to 30% of the total variation of responding runoff. Shape index and elevation difference are significant in two out of four runoff indices. However, watershed size and slope are not found to relate to any runoff indices. In multivariate regression analyses, watershed factors account for approximately 50-60% of the total variation in runoff indices. Rainfall and initial flow are significantly related to peak flow in all watersheds, whereas, there are no significant effects of rainfall intensity and seasonal interaction in any of the watersheds.

Chapter 4 identified required forest areas for protection of soil from erosion in Vietnam. Required forest areas are defined by analyzing the role of forest cover on erosion protection. The study uses an available soil loss equation for Vietnam to create two integrated indices, one is "index of vegetation" and the other is "index of erosion risk." Required forest areas are based on mathematical comparisons (inequality) of these two indices.

A map of erosion risk for Vietnam is generated by using GIS techniques (e.g., interpolation, raster calculation). The input layers for spatial analyses are DEM, monthly rainfall. Soil loss tolerance of 10 ton $ha^{-1}yr^{-1}$ is used to define required forest areas. For example, if the erosion risk is high than an area should be left in natural forest. The result is a map of required forest areas for soil erosion protection for different provinces of Vietnam.

Chapter 5 analyzed wave attenuation in relation to mangrove forest structures. The main objective of this study is defining minimum mangrove band width for coastal protection from waves. Thirty-two mangrove forest plots in five different locations were set up to measure forest structures and cross-shore distances of wave height. Minimum mangrove band width for wave attenuation is derived by statistically analyzing relationships between forest structures and wave height reduction.

Wave height reduction is an exponential function of initial wave height and mangrove forest structure. This regression equation is used to define required mangrove band width. It ranges from less than 40m to greater than 240m depending on the mangrove structure. The total required mangrove area for coastal protection from waves of Vietnam is about 38,000 ha.

6.2. Recommendations for Further Research

Four independent studies in this dissertation present a number of possibilities for further research.

The first study discussed the effects of deforestation on soil water retention and concluded that deforestation has caused a reduction of soil water retention. Four forest types in this study were selected to represent different levels of deforestation. Soil water retention depends on soil moisture, soil depth and bulk density, so deforestation is an indirect factor causing the reduction of soil water storage. Further research should take into account the influences of deforestation on soil depth and porosity. Additionally, as mentioned in the discussion, deforestation causes a decrease in soil water storage. Consequently, it may cause a decrease in outflow within a watershed. This conclusion is contrary to other previous research. Hence, paired watershed comparison or treatment vs. control experiment should be conducted to scientifically support the conclusion above. For the rainfall and soil moisture relationship, the study has used rainfall volume as a predictor in the model predicting soil moisture. Further study also should take into account the distribution of rainfall (i.e., surface runoff, infiltration, evapotranspiration).

The second study analyzed the relationship between watershed factors on runoff responses. Fifteen watersheds used in this study varied greatly in topography, vegetation, and climate. Therefore, the statistically significant or non-significant effect of an individual watershed factor (e.g., slope, size, forest cover) on runoff may be influenced by other uncontrolled factors. Paired watershed comparison or hypothesis computer model should be applied to isolate effect of these factors. Due to data limitations in this study, some watershed factors or runoff indices should be adjusted/added/removed in further research. For example, average watershed slope and average rainfall intensity should be replaced with average slope of stream network and maximum rainfall intensity in one hour, respectively. Lag time, defined as "time interval from center of rainfall to peak flow" should be changed to "time interval from center mass of rainfall to peak flow". As concluded in the first study, soil water storage varies among forest types, so vegetation cover may be divided into different cover types (e.g., natural forest, plantation forest, and shrub).

In the third study, a few assumptions were made for the calculations (i.e., soil loss tolerance). These may alter the results. In reality, soil loss tolerance varies depending on climate, topography, vegetation, land-use practice, etc. In this study, soil loss tolerance of 10 ton $ha^{-1}yr^{-1}$ is applied for all cases. Therefore, the output maps are averaged by this variable. Furthermore, the soil loss equation used was not validated for different locations, as well as compared with other models (e.g., RUSLE) to find which one is more robust. Indices of vegetation cover structure are simplified, only four vegetation classes are classified among an abundance of cover types in Vietnam. These limitations should be taken into account in further research. The GIS-based implementation is very robust and useful for spatial prediction. One of the most effective ways to reduce the uncertainty introduced by the lack of data in this study is to increase the range and reduce spatial resolution of input maps.

For the relationship of wave height to mangrove forest in the fourth study, safe wave height behind forest band of 30cm has been selected based on interviewing 50 respondents. To get more accurate results, a field study should be considered. Maximum initial wave height of 300 cm (or 500 cm) is applied for all coastline of Vietnam. In reality, maximum wave height may vary from the north to south coast due to differences in climate regime. Therefore, prediction mangrove band width is averaged by this variable. Conceptually, other factors strongly influent on wave attenuation are wind, tide, and cross-shore elevation should take into account in the further research.

In general, hydrological conclusions are often drawn from a long-term dataset. In this dissertation, data of soil moisture of sixty consecutive days, one-year streamflow, and 92 replication of wave height measurement may be a temporal/spatial limitation of these studies. The use of larger datasets and shorter frequency (e.g., rainfall, streamflow) can improve the regression model.

APPENDICES

Appendix 2.1. Forest Structures, Soil Porosiy, and Soil Moisture of Forty Forest Plots in Thuong Tien

Forest types	Density (tree ha^{-1})	DBH (cm)	Height (m)	Volume (m^3)	CC (%)	GC (%)	LC (%)	Po_5 (%)	Po_25 (%)	Po_55 (%)	W_5 (%)	W_25 (%)	W_40 (%)	W_90 (%)
M. Forest	509	18.7	16.2	113.4	63.8	56.2	68.5	53.7	45.3	40.2	38.5	35.6	31.6	35.9
M. Forest	500	22.4	15.3	150.5	67.1	52.7	72.4	62.2	53.8	49.6	40.2	34.6	35.2	
M. Forest	556	19.6	14.4	121.1	54.7	62.3	75.7	53.6	46.6	40.5	37.3	35.4	33.5	36.1
M. Forest	540	21.9	15.2	154.3	65.9	50.1	72.1	64	57.6	54.5	39.1	34	36.6	
M. Forest	480	18.2	15.7	97.7	67.7	43.2	66.3	48.6	36.8	34.3	40.1	36.8	33.8	35.6
M. Forest	576	19.1	15.3	125.5	58.3	52.7	68.7	58.5	51	47.6	41.8	35.6	34.7	36.7
M. Forest	693	18.9	17	164.5	70.4	38.9	81.2	54.5	45.4	43.7	38.2	33.4	33.5	
M. Forest	425	18	15.5	83.3	52.9	66.3	62.9	56.5	51.2	52.8	41.3	34.3	31.8	35.3
M. Forest	530	19.1	14.8	112.7	68.2	45.4	78.6	53.9	50.5	43.1	35.4	35.6	31.2	36.2
M. Forest	516	24.3	16	191.1	73.8	46.2	81.7	65.8	58.7	54.7	38.2	33.9	32.5	
P. Forest	289	21.8	16.5	89.3	60.2	46.2	68.9	58.7	50.3	45.7	36.2	33.5	34.2	
P. Forest	521	17.3	15.7	96.6	61.7	33.8	76.9	56.2	47	40.3	35.1	32.4	33.4	
P. Forest	340	16.3	14.2	50.4	48.9	63.7	60.2	52.2	47.7	45.3	32.2	29.5	25.6	32.8
P. Forest	498	17.9	14.2	89.2	58.2	36.2	78.8	53.7	50.5	48.8	32.9	30.2	31.7	
P. Forest	351	17.2	14.3	58.5	53.1	56.5	66.3	47.4	52.6	46.9	33.2	28.7	32.2	
P. Forest	415	16	11.9	49.4	51.3	60.1	48.2	46.6	43.5	42.6	35.4	32.7	26.9	33.4
P. Forest	368	14.2	16	46.6	44.7	65.1	38.7	44.9	42.6	41.2	36.5	31.7	31.8	
P. Forest	362	15.1	14.8	47.8	46.2	37.8	69.3	40.3	39.9	37.9	32.4	28.4	32.1	
P. Forest	219	17	14.1	34.8	48.7	64.7	36.2	35.7	33.6	33.5	30.8	32.2	30.9	
P. Forest	232	12.3	15	20.8	44.1	60.2	48.4	30.5	28.7	26.5	33.8	27.7	32.2	
R. Forest	674	15	12.8	76.2	57.2	40.6	60.2	46	45.7	44.8	34.9	31.5	27.9	32.1

Forest types	Density (tree ha^{-1})	DBH (cm)	Height (m)	Volume (m^3)	CC (%)	GC (%)	LC (%)	Po_5 (%)	Po_25 (%)	Po_55 (%)	W_5 (%)	W_25 (%)	W_40 (%)	W_90 (%)
R. Forest	745	13.4	13.2	69.3	48.3	60.2	42.7	47.9	48	45.8	34.5	30.5	30.5	
R. Forest	773	13.4	13.1	71.4	52.7	63.1	48.2	49.5	47.5	46.9	33.2	29.6	28.6	33.3
R. Forest	641	12.9	13.1	54.9	47.9	48.2	46.2	40.3	39.6	40.2	31.5	23.5	29.7	
R. Forest	658	15.4	13.5	82.7	62.8	36.8	63.7	43.3	42.2	41.7	30.3	26.6	30.8	
R. Forest	537	12.1	10.9	33.6	38.6	70.4	38.9	35.7	34.7	33.4	30	25.8	24.1	31.6
R. Forest	412	17	14.9	69.6	52.6	66.5	39.8	63.1	45.8	41.7	37.4	31.9	33.6	
R. Forest	584	13.4	12.5	51.5	46.1	46.7	44.2	37.6	35.7	32.1	29.2	23.2	28.2	
R. Forest	486	13.7	11.4	40.8	48.7	50.1	46.8	32.3	31.2	31	29.8	21.5	29.8	
R. Forest	452	20.5	12.7	94.7	60.3	37.2	60.2	57.7	50.5	48.6	36.3	27.6	30.5	
Mixed SG	0	0	0.8	0	0	76.4	90.4	40.4	37.9	42.9	29.6	24.6	26.2	
Mixed SG	0	0	0.9	0	0	72.4	64.1	43.6	42	39.9	31.5	25.5	26.1	
Mixed SG	0	0	1.2	0	0	80.1	62.8	45.3	43.7	38.4	30.3	26.7	22.4	26.5
Mixed SG	0	0	0.8	0	0	76.3	68.9	45	43.8	43.2	29.6	24.7	25.8	
Mixed SG	0	0	0.9	0	0	72.9	81.5	39.3	38.6	39	27.7	21.6	26.4	
Mixed SG	0	0	0.9	0	0	77.6	58.6	38.2	38	35.4	23.6	20.8	25.4	
Mixed SG	0	0	0.6	0	0	65.6	56.2	32.2	30.1	28.8	28.1	21	19.7	25.8
Mixed SG	0	0	0.9	0	0	87.2	80.7	43.7	43	37	22.9	20.3	24.7	
Mixed SG	0	0	0.5	0	0	80.6	63.5	33.3	30.3	29.9	26.9	22.3	20.6	25.7
Mixed SG	0	0	0.5	0	0	78.2	88.4	44.3	43	37.6	28.5	24.5	26	

** M. Forest: Moderate Forest; P. Forest: Poor Forest; R. Forest: Rehabilitation Forest; Mixed SG: Mixed Shrub and Grass*

** CC: Canopy Closure; GC: Ground Cover; LC: Litter Cover; Po_5, P_25, Po_55 are soil porosity at depth of 5cm, 25cm, 55cm , respectively; W5, W_25, W_40, W_90 are soil moisture at depths of 5cm, 25cm, 40cm, 90cm, respectively.*

Appendix 2.2. Bivariate Correlations Among Independent Variables

		Slope	Density	Diameters	Height	Volume	Canopy closure	Ground cover	Litter cover	Porosity 5cm
Slope	Pearson Correlation	1	.197	.496(**)	.531(**)	.160	.440(**)	-.351(*)	-.364(*)	.112
	Sig. (2-tailed)		.224	.001	.000	.325	.005	.027	.021	.491
Density	Pearson Correlation	.197	1	.799(**)	.829(**)	.748(**)	.871(**)	-.728(**)	-.237	.429(**)
	Sig. (2-tailed)	.224		.000	.000	.000	.000	.000	.141	.006
Diameters	Pearson Correlation	.496(**)	.799(**)	1	.960(**)	.873(**)	.979(**)	-.758(**)	-.098	.649(**)
	Sig. (2-tailed)	.001	.000		.000	.000	.000	.000	.549	.000
Height	Pearson Correlation	.531(**)	.829(**)	.960(**)	1	.784(**)	.968(**)	-.746(**)	-.219	.522(**)
	Sig. (2-tailed)	.000	.000	.000		.000	.000	.000	.175	.001
Volume	Pearson Correlation	.160	.748(**)	.873(**)	.784(**)	1	.868(**)	-.694(**)	.222	.790(**)
	Sig. (2-tailed)	.325	.000	.000	.000		.000	.000	.168	.000
Canopy closure	Pearson Correlation	.440(**)	.871(**)	.979(**)	.968(**)	.868(**)	1	-.814(**)	-.115	.591(**)
	Sig. (2-tailed)	.005	.000	.000	.000	.000	.	.000	.481	.000
Ground cover	Pearson Correlation	-.351(*)	-.728(**)	-.758(**)	-.746(**)	-.694(**)	-.814(**)	1	-.054	-.379(*)
	Sig. (2-tailed)	.027	.000	.000	.000	.000	.000		.741	.016
Litter cover	Pearson Correlation	-.364(*)	-.237	-.098	-.219	.222	-.115	-.054	1	.356(*)
	Sig. (2-tailed)	.021	.141	.549	.175	.168	.481	.741		.024
Porosity 5cm	Pearson Correlation	.112	.429(**)	.649(**)	.522(**)	.790(**)	.591(**)	-.379(*)	.356(*)	1
	Sig. (2-tailed)	.491	.006	.000	.001	.000	.000	.016	.024	

*** Correlation is significant at the 0.01 level (2-tailed).*

** Correlation is significant at the 0.05 level (2-tailed).*

Appendix 3.1. Distribution of different forest types in 15 watersheds

No.	Stations	Forest Cover (%)					Bare Land
		R.F [a]	M.F [b]	P.F [c]	Y.F [d]	PL.F [e]	(%)
1	Lam Son	0	0	0.7	9.6	13.5	76.2
2	Lang Son	0	0.7	1.1	2.9	6.1	89.3
3	Na Hu	20.2	34.4	3.3	15.4	0	26.7
4	Mu Cang Chai	0.2	8.3	0.2	11.6	17.5	62.2
5	Ngoi Hut	0.1	23.1	8.3	8.4	0.8	59.3
6	Vinh Yen	0	4.7	5.3	23.6	0	66.4
7	Binh Lieu	0	0.1	1.5	8	7.6	82.8
8	Thanh Son	0.2	3.4	4.7	15.9	5.8	69.9
9	Son Diem	34.1	14.5	17.8	7.4	1	25.3
10	Gia Vong	13.4	4.4	16.6	1.5	3.7	60.5
11	Thuong Nhat	27.5	9.2	19.8	9.8	2	31.7
12	An Chi	4.8	3	6.4	5.6	0.9	79.3
13	An Khe	9.7	14.6	11.9	8.1	1.2	54.4
14	Song Luy	1.8	70.1	1.3	6.8	0.2	19.8
15	Binh Tuong	8.3	19.1	8.5	14	0.8	49.4

[a] *Rich forest;* [b] *Moderate forest;* [c] *Poor forest;* [d] *Young forest;* [e] *Plantation forest.*

Appendix 3.2. Coefficients of selected models for four runoff indices

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
	B	Std. Error	**Beta**			Zero-order	Partial	Part	Tolerance	VIF
1) (Constant)	11.136	1.477		7.540	.000					
Average elevation difference	-.007	.002	**-.610**	-3.224	.007	-.700	-.681	-.589	.931	1.074
Forest cover	-.047	.026	**-.344**	-1.816	.094	-.504	-.464	-.331	.931	1.074
2) (Constant)	-1.523	8.093		-.188	.854					
Shape ratio	11.942	5.009	**.482**	2.384	.035	.529	.567	.479	.991	1.010
Average elevation difference	-.011	.005	**-.487**	-2.412	.033	-.534	-.571	-.485	.991	1.010
3) (Constant)	1.851	2.209		.838	.418					
Shape ratio	2.866	1.321	**.499**	2.170	.051	.156	.531	.446	.799	1.251
Integrated index	2.009	.603	**.766**	3.329	.006	.542	.693	.684	.799	1.251
4) (Constant)	241.186	17.727		13.605	.000					
Forest cover	-2.574	.789	**-1.737**	-3.262	.007	-.561	-.686	-.643	.137	7.307
Integrated index	74.993	31.541	**1.267**	2.378	.035	-.348	.566	.469	.137	7.307

1) Best model for index of decreasing flow rate;

2) Best model for index of increasing flow rate;

3) Best model for lag time to peak flow;

4) Best model for daily flow variation.

Appendix 4.1. 30-year Averaging Monthly Rainfall, Spatial Distribution, and Elevation of 158 Weather Stations in Vietnam

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
1	Tam Duong	37.1	47.4	68.9	200.6	363.8	487.5	507.2	385.6	235	159.3	97.4	31.8	22.42	103.48	900
2	Muong Te	25	33.6	44.2	124.6	243.6	477.2	610.5	499.2	198	118.2	71.9	30.9	22.35	102.83	310
3	Sin Ho	39.4	47.2	66.4	183.2	315	503	591.4	494.9	258.7	154.7	90.5	38.8	22.35	103.25	1529
4	Binh Lu	28.9	51.9	61.3	153.9	251.2	497.1	536.5	365.4	151.6	111.1	61.3	35.2	22.3	103.62	636
5	Lai Chau	23.6	41.3	55.5	134.7	271	423.2	434.1	370.6	158	80.8	52.7	20.6	22.05	103.15	244
6	Tua Chua	30.2	36	50.7	151.8	214.3	351	364.9	359.4	156.4	97.7	55.5	23.8	21.98	103.35	1250
7	Tuan Giao	27.5	30.4	53.9	131	199.8	304.8	289.2	290.3	153.2	67.9	45.6	19.1	21.58	103.42	570
8	Pha Din	31.1	30.7	60.2	132.3	224	301.3	327	369.6	181.2	88.4	51	21	21.57	103.5	1347
9	Dien Bien	19.3	32.8	52.4	106.3	182.1	275.4	313.5	346	147.3	63.8	25.6	18.6	21.35	103	479
10	Quynh Nhai	28.6	33.9	51	142.3	192.6	312.8	318	349.9	175.4	78.9	52.8	23.2	21.83	103.57	802
11	Son La	16.4	26	39.8	116.5	170.8	253.8	277.2	279.5	155.3	61.8	34.5	12.7	21.33	103.9	676
12	Phu Yen	21	21.2	32.6	124.2	183.5	221.8	229.7	305	234.3	107.9	43.8	11.6	21.27	104.65	182
13	Bac Yen	32.2	22.4	42	112.8	197.6	271.1	263.8	311.9	212.9	94.3	45.8	20.8	21.25	104.42	65
14	Co Noi	15.9	19	31.3	118.8	154.3	215.7	231.5	295.5	136.2	62.6	28.2	10.5	21.13	104.15	704
15	Song Ma	14.7	16.7	33.5	108.3	145.6	215.4	202.1	254.8	111.3	43.7	29.5	9.8	21.07	103.73	302
16	Yen Chau	13.1	16.7	32.1	99.5	115.7	196.7	212.2	279.6	150.5	65.4	26.5	9	21.05	104.28	59
17	Moc Chau	14.8	21.2	34	98.7	165.5	220.8	266.3	331.4	257.2	106.4	31.8	11.8	20.85	104.63	958
18	M. Khuong	32.2	43.5	52.4	102.7	202.9	282.6	390.7	368.9	191.6	131	82.8	32.2	22.77	104.12	772
19	Bac Ha	18.1	30.4	42.7	120.6	165.4	259.9	328.8	362.6	237.5	124.7	64.2	19.1	22.53	104.28	957
20	Lao Cai	20.7	35.5	59.9	119.7	209	236.3	301.3	330.5	241.2	131.2	54.6	24.5	22.5	103.95	99
21	H.L.Son	63.8	71.8	82	219.6	416.6	564.8	680	632.1	418.2	235.7	101.4	66.4	22.35	103.77	2170
22	Sa Pa	55.8	79.2	105.5	197.2	353.2	392.9	453	478.1	332.7	208.7	121.6	55.1	22.33	103.83	1570
23	Luc Yen	31.2	45	61.7	138.9	202.8	300.6	372.6	419.6	287.1	167.2	66.8	32.6	22.08	104.72	84

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
24	Than Uyen	33.7	39.3	56.5	166	238.7	391.2	409.4	406.8	176	78.6	49.9	20.8	22.02	103.92	556
25	M.C.Chai	25.3	37.1	49.9	135.5	211.2	345.5	371.4	351.9	152.2	75.9	40.4	17.1	21.85	104.83	975
26	Yen Bai	32.1	49.6	73.7	131.2	225.9	306.9	346	399.8	288.5	167.1	59.8	26.3	21.7	104.87	56
27	Van Chan	14.7	19.1	36.9	98.6	144.8	217.1	232.4	342.3	267.1	127.8	32.7	13.9	21.6	104.52	257
28	Pho Bang	21.4	23.6	38.3	93.2	184.3	301.7	379.4	317.8	178.9	114	65.7	26.3	23.25	105.18	1400
29	Ha Giang	33.7	43.5	49.7	116.3	283.7	437.2	515.6	420.6	242.5	152.2	103.6	31.5	22.82	104.98	118
30	H.Su.Phi	19.6	21.5	42.6	84.9	197.1	297.1	331.2	331.6	187.2	105.1	56.3	17.8	22.75	104.67	553
31	Bac Me	24.1	25.2	43.9	100.3	232.5	297.6	338.5	285.8	136.6	101.2	58.1	22.3	22.73	105.37	74
32	Bac Quang	68.8	68.1	86.5	244.3	821.2	900.9	893.8	626.4	424.4	384.1	194.8	88.8	22.32	104.87	74
33	Chiem Hoa	26.7	33.5	52.3	130.7	209.9	276.3	278.6	325.6	175.9	111.1	57.4	21.7	22.15	105.27	50
34	Ham Yen	26.7	38.5	55.9	127.3	211.5	310.5	331.8	355.3	219.9	125	50.4	22.7	22.07	105.03	47
35	TuyenQuang	20.6	31.6	44.2	102	211.4	253.7	284.7	304.5	214.1	111.5	44.4	18.7	21.82	105.22	42
36	Bao Lac	12.6	23.7	41.3	77	160.3	214.5	233.8	254.3	106.6	77.6	55	19.3	22.95	105.67	258
37	Ha Quang	24	21.9	40	96.4	217.1	308.5	294.4	297.6	177.9	98.8	43.1	18.1	22.92	106.17	209
38	TrungKhanh	29.2	40	46.6	101	212.1	292.8	309.8	308.1	151.2	95.9	47.9	30.9	22.83	106.52	520
39	NguyenBinh	36.9	33.8	47.9	98.9	199.9	287.4	284.2	325.5	200.9	115.9	67.2	38.4	22.65	105.95	208
40	Cao Bang	16.1	27.1	39.3	88	183.9	250.1	264.6	267.1	156.7	86	44.4	19.4	22.65	106.23	258
41	Cho Ra	10.9	23.7	34.6	91.6	190.5	241.6	243.1	268.7	144.6	73.8	38.7	16.5	22.45	105.72	210
42	Ngan Son	22.2	37.7	47.1	96.5	203.8	292.5	335.1	323	166.6	85	52.6	23.7	22.43	105.98	566
43	That Khe	27.8	37.9	49	92.1	186.8	229.5	238.1	282	168.5	91.9	46.9	31.6	22.25	106.47	275
44	Bac Son	35.3	30.3	51.6	122.8	199.8	232.6	262.8	279.1	176.5	79.9	46.6	23.6	21.9	106.32	400
45	Lang Son	24	41.3	53	96.3	164.8	199.6	257.9	255	164	78.7	34.3	23	21.83	106.77	258
46	Dinh Lap	18.8	26.8	38.6	97.5	162	227.7	282.2	275.4	177.6	93.7	33.6	14.7	21.53	107.1	174
47	Huu Lung	24	25	36.9	133.3	182.4	233.1	237.7	283.5	172.8	106.8	37.4	15.3	21.5	106.35	40
48	Bac Can	17.4	33.8	42.1	109.1	192.1	203.9	315.3	313.2	152.7	72.8	37.1	18.6	22.13	105.82	174

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
49	Dinh Hoa	15.8	31.8	48.3	97.2	204.1	265.4	336.6	368	198.6	98.7	39.9	14.5	21.9	105.63	220
50	ThaiNguyen	22	35	55.3	117.6	234	354.5	392.2	390.3	237.5	118	45.4	23.5	21.58	105.83	36
51	Phu Ho	31.5	39.8	50.3	108.9	202.3	247.9	382.5	328.5	219.4	159.7	54.3	24.9	21.45	105.23	36
52	Tam Dao	38.5	45.3	70.5	152	239.8	351.5	465.4	524.6	370.7	238	93.8	40.8	21.45	105.63	897
53	Viet Tri	23.5	29.8	38.9	98.3	189.7	243.4	288.8	312.4	224	144.6	53.9	15.7	21.3	105.42	17
54	Vinh Yen	19.4	24.1	30.4	106.5	174.1	240.2	262.8	333.4	221	127.2	48.2	16.2	21.3	105.6	10
55	Minh Dai	41.4	44	44.1	133.7	224.7	239.1	254.6	312.7	258.4	189	62.1	22.3	21.17	105.05	100
56	Mong Cai	37.6	49.8	69.4	111.8	287.6	455.1	598.6	545.5	319.4	168.2	67.7	38.3	21.52	107.97	7
57	Tien Yen	32	35.5	51.9	130	241.5	369.5	445.6	475.8	361.2	142.5	43.9	23.9	21.33	107.4	14
58	Cua Ong	28.3	31.2	43.1	105.3	206.2	292.7	373.2	535.6	366.7	169.1	73.7	24.8	21.02	107.35	60
59	Co To	23.5	26.6	33.8	79.7	147.4	226.7	268.4	409.4	307.4	125.9	55.3	29.2	20.98	107.77	70
60	Hong Gai	21.1	28	43	78	225.4	290.8	372	458.3	315.2	127.4	38.3	18.7	20.95	107.07	87
61	Hiep Hoa	21.5	23.4	31.2	124.3	180.6	204.1	259.1	294.1	210.7	153.1	46.1	20.1	21.37	105.97	20
62	Luc Ngan	17.4	20.7	31	110.5	152.8	219.8	235.9	265.5	178.8	109	29.1	14	21.37	106.55	15
63	Son Dong	15.2	22.6	35.5	101.3	187.7	225.5	302.4	303.6	205.7	117.4	30.8	16.2	21.33	106.83	59
64	Bac Giang	20.4	28.1	17.5	99.2	202.4	226.6	258.5	304.3	205.6	99.7	38.4	17.7	21.28	106.2	7
65	Son Tay	19.9	25	34.5	104.2	222	262.8	315.7	335.2	271.9	170.1	59.9	17.8	21.13	105.5	30
66	Ba Vi	28.6	29.3	35.7	112.8	307.1	305.4	370.6	382.2	308	228.8	64.9	15.4	21.1	105.43	100
67	Ha Noi	18.6	26.2	43.8	90.1	188.5	239.9	288.2	318	265.4	130.7	43.4	23.4	21.02	105.85	5
68	Ha Dong	20.1	23.2	32	81.6	158.1	226.8	234.5	270.4	241.1	143.5	71.9	17.5	20.97	105.77	5
69	Hoa Binh	14.6	21.1	27.3	95.8	233.5	258.3	331	341.9	343.1	177.6	53.5	12.3	20.82	105.33	23
70	Kim Boi	32.8	27.9	46	110.3	252.1	307.8	337.3	350.5	433.3	247.5	87	23.1	20.67	105.53	100
71	Mai Chau	16.4	9.4	21.3	103.6	199.8	264.1	314.2	344.4	336.1	183	34.8	6.3	20.65	105.05	160
72	Chi Ne	17.7	18.1	34.7	87.6	174.3	254.4	298.3	387	399.5	245.9	68	16.8	20.48	105.33	25
73	Lac Son	24.5	27	43.1	97.1	223.2	272.5	323.6	348.5	343.3	175.4	85.3	23.3	20.45	105.45	40

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
74	Hai Duong	20.1	25.1	37.7	96.9	199.3	228.1	237.8	294.9	225.3	131.7	45.4	19.6	20.95	106.3	2
75	Hung Yen	24.8	34.4	42.3	85.4	162.7	237	260	328.1	280.5	185.2	64.4	24.1	20.67	106.05	4
76	Phu Lien	25.4	34.3	48.2	92.9	203.1	240.1	274	348.6	299.1	156.2	54.4	31.9	20.8	106.63	113
77	Hon Dau	20.3	23.2	36.8	81.4	143.3	219.5	124.5	352	282.9	164.5	32.7	13.6	20.67	106.8	38
78	B.L. Vi	23	22.4	24.3	61.4	80.9	140.5	125.4	281	211.3	106.1	32	18.5	20.07	107.72	63
79	Thai Binh	27.5	31	45.8	87.2	167.8	206.1	233.8	342.4	343.8	216.6	80.1	22.6	20.45	106.35	3
80	Phu Ly	29.9	29.3	50.2	103.6	177.3	254.1	251.3	312	325.8	233.4	86.1	36	20.52	105.42	3
81	Nam Dinh	27.8	35	50.8	81.6	174.7	192.7	230.2	325.2	347.7	194.6	67.5	29.2	20.43	106.17	3
82	Nho Quan	21.4	28.3	42.8	97.6	169.2	253.9	248.2	352	358.7	233.5	77.2	25.8	20.32	105.73	12
83	Ninh Binh	23.7	35.6	46	82.7	166.8	224.1	227.2	301.5	381.8	235.2	69.8	34.1	20.27	105.98	2
84	Hoi Xuan	11.5	15	28.7	87	213	248.6	337.2	318	271	129.2	36.9	11.2	20.37	105.12	87
85	Yen Dinh	16	18.2	29.9	61.8	125.7	209.4	172.7	260.2	320.4	215.2	72.6	17.3	19.97	105.65	9
86	Bai Thuong	30.1	34.4	44.2	79	231.1	252	267.5	319.7	332.7	224.2	95.3	27.1	19.9	105.38	21
87	Thanh Hoa	24.9	30.9	40.8	59.2	156.9	178.7	202.7	278.3	404	263.5	76.5	28.5	19.82	105.77	5
88	Nhu Xuan	26.7	25.8	41.3	56.5	139	175.9	201.7	278.3	436.7	268.8	108.3	31.4	19.63	105.57	10
89	Tinh Gia	41.7	41.8	49.6	53.2	95.3	148.6	150.8	258	496.3	401.2	108.2	33.5	19.53	105.78	5
90	Quy Chau	17.6	12.6	23.8	82.5	198.7	226.4	199.8	276.2	368.1	244.8	65.9	18.1	19.55	105.12	87
91	Quy Hop	27	22.1	26.4	78.3	169.2	222.8	175.9	300.6	298.5	245	57.5	17.1	19.32	105.12	88
92	Tay Hieu	21.4	24.2	29.4	68.2	138.7	175.1	148.4	266.2	368	265.4	67.5	19.2	19.32	105.4	72
93	TuongDuong	11.4	15.3	37.7	93.2	144.1	145.2	137.2	221.6	260	153.1	40.5	9	19.28	104.43	97
94	Quynh Luu	20.2	24.8	27.2	55.8	97.5	147.8	91.2	233	432.9	361.5	88.5	30.8	19.13	105.6	3
95	Con Cuong	35.6	34.4	43.6	92	171.4	163.2	158.2	268.2	386	300.5	104.5	33.5	19.05	105.88	27
96	Do Luong	27.5	32	37.9	82.6	144.3	131.4	145.1	248.6	409.7	303.6	106.8	37.1	18.9	105.3	27
97	Hon Ngu	56.2	73	57.1	87.3	127.9	111.9	77	214.4	578.1	458.9	199.3	58.3	18.8	105.77	113
98	Vinh	52	44	46.6	61.2	136.3	116.4	122.5	188	490.1	427.4	191.1	68.7	18.67	105.67	6

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
99	Kim Cuong	66.3	57.8	67.4	126.1	199.8	163.3	144.2	261.5	537.7	445.2	226.3	88.1	18.45	105.27	10
100	Ha Tinh	102	68	56	71.1	136.6	139.5	137.2	209.7	531.8	651.8	378.9	159.6	18.35	105.9	3
101	Huong Khe	40	41	57.5	97.7	193.6	172.7	145	255.1	543.1	481.2	210.6	67	18.18	105.7	10
102	Ky Anh	130.2	86.5	72.1	76.4	132.6	126.7	141.3	192.7	641.7	680.2	442.7	205.8	18.08	106.28	3
103	Tuyen Hoa	50.7	34.9	47.2	66	140.7	170	136.1	209.5	530.1	582	231.4	67.9	17.83	106.13	25
104	Ba Don	50.5	36.5	38.5	48	95.5	106.4	90	139.7	445.2	592.9	197.7	91.5	17.75	106.42	8
105	Dong Hoi	62.4	43.4	43.8	56.1	106	84.2	86.9	140.4	444.6	596.5	366.2	128.9	17.47	106.62	7
106	Con Co	144.6	78	34.6	39.5	79.5	100.1	71.3	159.3	513.6	496.6	374.4	186.3	17.17	107.37	6
107	Dong Ha	56.5	28.9	24.5	75.5	94.9	114.3	58	140.4	418.9	707.2	521.2	135.3	16.83	107.08	4
108	Khe Sanh	23.3	17.3	25.3	65.8	159.6	243.5	219.6	304	469.6	380.9	302.2	51.3	16.5	106.83	367
109	Hue	161.3	62.6	47.1	51.6	82.1	116.7	95.3	104	473.4	795.6	580.6	297.4	16.4	107.68	17
110	A Luoi	64.5	16.4	58.3	161.3	194.7	251.4	148.1	150	433.6	732	639.1	168.8	16.2	107.42	550
111	Nam Dong	117.1	40.8	42.3	114.3	182.2	298.5	169.2	176	477.2	890.5	696	195.4	16.15	107.72	10
112	Da Nang	96.2	33	22.4	26.9	62.6	87.1	85.6	103	349.7	612.8	366.2	199	16.03	108.18	6
113	Tam Ky	72.9	24.8	8	39.5	94.6	181.8	67.9	114.3	263.8	693.1	659.3	311.5	15.55	108.5	6
114	Truong Sa	119.3	57.6	36.8	47.1	91.6	323.5	220.5	252.2	246.8	314	417.1	383.9	8.65	111.92	2
115	Quang Ngai	156.4	37.1	37	99.3	231.7	270.4	201.7	202.2	391.2	932.8	915.5	365.5	15.13	108.78	8
116	Ba To	131.1	52.5	37.5	37.6	66.3	89.8	75.5	121.8	282.4	586.7	541.5	267.8	14.77	108.72	8
117	Hoai Nhon	167.4	59.7	46.3	60.1	138.6	170.9	143.8	142.2	307	707.6	1055	609.5	14.53	109.02	8
118	Quy Nhon	40.7	10.3	4.2	27.2	102	156.2	69	126.1	274.5	629.3	509.2	155.6	13.77	109.22	5
119	Mien Tay	64.6	32.2	24	32.4	63.4	61.5	54.6	58.6	245.1	463.3	422.7	169.9	13.2	108.95	5
120	Tuy Hoa	59.6	21.3	21.1	38.1	83.9	49.1	42.7	51.7	210.6	449	413.2	151.3	13.08	109.22	12
121	Son Hoa	19.8	4.5	10.8	43.6	157.4	135.2	106.4	77.1	232.8	412.1	400.9	66.8	13.05	108.98	12
122	Nha Trang	46.9	17.4	32.4	33.1	55.3	48.8	43	50.7	167.2	323.5	373.6	167	12.25	109.2	5
123	Cam Ranh	34	5.2	14.9	59.6	95	67.5	28	77.5	178.9	371.2	308.7	132.4	11.95	109.17	5

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
124	Dac To	5.5	10.8	32	105.8	162.2	494.6	282.2	537.3	249.2	216.9	70.4	5.2	14.7	107.82	536
125	Kon Tum	2.5	6.3	35.3	103.7	196	262.8	324.3	339.2	319.7	148.9	58.4	7.5	14.5	108.02	536
126	Play Ku	3	6.8	27.5	94.9	225.7	357	452.9	492.6	360	181	57.4	13.3	13.98	108	800
127	An Khe	15.6	2.4	14.5	74.8	154.7	127	93.1	95.9	153.8	347.8	321.9	64.7	13.95	108.63	800
128	Phu Quy	3.7	7.6	26.2	47.9	130.3	145.2	73.6	161.6	192.4	229	140.8	40.8	13.95	108.63	800
129	Ayunpa	2.2	4.1	8.6	70.4	143.1	142.3	136.8	157.6	212.1	226.2	119	26.4	13.42	108.43	150
130	B.Ma.Thuot	4	6	22.2	97	226	241.4	265.6	292.8	298.3	204.6	93	22.1	12.68	108.05	490
131	M.Drac	93.8	22.7	18	80.7	206.9	141.9	144.1	124.9	248.4	453	523.4	222	12.68	108.78	479
132	Dac Nong	19	23.3	67.1	171.3	240.1	380.4	337.8	464.5	391.2	243.4	69.4	5.5	12	107.68	660
133	Da Lat	7.5	22.9	50.5	152.1	224.5	182.7	223	209.2	290.2	251.2	86.9	28.9	11.95	108.43	1513
134	LienKhuong	7.5	22.9	50.5	152.1	224.5	182.7	223	209.2	290.2	251.2	86.9	28.9	11.75	108.38	961
135	Bao Loc	56.3	46	86.9	170	218.7	289.2	390.1	401	382.7	286.8	140	74.7	11.47	107.8	850
136	Nha Ho	8.2	2.5	16.2	26.4	87.4	58.4	62.4	59.5	137.8	144.1	133.2	57.9	11.67	108.9	27
137	Phan Thiet	1.2	0.7	4.7	32	135.1	148.1	224.3	175.3	190.2	169.7	50.2	20.7	10.93	108.1	9
138	Ham Tan	0	0	12.2	72.7	212.6	294.8	258.4	385.9	228.4	252.6	35.8	13.7	10.68	107.75	5
139	Bien Hoa	8.1	4.2	13.4	46.5	158.7	235	268	281.9	297.5	211.5	89.1	27.7	10.95	106.82	3
140	Phuoc Long	8.1	4.2	13.4	46.5	158.7	235	268	281.9	297.5	211.5	89.1	27.7	11.85	107	24
141	Dong Phu	8.1	4.2	13.4	46.5	158.7	235	268	281.9	297.5	211.5	89.1	27.7	11.53	106.9	10
142	So Sao	7.2	5.3	26.4	87.1	207.9	236.3	246.8	224.8	317.6	294.5	124.5	38.8	11.03	106.65	10
143	Tay Ninh	7.2	5.3	26.4	87.1	207.9	236.3	246.8	224.8	317.6	294.5	124.5	38.8	11.32	106.07	10
144	T.S. Nhat	13.8	4.1	10.5	50.4	218.4	311.7	293.7	269.8	327.1	266.7	116.5	48.3	10.82	106.67	9
145	Vung Tau	2.2	0.6	4.6	33	188.1	206.1	213.4	177.6	214.3	215.4	68.8	22.7	10.33	107.08	4
146	Con Dao	12	6.1	8.8	35.6	208.7	322.3	281.2	318.7	322.3	338.1	183.5	58.1	8.68	106.6	3
147	Moc Hoa	12.3	3.5	9.4	48.1	182.7	167.1	155.2	159.2	246.8	291.9	128.2	43.3	10.75	105.93	3
148	Ba Tri	4	1.8	2.4	35.8	163.1	211.7	194.1	192.2	251.9	272	110.2	33.6	9.98	106.2	3

No.	Stations	Monthly Rainfall												Lat.	Long.	Elevation
		Jan.	Feb.	March	April	May	June	July	Au.	Sep.	Oct.	Nov.	Dec.			
149	Cang Long	1.2	0.1	14.5	42.4	212.2	266.7	192.7	268.5	249.3	283.8	121.1	19.4	9.98	106.2	3
150	My Tho	5.2	2.4	4	55.4	166.6	197.8	202.4	162.1	245.4	269.6	116	40.1	10.35	106.38	3
151	Can Tho	12.4	2.2	10.4	49.7	176.6	206.4	226.6	216.8	273.1	277.1	155.3	40.9	10.03	105.78	3
152	Soc Trang	8	2.3	13.1	65.3	225.7	257.9	247.8	265.8	272.4	293	166	41.8	9.6	105.97	3
153	Cao Lanh	8.3	1.7	15	46.2	153.5	146	132.9	175.9	246.6	257.7	117.6	31.1	10.47	105.63	2
154	Phu Quoc	30.4	28.1	61.2	163.4	319.3	412.5	451.7	506.3	486.1	350.1	176	82.3	10.22	103.97	2
155	Rach Gia	11	6.7	36	97.8	227.8	260.6	299.2	329.8	299.7	271.8	171.8	44.7	10	105.08	2
156	Chau Doc	2.1	0.8	27	78.2	196.4	122.6	123.7	152.2	152.2	306.6	201.4	53.5	10.77	105.13	5
157	Bac Lieu	11.4	1.9	4.4	41.3	189	232	236.5	244.3	266.5	280.1	153.1	51.9	9.28	105.72	3
158	Ca Mau	16	8.3	34.3	100.4	276.2	322.5	322.6	348.6	347.5	325.8	181.8	81.6	9.17	105.17	3

* *Weather stations are listed from north to south*

Appendix 4.2. Required Forest Areas for Different Provinces of Vietnam

No.	Provinces	Forest (ha)	Natural Forest (ha)	No.	Provinces	Forest (ha)	Natural Forest (ha)
1	Lai Chau	273976	467184	33	Da Nang	20735	23848
2	Dien Bien	327526	138402	34	Quang Nam	291769	236391
3	Son La	427829	95505	35	Quang Ngai	124322	107814
4	Hoa Binh	106186	41412	36	Binh Dinh	107357	43611
5	Lao Cai	180414	205175	37	Phu Yen	33701	3913
6	Yen Bai	213372	110327	38	Khanh Hoa	66630	16965
7	Ha Giang	276718	222054	39	Ninh Thuan	26475	1856
8	Tuyen Quang	126892	67459	40	Binh Thuan	50237	11281
9	Phu Tho	44754	12138	41	Kon Tum	204204	46924
10	Vinh Phuc	7226	7597	42	Gia Lai	60062	4227
11	Cao Bang	184269	40184	43	Lam Dong	121894	18136
12	Bac Kan	98932	16650	44	Dak Lak	84852	20506
13	Thai Nguyen	32358	18564	45	Dak Nong	24990	2485
14	Quang Ninh	81739	29445	46	Dong Nai	2028	228
15	Lang Son	68658	3570	47	Vung Tua	942	29
16	Bac Giang	11053	743	48	TP. Ho Chi Minh	0	0
17	Bac Ninh	0	0	49	Binh Duong	0	0
18	Hai Phong	2570	86	50	Binh Phuoc	1142	0
19	Hai Duong	600	0	51	Tay Ninh	714	486
20	Hung Yen	0	0	52	Long An	0	0
21	Ha Noi	971	57	53	Dong Thap	57	29
22	Ha Tay	4398	1485	54	Tien Giang	0	0
23	Ha Nam	2770	286	55	Ben Tre	0	0
24	Nam Dinh	0	0	56	Vinh Long	0	0
25	Thai Binh	0	0	57	Tra Vinh	0	0
26	Ninh Binh	6198	600	58	Can Tho	0	0
27	Thanh Hoa	207831	67944	59	Hau Giang	0	0
28	Nghe An	372080	70857	60	Soc Trang	0	0
29	Ha Tinh	79939	44696	61	Bac Lieu	0	0
30	Quang Binh	186011	109071	62	An Giang	2342	543
31	Quang Tri	78054	33044	63	Kien Giang	4912	2827
32	Hue	89250	122865	64	Ca Mau	0	0

Appendix 5.1. Averaging Mangrove Forest Structures in Five Locations along Coastal Vietnam

No.	Locations	*Species*	Dbh (cm)	D_c (m)	H_{bc} (m)	Height (m)	N (tree ha^{-1})	CC (%)
1	Cat Ba	*Aegiceras corniculatum*	0.0	2.3		2.22	2950	95
2	Cat Ba	*Avicennia marina*	0.0	2.7		2.63	1860	85
3	Can Gio	*Avicennia marina*	8.3	2.9	4.75	8.86	3775	75
4	Can Gio	*Avicennia marina*	9.8	2.5	5.21	10.28	3175	70
5	Can Gio	*Avicennia marina*	7.5	2.0	5.88	10.56	2000	85
6	Can Gio	*Avicennia marina*	10.9	2.6	5.95	10.10	2600	55
7	Can Gio	*Rhizophora mucronata*	11.2	2.8	7.03	11.63	2875	60
8	Can Gio	*Avicennia marina*	9.5	3.1	6.86	11.27	3400	71
9	Can Gio	*Avicennia marina*	9.2	3.1	6.09	11.96	4600	71
10	Can Gio	*Rhizophora mucronata*	9.7	3.0	6.14	11.97	4475	80
11	Can Gio	*Rhizophora mucronata*	8.4	2.7	5.33	10.34	5075	90
12	Can Gio	*Avicennia marina*	6.4	2.0	1.53	5.03	2650	71
13	Can Gio	*Avicennia marina*	6.8	1.9	1.47	5.10	2900	64
14	Can Gio	*Avicennia marina*	6.8	1.8	1.99	5.75	3075	74
15	Can Gio	*Avicennia marina*	6.9	2.0	1.36	7.08	2825	85
16	Can Gio	*Avicennia marina*	6.7	2.0	1.40	6.84	3800	85
17	Can Gio	*Sonneratia caseolaris*	7.1	2.0	2.24	7.70	4025	90
18	Can Gio	*Sonneratia caseolaris*	10.3	3.2	1.94	11.76	2400	60
19	Can Gio	*Sonneratia griffithii*	8.7	2.6	2.08	8.86	2100	65
20	Can Gio	*Sonneratia caseolaris*	8.5	2.5	2.12	9.02	2750	75
21	Hoang Tan	*Sonneratia griffithii*	16.0	3.3	1.24	4.26	1600	90
22	Hoang Tan	*Sonneratia caseolaris*	14.5	3.0	1.17	3.78	1800	88
23	Hoang Tan	*Avicennia marina*	9.9	2.6	1.12	3.07	2000	86
24	Hoang Tan	*Aegiceras corniculatum*	0.0	2.0		1.96	2500	84
25	Thai Binh	*Kandelia candel*	3.6	0.7	0.42	1.19	18880	94
26	Thai Binh	*Kandelia candel*	4.4	0.7	0.44	1.69	20160	96
27	Thai Binh	*Aegiceras corniculatum*		0.9		1.05	11200	65
28	Thai Binh	*Aegiceras corniculatum*		0.9		1.34	15600	88
29	Tien Lang	*Sonneratia caseolaris*	16.2	3.5	1.26	4.40	980	80
30	Tien Lang	*Sonneratia caseolaris*	12.9	2.5	1.12	3.53	1830	75
31	Tien Lang	*Sonneratia caseolaris*	16.1	3.4	1.24	4.33	890	70
32	Tien Lang	*Sonneratia caseolaris*	12.9	2.5	1.11	3.53	1670	65

** Dbh: Diameter at breast height; D_c: Diameter of canopy; H_{bc}: height below canopy; N: Density; CC: canopy closure; Lat.:Latitute*

Appendix 5.2. Averaging Wave Height and Cross-shore Distance along Coastal Vietnam

No.	Locations	Routes	Replication	Cross shore distance to mangrove forest (m)						
				0	**20**	**40**	**60**	**80**	**100**	**120**
1	Cat Ba	1	1	25.3	20.3	16.0	14.0	11.7	9.0	
2	Cat Ba	1	2	27.0	23.8	20.7	17.3	15.3	12.3	
3	Cat Ba	1	3	37.3	32.3	29.7	25.0	22.0	19.0	
4	Cat Ba	1	4	45.3	39.7	36.0	32.7	28.7	26.0	
5	Cat Ba	1	5	53.0	47.7	43.3	38.3	36.7	34.7	
6	Cat Ba	1	6	28.3	23.0	20.3	18.0	15.3	12.3	
7	Cat Ba	1	7	32.0	28.0	25.3	22.3	20.0	17.7	
8	Cat Ba	1	8	37.3	32.3	29.7	25.0	22.0	19.0	
9	Cat Ba	1	9	44.3	39.7	36.7	33.7	31.0	27.3	
10	Cat Ba	1	10	53.0	47.7	43.3	38.3	36.7	34.7	
11	Cat Ba	2	1	30.7	27.3	23.7	20.7	17.7	15.0	
12	Cat Ba	2	2	35.7	32.0	28.7	25.3	22.0	19.0	
13	Cat Ba	2	3	40.7	37.0	33.7	30.7	27.7	24.7	
14	Cat Ba	2	4	25.0	21.7	18.7	15.7	12.7	9.7	
15	Cat Ba	2	5	42.0	38.7	35.7	33.0	29.7	26.7	
16	CanGio	1	1	55.7	38.0	28.3	20.3	14.0	10.3	6.7
17	CanGio	1	2	77.3	58.0	40.7	27.7	18.7	14.0	11.0
18	CanGio	2	1	41.0	37.3	38.3	20.7	16.3	11.7	8.7
19	CanGio	2	2	36.0	21.0	17.0	10.7	8.3	6.3	4.3
20	CanGio	3	1	56.0	40.3	28.3	17.0	11.0	7.7	4.7
21	CanGio	3	2	40.5	29.5	19.5	14.0	8.5	5.5	4.5
22	CanGio	4	1	48.5	37.0	27.5	20.0	14.0	10.5	4.0
23	CanGio	5	1	52.5	38.5	26.5	21.0	14.5	10.0	8.0
24	CanGio	6	1	48.0	37.0	28.5	21.5	15.0	11.0	8.5
25	Thai Binh	1	1	15.0	12.3	10.7	9.0	8.3	7.7	7.7
26	Thai Binh	1	2	22.7	18.7	17.3	14.7	14.0	13.3	12.0
27	Thai Binh	1	3	28.0	23.3	20.0	17.0	15.7	14.0	13.3
28	Thai Binh	1	4	32.0	29.0	25.3	22.7	20.3	19.0	17.7
29	Thai Binh	1	5	42.7	38.7	34.3	33.7	31.0	29.7	29.3
30	Thai Binh	1	6	48.0	45.7	42.0	36.3	35.3	32.0	29.0
31	Thai Binh	2	1	17.0	12.0	11.7	10.3	9.0	8.3	7.3
32	Thai Binh	2	2	23.7	20.0	19.0	17.3	16.0	16.3	14.0
33	Thai Binh	2	3	30.3	25.3	21.7	19.7	18.3	17.0	15.3
34	Thai Binh	2	4	35.3	29.7	27.7	26.0	22.7	19.3	17.0
35	Thai Binh	2	5	44.7	37.3	35.3	30.3	29.7	27.3	26.7
36	Thai Binh	2	6	49.7	45.0	42.7	37.7	35.7	32.0	31.0
37	Thai Binh	3	1	22.7	20.0	18.7	17.7	17.0	16.0	14.3
38	Thai Binh	3	2	29.7	26.0	22.0	21.7	20.7	18.0	17.0
39	Thai Binh	3	3	32.7	30.3	27.7	26.7	25.3	22.7	21.7
40	Thai Binh	3	4	42.3	37.3	36.7	32.7	31.0	29.7	27.3
41	Thai Binh	3	5	51.7	46.7	43.7	43.0	39.7	38.0	35.7
42	Thai Binh	4	1	25.3	18.7	16.0	13.3	11.7	9.0	6.7
43	Thai Binh	4	2	28.3	23.0	20.3	18.0	15.3	12.3	9.3
44	Thai Binh	4	3	37.3	32.3	29.7	25.0	22.0	19.0	17.3
45	Thai Binh	4	4	45.3	39.7	36.0	32.7	28.7	26.0	23.3
46	Thai Binh	4	5	53.0	47.7	43.3	38.3	36.7	34.7	31.7

No.	Locations	Routes	Replication	Cross shore distance to mangrove forest (m)						
				0	20	40	60	80	100	120
47	Tien Lang	1	1	26.3	24.3	22.3	20.0	17.7	15.0	
48	Tien Lang	1	2	32.0	29.7	27.7	25.7	23.0	20.7	
49	Tien Lang	1	3	34.3	32.7	30.0	27.3	24.7	22.0	
50	Tien Lang	1	4	42.0	39.7	37.0	34.3	32.2	29.7	
51	Tien Lang	1	5	49.0	46.3	43.7	40.7	38.7	36.7	
52	Tien Lang	1	6	19.3	17.0	14.3	12.7	11.0	9.0	
53	Tien Lang	1	7	26.3	24.3	22.3	19.3	17.3	15.3	
54	Tien Lang	1	8	32.0	30.0	27.0	24.0	21.0	18.3	
55	Tien Lang	1	9	37.3	35.3	33.3	31.3	28.3	26.3	
56	Tien Lang	1	10	45.0	42.3	40.3	38.0	35.3	33.3	
57	Tien Lang	2	1	25.0	23.0	21.3	19.5	18.2	16.3	
58	Tien Lang	2	2	31.0	29.0	18.7	25.0	23.3	21.7	
59	Tien Lang	2	3	36.3	34.0	32.0	30.0	28.0	25.7	
60	Tien Lang	2	4	43.7	42.0	40.0	37.7	35.7	34.0	
61	Tien Lang	2	5	49.0	47.0	45.0	42.7	40.7	38.7	
62	Tien Lang	2	6	16.3	14.3	12.3	10.7	8.7	7.3	
63	Tien Lang	2	7	26.0	24.0	22.0	20.3	18.3	16.7	
64	Tien Lang	2	8	30.7	28.7	26.7	24.7	22.7	21.7	
65	Tien Lang	2	9	37.7	35.7	33.7	31.7	30.0	28.0	
66	Tien Lang	2	10	45.7	43.7	42.0	40.0	38.0	36.0	
67	Tien Lang	3	1	20.3	18.3	16.3	14.3	12.7	11.0	
68	Tien Lang	3	2	27.7	25.3	23.3	21.3	19.3	18.3	
69	Tien Lang	3	3	31.3	29.3	27.3	25.3	23.3	21.7	
70	Tien Lang	3	4	35.7	33.7	32.0	30.0	28.0	26.3	
71	Tien Lang	3	5	46.0	44.0	42.0	40.0	38.0	36.3	
72	Tien Lang	3	6	20.3	19.3	17.8	16.0	14.8	13.7	
73	Tien Lang	3	7	27.7	26.7	24.8	23.7	22.7	21.7	
74	Tien Lang	3	8	31.3	29.8	28.5	27.3	26.3	25.3	
75	Tien Lang	3	9	35.7	34.0	32.7	31.7	30.3	29.3	
76	Tien Lang	3	10	46.0	44.3	43.0	42.0	41.0	40.0	
77	Tien Lang	4	1	23.0	22.0	20.7	19.3	17.7	17.5	
78	Tien Lang	4	2	24.7	23.7	23.2	22.0	21.0	20.7	
79	Tien Lang	4	3	30.7	29.8	28.7	27.7	26.7	25.8	
80	Tien Lang	4	4	42.7	41.7	40.3	39.2	38.0	37.3	
81	Tien Lang	4	5	40.3	39.0	37.8	36.7	36.2	35.2	
82	Tien Lang	4	6	24.7	23.7	23.2	22.0	21.0	20.7	
83	Tien Lang	4	7	42.7	41.7	40.3	39.2	38.0	37.3	
84	Tien Lang	4	8	18.5	17.3	16.7	16.0	15.0	14.2	
85	Tien Lang	4	9	34.3	33.3	32.5	31.7	31.0	30.0	
86	Tien Lang	4	10	30.7	29.8	28.7	27.7	26.7	25.8	
87	Tien Lang	5	1	20.3	19.8	19.3	18.8	18.3	17.7	
88	Tien Lang	5	2	30.0	29.5	29.0	28.5	28.0	27.2	
89	Tien Lang	5	3	25.7	25.2	24.7	24.2	23.5	22.8	
90	Tien Lang	5	4	33.0	32.2	31.7	31.2	30.7	30.0	
91	Tien Lang	5	5	15.3	14.7	14.2	13.7	13.2	12.3	

Appendix 5.3. Regression Coefficients of Wave Height to Cross shore distances

No.	Locations	Intercept (α)	Slope (β)	R^2	I_{Wh} (cm)	Forest Structures			
						H_{bc} (m)	Height (m)	N (tree ha^{-1})	CC (%)
1	Cat Ba	24.94	-0.0100	0.986	25.0		2.2	2950	95
2	Cat Ba	27.62	-0.0077	0.986	26.7		2.2	2950	95
3	Cat Ba	37.54	-0.0076	0.990	37.3		2.2	2950	95
4	Cat Ba	44.92	-0.0055	0.994	45.5		2.2	2950	95
5	Cat Ba	51.91	-0.0043	0.953	53.3		2.2	2950	95
6	Cat Ba	27.94	-0.0079	0.978	28.1		2.2	2950	95
7	Cat Ba	31.83	-0.0059	0.998	31.8		2.2	2950	95
8	Cat Ba	37.56	-0.0067	0.990	37.3		2.2	2950	95
9	Cat Ba	44.13	-0.0046	0.988	44.5		2.2	2950	95
10	Cat Ba	51.91	-0.0043	0.953	53.3		2.2	2950	95
11	Cat Ba	31.27	-0.0072	0.994	30.5		2.6	1860	85
12	Cat Ba	36.28	-0.0063	0.990	35.6		2.6	1860	85
13	Cat Ba	40.90	-0.0050	0.996	40.7		2.6	1860	85
14	Cat Ba	26.15	-0.0093	0.968	24.6		2.6	1860	85
15	Cat Ba	42.41	-0.0045	0.990	42.1		2.6	1860	85
16	Can Gio	54.80	-0.0168	0.998	56.1	5.3	9.9	2983	76
17	Can Gio	79.90	-0.0176	0.994	78.3	5.3	9.9	2983	76
18	Can Gio	48.42	-0.0134	0.823	41.0	6.6	11.0	2958	61
19	Can Gio	32.60	-0.0170	0.966	35.9	6.6	11.0	2958	61
20	Can Gio	59.20	-0.0205	0.990	56.4	5.9	11.4	4717	80
21	Can Gio	42.95	-0.0201	0.990	40.5	5.9	11.4	4717	80
22	Can Gio	49.88	-0.0155	0.996	48.7	1.7	5.3	2875	70
23	Can Gio	52.97	-0.0164	0.994	52.8	1.7	7.2	3550.0	86
24	Can Gio	49.77	-0.0148	0.992	48.2	2.0	9.9	2416.7	66
25	Thai Binh	14.29	-0.0076	0.945	14.4	0.4	1.2	18880	94
26	Thai Binh	21.45	-0.0053	0.895	22.3	0.4	1.2	18880	94
27	Thai Binh	26.97	-0.0069	0.966	27.7	0.4	1.2	18880	94
28	Thai Binh	31.84	-0.0054	0.984	31.8	0.4	1.2	18880	94
29	Thai Binh	41.52	-0.0036	0.925	42.8	0.4	1.2	18880	94
30	Thai Binh	48.70	-0.0042	0.955	48.2	0.4	1.2	18880	94
31	Thai Binh	15.33	-0.0065	0.845	16.4	0.4	1.7	20160	96
32	Thai Binh	22.36	-0.0037	0.814	23.3	0.4	1.7	20160	96
33	Thai Binh	28.69	-0.0057	0.920	30.1	0.4	1.7	20160	96
34	Thai Binh	34.70	-0.0055	0.949	35.2	0.4	1.7	20160	96
35	Thai Binh	42.58	-0.0047	0.904	44.8	0.4	1.7	20160	96
36	Thai Binh	49.64	-0.0043	0.982	49.9	0.4	1.7	20160	96
37	Thai Binh	21.83	-0.0033	0.918	22.3		1.1	11200	65
38	Thai Binh	28.53	-0.0046	0.884	29.4		1.1	11200	65
39	Thai Binh	32.49	-0.0034	0.962	32.5		1.1	11200	65
40	Thai Binh	41.32	-0.0035	0.931	42.4		1.1	11200	65
41	Thai Binh	50.38	-0.0029	0.933	52.0		1.1	11200	65
42	Thai Binh	24.03	-0.0097	0.970	25.0		1.3	15600	88
43	Thai Binh	27.94	-0.0079	0.978	28.1		1.3	15600	88
44	Thai Binh	37.56	-0.0067	0.990	37.3		1.3	15600	88
45	Thai Binh	44.92	-0.0055	0.994	45.5		1.3	15600	88
46	Thai Binh	51.91	-0.0043	0.953	53.3		1.3	15600	88

No.	Locations	Intercept (α)	Slope (β)	R^2	I_{Wh} (cm)	Forest Structures			
						H_{bc} (m)	Height (m)	N (tree ha^{-1})	CC (%)
47	Tien Lang	27.15	-0.0055	0.962	26.0	1.3	4.4	980	80
48	Tien Lang	32.47	-0.0043	0.978	31.8	1.3	4.4	980	80
49	Tien Lang	35.30	-0.0045	0.972	34.2	1.3	4.4	980	80
50	Tien Lang	42.33	-0.0035	0.996	42.1	1.3	4.4	980	80
51	Tien Lang	49.00	-0.0029	0.994	49.2	1.3	4.4	980	80
52	Tien Lang	19.57	-0.0075	0.990	18.8	1.3	4.4	980	80
53	Tien Lang	26.98	-0.0055	0.982	26.0	1.3	4.4	980	80
54	Tien Lang	33.10	-0.0057	0.974	31.8	1.3	4.4	980	80
55	Tien Lang	37.90	-0.0035	0.976	37.3	1.3	4.4	980	80
56	Tien Lang	45.15	-0.0030	0.994	45.1	1.3	4.4	980	80
57	Tien Lang	25.08	-0.0042	0.994	24.6	1.1	3.5	1830	75
58	Tien Lang	28.48	-0.0031	0.141	30.8	1.1	3.5	1830	75
59	Tien Lang	36.51	-0.0034	0.992	36.3	1.1	3.5	1830	75
60	Tien Lang	44.00	-0.0026	0.992	43.8	1.1	3.5	1830	75
61	Tien Lang	49.23	-0.0024	0.996	49.2	1.1	3.5	1830	75
62	Tien Lang	16.76	-0.0081	0.988	15.8	1.1	3.5	1830	75
63	Tien Lang	26.20	-0.0044	0.994	25.7	1.1	3.5	1830	75
64	Tien Lang	30.69	-0.0036	0.990	30.5	1.1	3.5	1830	75
65	Tien Lang	37.79	-0.0029	0.996	37.6	1.1	3.5	1830	75
66	Tien Lang	45.87	-0.0024	0.994	45.8	1.1	3.5	1830	75
67	Tien Lang	20.63	-0.0062	0.994	19.9	1.2	4.3	890	70
68	Tien Lang	27.57	-0.0042	0.990	27.4	1.2	4.3	890	70
69	Tien Lang	31.54	-0.0037	0.996	31.1	1.2	4.3	890	70
70	Tien Lang	35.85	-0.0030	0.994	35.6	1.2	4.3	890	70
71	Tien Lang	46.10	-0.0024	0.998	46.2	1.2	4.3	890	70
72	Tien Lang	20.69	-0.0041	0.984	19.9	1.2	4.3	890	70
73	Tien Lang	27.71	-0.0025	0.986	27.4	1.2	4.3	890	70
74	Tien Lang	31.16	-0.0021	0.994	31.1	1.2	4.3	890	70
75	Tien Lang	35.47	-0.0019	0.992	35.6	1.2	4.3	890	70
76	Tien Lang	45.69	-0.0014	0.982	46.2	1.2	4.3	890	70
77	Tien Lang	23.13	-0.0030	0.953	22.6	1.1	3.5	1670	65
78	Tien Lang	24.66	-0.0018	0.968	24.3	1.1	3.5	1670	65
79	Tien Lang	30.76	-0.0018	0.996	30.5	1.1	3.5	1670	65
80	Tien Lang	42.68	-0.0014	0.988	42.8	1.1	3.5	1670	65
81	Tien Lang	40.10	-0.0013	0.974	40.4	1.1	3.5	1670	65
82	Tien Lang	24.66	-0.0018	0.968	24.3	1.1	3.5	1670	65
83	Tien Lang	42.68	-0.0014	0.988	42.8	1.1	3.5	1670	65
84	Tien Lang	18.45	-0.0026	0.986	18.0	1.1	3.5	1670	65
85	Tien Lang	34.28	-0.0013	0.994	34.2	1.1	3.5	1670	65
86	Tien Lang	30.76	-0.0018	0.996	30.5	1.1	3.5	1670	65
87	Tien Lang	20.39	-0.0014	0.988	19.9	0.5	1.9	3550	55
88	Tien Lang	30.09	-0.0010	0.974	29.8	0.5	1.9	3550	55
89	Tien Lang	25.77	-0.0012	0.984	25.3	0.5	1.9	3550	55
90	Tien Lang	32.89	-0.0009	0.986	32.8	0.5	1.9	3550	55
91	Tien Lang	15.36	-0.0021	0.974	14.7	0.5	1.9	3550	55

* *I_{wh}: Initial wave height; N: tree density; H_{bc}: height below canopy; CC: canopy closure*

Appendix 5.4. Index of Mangrove Structures and Level of Wave Prevention

No.	Locations	Species	Latitude (degree)	V index	Level
1	Cat Ba	*Aegiceras corniculatum*	20.9	0.00484	I
2	Cat Ba	*Avicennia marina*	20.9	0.00382	I
3	Can Gio	*Avicennia marina*	9.1	0.01408	III
4	Can Gio	*Avicennia marina*	9.1	0.01551	IV
5	Can Gio	*Avicennia marina*	9.1	0.01663	IV
6	Can Gio	*Avicennia marina*	9.1	0.01301	III
7	Can Gio	*Rhizophora mucronata*	9.1	0.01631	IV
8	Can Gio	*Avicennia marina*	9.1	0.01733	IV
9	Can Gio	*Avicennia marina*	9.1	0.01897	IV
10	Can Gio	*Rhizophora mucronata*	9.1	0.01986	IV
11	Can Gio	*Rhizophora mucronata*	9.1	0.01838	IV
12	Can Gio	*Avicennia marina*	9.1	0.0069	II
13	Can Gio	*Avicennia marina*	9.1	0.00637	II
14	Can Gio	*Avicennia marina*	9.1	0.00864	II
15	Can Gio	*Avicennia marina*	9.1	0.01168	III
16	Can Gio	*Avicennia marina*	9.1	0.01182	III
17	Can Gio	*Sonneratia caseolaris*	9.1	0.01374	III
18	Can Gio	*Sonneratia caseolaris*	9.1	0.0162	IV
19	Can Gio	*Sonneratia griffithii*	9.1	0.01194	III
20	Can Gio	*Sonneratia caseolaris*	9.1	0.01377	III
21	Hoang Tan	*Sonneratia griffithii*	21.2	0.0066	II
22	Hoang Tan	*Sonneratia caseolaris*	21.2	0.00587	II
23	Hoang Tan	*Avicennia marina*	21.2	0.00474	I
24	Hoang Tan	*Aegiceras corniculatum*	21.2	0.00318	I
25	Thai Binh	*Kandelia candel*	20.8	0.00641	II
26	Thai Binh	*Kandelia candel*	20.8	0.00749	II
27	Thai Binh	*Aegiceras corniculatum*	20.8	0.00242	I
28	Thai Binh	*Aegiceras corniculatum*	20.8	0.00581	II
29	Tien Lang	*Sonneratia caseolaris*	20.8	0.00504	II
30	Tien Lang	*Sonneratia caseolaris*	20.8	0.00426	I
31	Tien Lang	*Sonneratia caseolaris*	20.8	0.00373	I
32	Tien Lang	*Sonneratia caseolaris*	20.8	0.003	I

* *V: index of mangrove structure*

Appendix 5.5. Maximum Index of Mangrove Structure, Required Minimum Ban Width, Length, and Areas for Coastal Provinces of Vietnam

Provinces	Latitude (degree)	Max D Index	Widths (m)	Lengths (km)	Areas (ha)
Quang Ninh	21.2413	0.0057577	489	220	10750
Hai Phong	20.8091	0.0062634	449	37	1662
Thai Binh	20.5051	0.006619	425	43	1828
Nam Dinh	20.2309	0.0069398	405	69	2797
Ninh Binh	20.1934	0.0069837	403	15	604
Thanh Hoa	19.9794	0.0072341	389	38	1478
Nghe An	19.275	0.0080583	349	43	1501
Ha Tinh	18.3373	0.0091554	307	38	1168
Quang Binh	17.5063	0.0101276	278	23	639
Quang Tri	16.7336	0.0110317	255	30	765
Hue	16.3699	0.0114572	246	32	786
Da Nang	16.0657	0.0118131	238	4	95
Quang Nam	15.5094	0.012464	226	15	339
Quang Ngai	14.9813	0.0130819	215	18	387
Binh Dinh	14.1129	0.0140979	200	10	200
Phu Yen	13.2014	0.0151644	186	15	278
Khanh Khoa	12.3389	0.0161735	174	40	696
Ninh Thuan	11.7312	0.0168845	167	20	333
Binh Thuan	11.0665	0.0176622	159	35	558
Vung Tau	10.5635	0.0182507	154	27	416
Ho Chi Minh City	10.7674	0.0180121	156	41	640
Tien Giang	10.3995	0.0184426	153	40	610
Ben Tre	10.0775	0.0188193	149	83	1241
Tra Vinh	9.8063	0.0191366	147	68	1000
Soc Trang	9.635	0.0193371	145	71	1033
Bac Lieu	9.3253	0.0196994	143	70	1000
Ca Mau	9.0642	0.0200049	141	211	2967
Kien Giang	9.9704	0.0189446	149	140	2079

Σ 37,850 ha

- Assumptions for calculations: initial wave height is 500cm; safe wave height behind forest band is 30cm; coastal lengths are identified with elevation less than 5m.

- Provinces are listed north to south.