Modelling Runoff and Erosion in Namchun Watershed, Thailand

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by

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Disclaimer

Dedicated to my mother

Abstract

Use of runoff and erosion prediction models is a common practice. However, the results of the model are always constrained by the lack of proper validation. Furthermore, erosion models are region and scale specific and also require a lot of input parameters which are not readily available in most of the data poor situation. Therefore, the principal aim of this study is to perform a detailed erosion assessment in a small and representative sub-watershed to develop a knowledge based GIS model to map the erosion pattern in the whole watershed area.

A three step research approach is applied in Namchun watershed, Thailand. Firstly, geostatistical analysis is carried to understand the spatial structure of the topsoil properties (e.g. topsoil clay, silt, organic matter content and crusting index) to map their distribution. In the second step, erosion modelling is done in the sub-watershed. Relationships of soilloss with soil properties, landcover, and slopes are explored. Validation of the modelling is done in different spatial and temporal scale. Finally, qualitative and quantitative approaches to up-scale the results of the detailed assessment of erosion in the sub-watershed to the watershed scale are applied. Two different methods of discharge up-scaling are tested. Similarly, based on the analysis of causal factors in the sub-watershed, a decision rule is set and applied in a GIS environment to map the spatial pattern of erosion in the whole watershed qualitatively.

Topsoil silt and clay content have very strong spatial structure where as organic matter and crusting index has moderate spatial structure. High Mountain areas have high organic matter content and low crusting index where as plateau landscapes have low organic matter content and high crusting index. However, the variation in silt and clay content is not significant in different landscapes. Highest rate of soil loss is found in agriculture area (11.92 $kg/m^2/y$), followed by orchard (10.29 $kg/m^2/y$), whereas, dense forest have very low rate of soil loss (1.03 $kg/m^2/y$). Steeper slopes (more than 25^0) have high soil erosion. Soilloss is negatively correlated with OM (-47%), silt content (-30%) and clay content (-9%) and positively correlated with sand content (28%) and crusting index (25%). We found promising performance of the model in predicting discharge, with the predicted to measured discharge ratios of 0.53 (sub-watershed in September), 1.08 (watershed for September) and 0.81 (watershed annually in the water year 2005) respectively. The study revealed that, the sub-watershed discharge can be up-scaled to the watershed scale with a reasonable accuracy.

The research concludes that the detailed study of erosion in small spatial scale to understand the processes and underlying causes can add to develop a knowledge based GIS model to map the spatial pattern of soil erosion in a bigger area. The technique offers the possibility to prioritise factors responsible for soil erosion and assess erosion hazards.

Keywords: Erosion modelling, validation, soil property mapping, knowledge based model, up-scaling, Thailand

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1. Introduction

1.1. Soil erosion by water

Land degradation is a major global concern as the ecological integrity and productivity of about 2 billons ha of land under human use is being seriously affected by its process. It damages soil structure and leads to the loss of soil and its nutrients through processes such as water or wind erosion; water logging and salinization; and soil compaction(UNDP/GEF, 2003). Soil erosion by water is one of the most significant causes of land degradation. According to the report of Global Assessment of Soil Degradation (GLASOD), water erosion contributes to about 56% of the total human induced soil degradation in the world (Liniger and Critchley, 2007). Anthropogenic perturbations such as inappropriate land use, mainly unscientific and unsustainable agricultural practices along with deforestation and over grazing have contributed for the accelerated soil erosion(Lal, 2001; Vrieling, 2007).

Soil erosion has both on-site and off-site effects. Its on-site effects are decline of soil fertility, decrease of organic matter and rooting depth thus leading to the decreased agricultural production. Off-site effects consist of damage to the infrastructures such as irrigation dams, hydropower etc, and also the pollution in water bodies downstream. Due to off-site effect, the productive capacity of the valley floor downstream declines and people start to migrate towards upland slopping areas for agricultural expansion, which in turn is a triggering cause of soil erosion.

There are several causative factors that control the spatial pattern and amount of soil loss in an area. The most important of such factors are the erosivity of rainfall, erodibility of the soil, nature of the vegetation and the slope of the terrain. Erodibility of the soil is the function of topsoil properties such as particle size of the topsoil, organic matter content, structural stability of the soil and so on (Morgan, 1995).

In order to mitigate the adverse effects of soil erosion, effective soil conservation strategies are required at different spatial scale and at different organizational levels. Spatial information on soil erosion helps to prioritize the conservation strategies and to design effective conservation measures as well as to monitor their effectiveness (Morgan, 2005; Vrieling, 2007). It is impractical to have soil conservation programs in all the areas as it requires high technical, financial and management investment (Liniger and Critchley, 2007). Therefore, a method that helps in quick assessment of erosion rates along with their spatial distribution is essential to prioritize the conservation efforts. In many countries, tools for locating soil erosion sources are, however, still lacking (Vigiak, 2005).

Several methods have been developed for the spatial assessment of soil erosion. These methods are broadly classified into three approaches. The first approach consists of quantifying erosion from experimental erosion plot measurement. The second approach is to map erosion features by executing erosion survey or by visual interpretation of satellite image and aerial photographs. The third and most widely used approach is through integrating spatial data on erosion factors by using erosion models (Vrieling, 2007). Starting from Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), several other erosion prediction models are developed for the spatial assessment of soil erosion (Aksoy and Kavvas, 2005; Jetten et al., 1999). Jetten et al (2003) indicated that erosion models are region and scale specific and therefore, transferring the model to another region and scale may provide poor results. Therefore, development and validation of erosion model for a particular region is still a valid need.

Many erosion models require a large amount of input data which may not be available readily in many of the developing countries. In such context, integrating qualitative data in a GIS environment that allows some flexibility in the selection of erosion factors can provide a good alternative (Shrestha et al., 2004; Vigiak, 2005; Vrieling, 2007). Causal factors are analyzed and erosion is mapped by applying some knowledge base fuzzy logic or by a decision tree. Selection of erosion factors can be region specific, depending on the processes and the key parameters that explain the variability of these processes within the region. Local or expert knowledge can provide important input to this approach (Mitra et al., 1998; Nisar Ahamed et al., 2000).

1.2. Problem Statement

Human induced soil degradation is one of the crucial environmental problems in Thailand. According to GLASOD report, about 38% of the total land area of the country is under severe to very severe prone to soil degradation(FAO/AGL, 2005). According to the report of Land Development Department (LDD) of Thailand, 2001, it has been mentioned that suitable land to feed the growing population in the country is insufficient and as a result marginal lands are brought under cultivation which has accelerated the land degradation. Deforestation, either for timber or fuel wood or for cultivation has enormously increased the soil erosion in slopping areas thus causing the loss of life, properties and economic productivity of the country (Patanakanog et al., 2004). In order to control the land from further degradation, conservation strategies need to be emphasized and prioritized in the country. Information regarding the spatial distribution of soil erosion and their magnitude is therefore important to tackle the problem properly.

Many previous researchers such as Bamutaze (2003); Saengthongpinit (2004) and Amare Kassa (2007) has used Revised Morgan, Morgan & Finny Model (RMMF) to predict soil erosion in the area. All of them have used the empirical relation to calculate the kinetic energy of the leaf drainage as mentioned by Morgan(2001) in which the component of leaf drainage part of the effective rainfall is missing. However, above mentioned incompleteness is later incorporated in Morgan (2005). Application of updated relation to predict the runoff and soil erosion in the area is not done yet. In addition, many erosion studies (Amare Kassa, 2007; Bamutaze, 2003; Endale, 2003; Gebrekirstos, 2003; Saengthongpinit, 2004) are often constrained by the lack of validation data. Development of simple and appropriate techniques for the validation of a model is therefore very important in the region. Furthermore, most of the erosion models are region and scale specific and needs a lot of input data which are not available easily in a data poor situation. Therefore, a simple approach of mapping the spatial pattern of soil erosion is important.

Spatial variability of soil erosion is highly influenced by the distribution of topsoil properties such as clay, silt, sand content and organic matter content (Morgan, 1995). Erosion studies in relation to the topsoil properties have not been done in the area. Continuous maps of topsoil properties are also lacking in the area.

1.3. Research Objectives

1.3.1. Overall Objective:

The main objective of the study is to perform a detailed erosion assessment in a small and representative sub-watershed, in relation to topsoil properties and other causal factors of erosion, to develop a knowledge-based GIS model to map the erosion pattern in the whole watershed area.

1.3.2. Specific Objectives

- To map the distribution of topsoil properties in the area.
- To evaluate the performance of an erosion model in predicting runoff and soil loss.
- To analyze the relationships of soil loss with causal factors of soil erosion (e.g. topsoil particle size, organic matter content, land cover types and slope) in the sub-watershed.
- To explore the possibility to extrapolate the results in the whole watershed from the detailed study in the sub-watershed.

1.4. Research questions

- What is the overall pattern of spatial structure of the topsoil properties such as clay content, silt content, organic matter and crusting index? And which property is best explained by the regional factor of soil variation?
- What is the overall pattern of the distribution of these soil properties in different landscapes in the area?
- How accurately can we measure monthly discharge and sediment by simple method?
- What are the goodness of fit between predicted discharge and measured discharge for the different spatial and temporal scale in the area?
- To what extend can we explain the variability of the model predicted soil loss with regionalized factors such as landcover and slope classes?
- What types of relations can be explained between topsoil properties and predicted soil loss in the area?
- Which method is more reasonable to upscale the measured discharge of a sub-watershed to that of the whole watershed in which it is nested and vice versa?

1.5. Research Hypotheses

- Topsoil organic matter and crusting index is significantly correlated with land cover types.
- Topsoil clay and silt content is significantly correlated with lithology types.
- Soil erosion is significantly different in different landuse/cover class and slope classes.
- Soil loss is significantly correlated with topsoil properties such as clay, silt, sand and organic matter content and crusting index.
- Sub-catchment discharge can be up-scaled to the watershed discharge with a reasonable accuracy.

1.6. Research approach

To achieve the objectives of the study, a three step research approach is applied in Namchun watershed, Thailand (Figure 1-1). In first step, geostatistical analysis is carried out to understand the spatial structure of the topsoil properties to map their distribution. Topsoil properties such as percentage clay, silt and organic matter (OM) content as well as topsoil crusting index are mapped by using geostatistical techniques.

In second step, runoff and erosion modelling is done in the sub-watershed monthly as well as annually. Also to evaluate the performance of the model in a bigger spatial scale, monthly as well as annual runoff modelling is done in the whole watershed. Spatial pattern of soil loss is explored in the sub-watershed. Similarly, relationships of soil loss with top soil properties are explored.

In third step, two different approaches of up-scaling sub-watershed discharge to that of the whole watershed is applied and tested to explore the possibilities of validation of the model in a bigger watershed with the data generated from the small representative sub-watershed. Furthermore, based on the detailed assessment of erosion in relation to land cover, slope, and topsoil properties, decision rules are set and applied in a GIS environment to produce the qualitative erosion susceptibility map of the whole watershed.

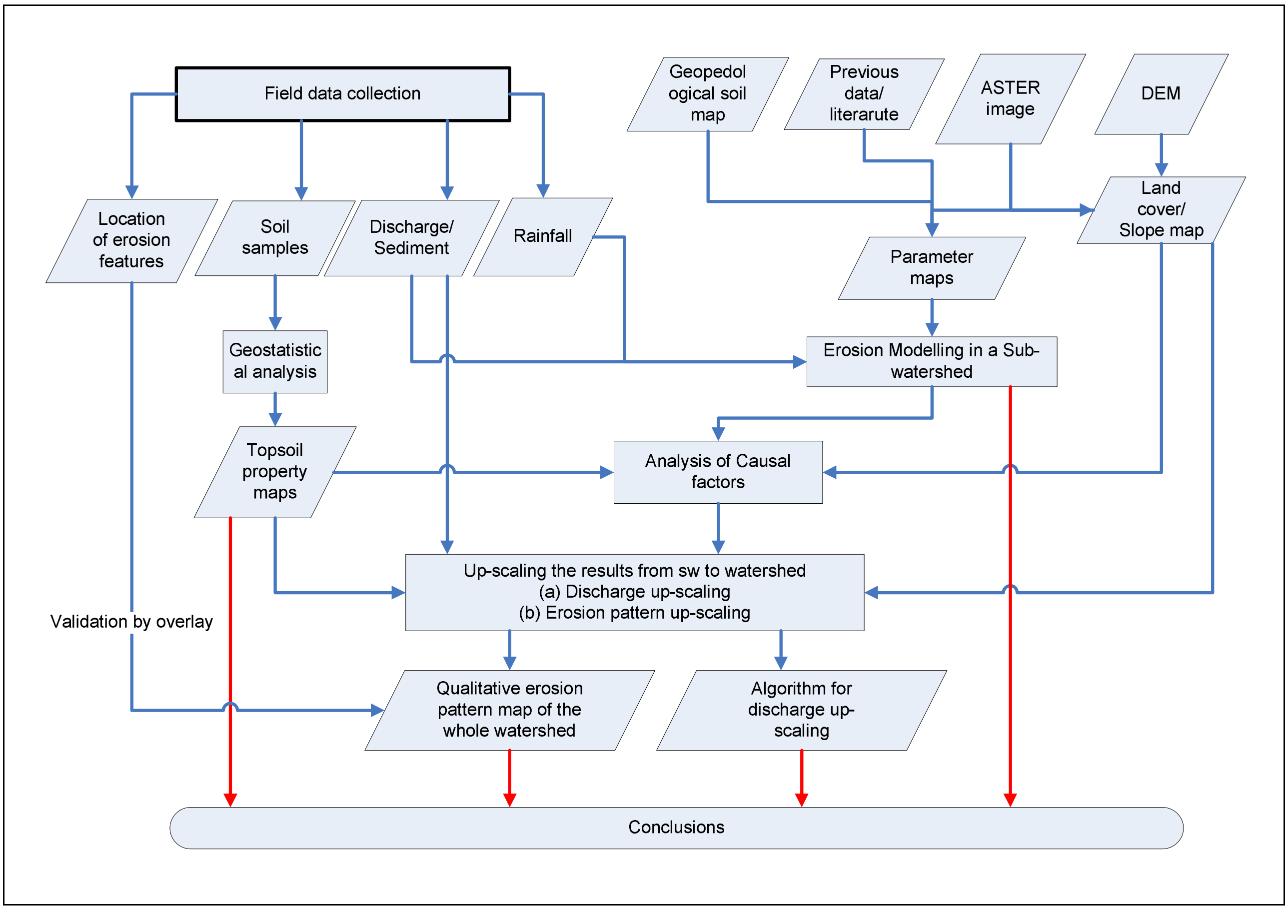


Figure 1-1: Basic research approach

1.7. Thesis outline

The thesis is organized in six different chapters. First chapter of the thesis consists of the introduction of soil erosion by water, the problem of soil erosion, rational of the study, study objectives, research questions, hypothesis and the description of the research approach. Second chapter deals with literature review regarding factors affecting soil erosion, soil erosion modelling, and field techniques of discharge and sediment measurement. Third chapter explains briefly the study area. Similarly, in an elaborated fourth chapter step by step methods and materials used to generate, process and analyze the data to achieve the result is explained. Results of the study along with discussions are compiled in the fifth chapter. Finally, sixth chapter concludes the research with some practical recommendations. Various data, maps and materials used in the study are accompanied in the annexes.

2. Literature Review

2.1. Factors affecting soil erosion

A clear understanding of erosion controlling factors is important for understanding erosion modelling. Morgan(1995) has stated four factors as being the most important for soil erosion: erosivity of rain, the erodibility of soil, the slope of terrain and the nature of plant cover.

2.1.1. Erosivity

Rainfall is one of the most important erosive agents contributing erosion. Soil particles are detached by raindrops as well as by overland runoff. Runoff also transports the detached soil down slope. Amount and intensity of rainfall as well as the size of the rain drop has greatest influence in the rate of soil erosion (Lal, 1994). Similarly, rainfall duration is also an important element for the rate of soil loss because a long duration rainfall with low intensity also can cause considerable soil erosion (Morgan, 2005).

2.1.2. Soil Erodibility

Resistance of the soil to detachment as well as to transport is termed as erodibility. The susceptibility of the soil to erosion or its erodibility is a function of various soil properties such as soil texture, aggregate stability, shear strength, infiltration capacity, organic matter content and chemical constituents of the soil along with some management options such as tillage operations and topographic positioning of the soil. Figure 2-1, explains the influence of particle size in detachment and transportation. Usually clay sized particles are hard to detach but easy to transport while sand particles are easy to detach but hard to transport. Silt and fine sand sized particles are most vulnerable to soil erosion (Lal, 1994; Morgan, 1995).

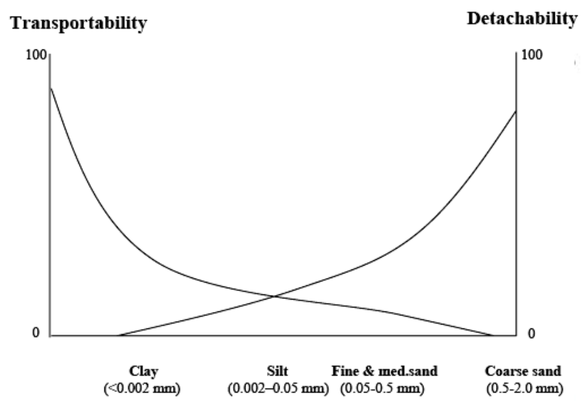


Figure 2-1: Detachability and transportability of different particle size, adopted from (Shrestha, 2007)

2.1.3. Terrain Conditions

Slope steepness and slope length are also important factors influencing soil erosion. As the slope length increases, the volume of overland flow increases. Similarly with slope steepness, the velocity of the flow increases which in-turn increases the kinetic energy of the overland flow that governs the detachment and transport of the particles. Steep slope with short slope length may become less danger as compared to long slope with gentle slope (Morgan, 1995; Wischmeier and Smith, 1978). Slope curvature and the nature of the slope also determine the rate of soil detachment and sedimentation. For example, if the slope declines in angle as the length increases, soil loss may decrease as a result of deposition.

2.1.4. Vegetative Cover

Vegetative cover has significant control over the rate of soil detachment and transport. Its effect can be categorized in above ground cover such as crown cover and ground cover. The above ground vegetation plays important role acting as an intercepting agent for the rainfall which in-tern reduces the amount of rainfall reaching directly to the soil surface. Similarly, the ground cover reduces rate of runoff and reduces the energy of the overland flow and the root zone below soil surface provides mechanical strength to the soil (Morgan, 2005). In a recent study using USLE plots, Marques et al.(2007), found that the erosive power of a single light rainfall event of 20.75 mm h^{-1} with a kinetic energy 13.5 J m^{-2} mm^{-1} is negligible when plots are covered with vegetation. However, it produces an average soil loss of 74 kg ha^{-1} when the soil is bare.

2.2. Modelling soil erosion

Erosion models are representation of some real world erosion phenomenon that describe the underlying principles and process of soil erosion. A large number of models for the prediction of soil loss and erosion have been designed and new developments are still in progress. A particular model, developed in certain environmental condition, however cannot be directly applicable to other locations, thus leading to the development of new models and modification of existing ones (Jetten et al., 1999; Jetten et al., 2003).

Depending upon the objective of the users, there is a wide range of erosion models ranging from very simple to very complex ones. In general, there are three types of erosion models: empirical, physical based and empirical-physical based (mixed). Most of the models used in soil erosion studies are empirical gray box type where some details of how the system works is analyzed. They are mainly based on defining some important factors, and use of observations, experiments and statistical techniques, relating them to soil loss (Morgan, 1995). This type of models are quick and easy but need long term data and are location specific and need to be adopted for the particular situation (Shrestha, 2007). However, in recent years physically based and white box types of models are getting more popularity in soil erosion studies.

Before choosing any model that can serve one’s objectives, we should understand basic underlying processes of soil erosion. Figure 2-2 gives a clear and scientific vision of erosion processes. After understanding those processes, a model can be simplified by concentrating on those processes having higher influence over the output and ignoring those with less effect. Some of the widely used soil erosion models are discussed as follows:

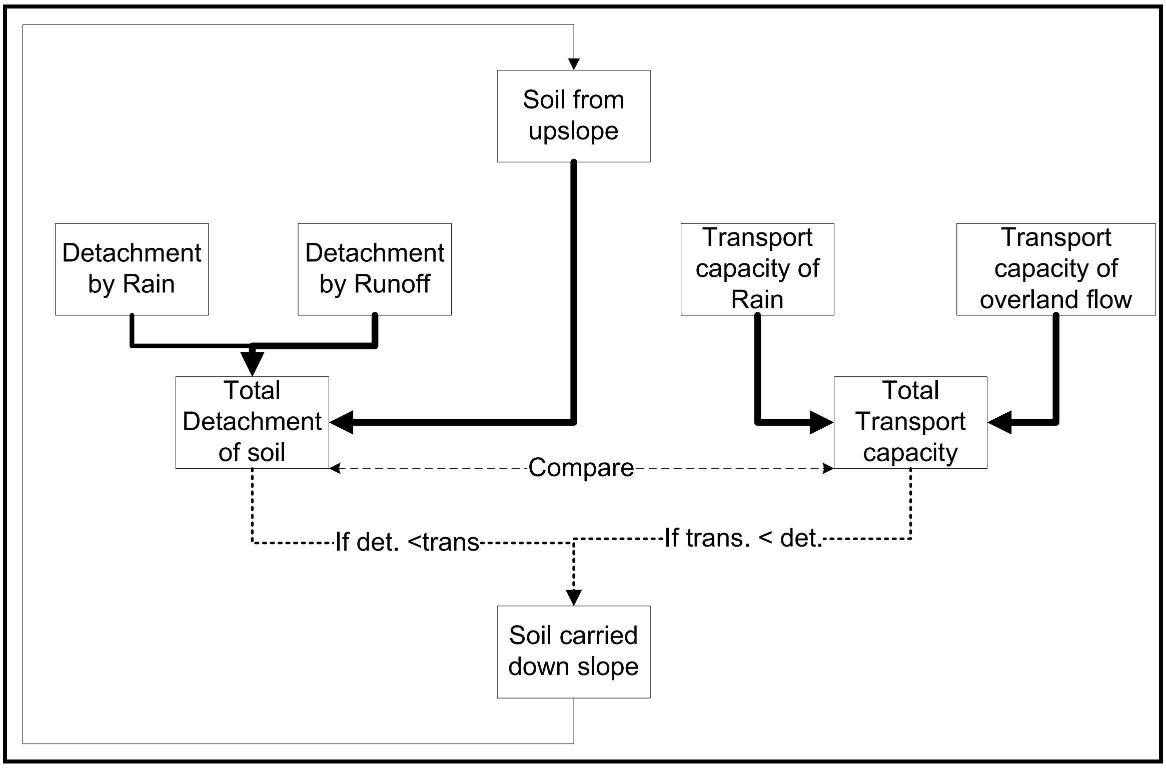


Figure 2-2: Flowchart of erosion processes by water after Morgan (1995).

2.2.1. Universal Soil Loss Equation (USLE)

Universal soil loss equation (USLE) is an empirical model developed to compute long-time average soil losses from sheet and rill erosion under specified conditions. It predicts average annual soil loss using the following equation:

$$E = RKLSCP$$

Where, E is the average soil loss in tones per hectare, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope-length factor, S is the slope steepness factor, C is the cover management factor and P is the support practice factor. The model is useful for construction sites and other non-agricultural conditions, but it does not predict deposition and does not compute sediment yields from gully, streambank, and streambed erosion (Wischmeier and Smith, 1978). Another important limitation of the model is that it is not an event based model so that it can not identify those events causing large scale erosion and mass movement (Merritt et al., 2003).To overcome some of the limitations of the USLE, revised universal soil loss equation **(**RUSLE**)** is developed. In the revised version some modification has been made in the previously used factors such as rainfall erosivity factor corrected for surface ponding, crop cover management factor, K factor corrected for seasonal variability and so on (Renard et al., 1996). Nevertheless, USLE is one of the most widely used and adopted model throughout the world.

2.2.2. SLEMSA

The soil loss estimation for southern Africa, SLEMSA, is also an empirical model developed to predict average annual soil loss. It was developed based on the data from Zimbabwe to predict soil loss from various farming system. Like USLE, it predicts annual soil loss based on the following equation (Elwell, 1978; Morgan, 1995; Shrestha, 2007).

$Z = KXC$

Where, Z is the average annual soil loss per unit area, K is the mean soil loss from a standard bare field plot ($30 \times 10\ m^2$ at 2.5^o slope) of known erodibility, X is the slope length and steepness factor and C is the crop management factor.

2.2.3. EUROSEM

The European soil erosion model, EUROSEM, is a process-based physical model developed to predict soil erosion in an individual event and to evaluate soil protection measures. The model uses a mass balance equation to compute sediment transport, erosion and deposition over the land surface. It simulates the volume of rainfall reaching to the ground as direct through fall, leaf drainage, and stem flow (Morgan et al., 1999). The rate of soil detachment by rainfall impact is calculated as a function of the energy of direct through fall and leaf drainage, the detachability of the soil and the depth of the surface water. The flow detachment is determined as a function of the difference between the transport capacity and existing sediment concentration in the flow, simultaneous deposition of sediment from the flow and the cohesion of the soil. It calculates tillage and crop cover effects in a dynamic way taking into account the soil protection measures by describing soil micro-topographic and vegetation conditions associated with each particle (Botterweg et al., 1998).

2.2.4. AGNPS

The agricultural non-point source model, AGNPS, developed by US department of agriculture in cooperation with Minnesota Pollution Control Agency in USA, is a hybrid model as it has both empirical and physical base. It is a distributed model, for each grid cell the input parameters consist of cell number, receiving cell number, Soil Conservation Service (SCS) curve number, a channel indicator, land slope, land shape factor, field slope length, channel slope, channel side slope, Manning's roughness coefficient, soil erodibility factor, cover and management factor, support practice factor, surface condition constant, aspect, soil texture, fertilization level, fertilization availability factor, point source indicator, gully source level, impoundment factor and channel indicator. Because of the requirement of a large input data, its applicability may be restricted to some developed countries only (Aksoy and Kavvas, 2005; Merritt et al., 2003).

2.2.5. Morgan, Morgan and Finny Model

The Morgan, Morgan and Finny model is an empirical model developed to estimate annual soil loss from field-sized area in hill slope (Morgan, 1995). The model has widespread use in the tropical climate from Africa to Asia (Shrestha et al., 2004; Vigiak, 2005). The model separates the erosion process in water phase and sediment phase. In water phase kinetic energy of the rain fall and the volume of the overland flow is calculated. In the sediment phase, splash detachment and transport capacity is calculated. Recently the model is revised in which the detachment of the soil particles by overland flow is also incorporated. Total detachment is then compared with the available transport capacity and the minimum of the two is considered as net soil erosion (Morgan, 2001). Detailed description of the revised form of the model is explained in chapter methods and materials.

2.3. Field techniques to measure soil loss and discharge

2.3.1. Measurement of soil loss

Depending on the spatial scale there are four fundamental ways of erosion measurements: (1) change in weight, (2) change in surface elevation, (3) change in channel cross section and (4) sediment collection from erosion plots and watersheds (Stroosnijder, 2005). Change in weight method is used to measure splash (interrill) erosion by using splash cup or funnels or bottles. Similarly rill erosion can be measured by measuring cross sectional area of rills found in a number of transects. Cross sectional area of the rill multiplied by average length of the rills gives the measure of the volume of soil loss(Morgan, 2005; Vigiak, 2005). Change in surface elevation is used to determine soil loss in a hillslope scale by using erosion pins.

At catchment scale, measurements of the quantity of sediment leaving a catchment from the stream or river outlet over a time is used to calculate soil loss from the catchment. The sediment movement in a stream takes place in two forms: suspended sediment and the bedload. There are several methods to measure suspended sediment. A simple method of measuring suspended sediment is to use a grab sampler. Flowing water along with suspended sediment is collected in a bucket of known volume and dried or filtered/dried and weighed to calculate the suspended sediment load. Similarly, to measure the bedload, one can use direct measurement in a hole or pit in the streambed or we can use sophisticated samplers as well as radio-active tracers to measure the bed load. Such a number of measurements along with discharge measurements are taken in a subsequent days and a sediment discharge rating curve is produced to estimate annual soil loss based on the equation:

$$\mathbf{C = aQ^b}$$

Where, C and Q are sediment concentration and water discharge respectively. Similarly, standard erosion plots are used to measure soil loss. However, due to its expensive establishment and operational cost along with difficulties in extrapolation of the results outside the measurement plot, applicability of plot measurement is more limited to the demonstration of erosion and effect of conservation measures rather than scientific research(Hudson, 1993; Stroosnijder, 2005).

A quick field method of soil erosion hazard assessment can be done by recording certain erosion features of the micro-topography on the soil surface (Bergsma et al., 1992). Seven such micro-topographic features such as resistant clods, eroded parts, flow surface, prerills, rills, depressions and vegetative matter are recorded with a measuring tape of 2.5 meter long, subdivided in parts of 25 cm. The tape is stretched along the contour and the features that occur in the interval of 25 cm are recorded. The tape is used five times, to cover a total of 12.5 meters of a particular area. A relative erosion hazard can be determined by the judgment and occurrence of such erosion features. This method can be used to extrapolate the result of soil loss measurement outside the area of measurement (Bergsma and Kwaad, 1992).

2.3.2. Measurement of discharge

Depending on the nature of the stream and the volume of the flow, several methods are developed to measure the discharge. Some of those methods are discussed shortly in this section.

2.3.2.1. Volumetric Methods

For a small stream flow, a simple way to measure the discharge is the direct measurement by recording the time to fill a container of known volume. The time to fill must be measured accurately, especially when the time interval is very short. The variation between successive measurements can give an indication of accuracy of the result (Hudson, 1993).

2.3.2.2. Velocity/Area Method

This method measures the average velocity (V) of the flow and the cross sectional area (A) of the stream to calculate the discharge (Q) by the equation:

$Q\ (m^3/s) = A\ (m^2) \times V\ (m/s)$

To determine the cross sectional area of the stream, the streambed is divided into several sections and the width of the section and depth of water in each section is measured. Similarly, average velocity of flow is measured in each section and total discharge is calculated by adding up the discharge in all sections. Several methods has been developed and tested to measure the velocity of the stream. A simple method is to use a float and record the time taken by the float to reach a known distance downstream. In this method, if the float is moving from the surface of the flowing water, then the average velocity of the flow in the stream can be determined by multiplying the surface velocity by 0.8 (Hudson, 1993). Float method is suitable for straight stream or canals where the flow is fairly even and regular. Another method to measure the velocity is to use a colored dye, and to measure the time taken by the dye to travel a known distance downstream. For more accurate measurement of velocity, a current meter can be used. Several velocities are measured in different depth of the stream sections and the average velocity in each section is calculated and consequently the discharge in each section is calculated by multiplying the average velocity and the area of the particular section (Buchanan and Somers, 1976).

3. Study area description

3.1. Location

The study was conducted in Namchun watershed, Petchabun province, Thailand (Figure 3-1). It is located between $16^{0}44^{'}$ and $16^{0}48$'N latitude and between 101^{0} 02' and 101^{0} 09' E longitude and about 400 km north from the capital city, Bangkok. The watershed covers an area of 66.5 km^{2} and elevation varies from 186 m to 1490 m above sea level. Detail erosion study was conducted in the sub-watershed of Nampong, within the Namchun watershed, which is located in between $16^{0}46$'01'' and $16^{0}46$'48''N and $101^{0}05$'28" and $101^{0}07$'39" E and covers an area of about 2.25 km^{2} (Figure 3-1).

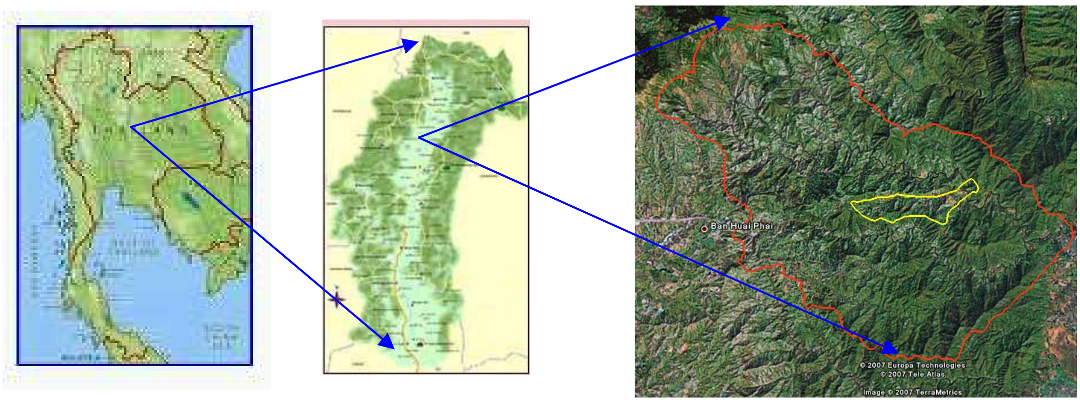


Figure 3-1: Location map of the study area (source Google earth).

3.2. Climate

The climate is characterized by tropical climate with average annual rainfall of 1495 mm and average monthly temperature of 26^{0}C (Figure 3-2). The hottest months are March and April with maximum temperature of 36^{0}C and the coldest months are December and January with minimum temperature of around 15^{0}C. Most of the rainfall occurs during the months of May to September.

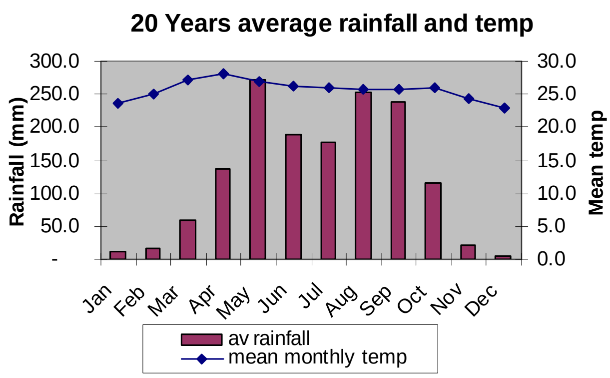


Figure 3-2: Average monthly rainfall and mean temp (from 1987 to 2007, Kao Khor, Petchabun).

3.3. Geology, geomorphology and soil

The Cenozoic, Mesozoic and Paleozoic formations are the major geological formation in the area. The upper part of the watershed is mainly dominated by uplifted sedimentary rocks of the “korat” group formed in the Mesozoic period and the lower part is characterized by quaternary colluvial and alluvial terrace deposits (Kunda, 2004; Solomon, 2005).

The main landscapes of the area consists of high plateaus, high and low mountains and low lying narrow valleys. In plateau landscape scarp, talus and undulating slope complex are the main land forms, whereas the mountain landscapes consist of summit, backslope complex, footslopes and that of the valley are bottom slope/ side slope complex.

Soils of the area are mainly categorized into silt loam (refer result and discussion chapter) and silt clay loam. Solomon (2005) has classified the soil into different groups of Inceptisols, Ultisols, Alfisols and Entisols. In Plateau area soils are mainly Typic Haplustalts, whereas, in High Mountain and low land area Ultic and Lithic Haplustolls are dominant.

3.4. Landuse/Land Cover and Farming practice

The major landuse/cover types in the area consist of mixed forest, agricultural land, orchards and grassland. Main agricultural crops commonly grown are maize and beans in the upland sloping area and rice and vegetables in the lowland area. The dominant orchard type is tarmarind but other orchard types such as mango, papaya and banana also exist in the area.

Slash and burn is the common approach to encroach forest area by the local farmer. Forests are more degraded in the low mountain area than in high mountain area because of the easy accessibility to the people and also being near to the agricultural area. Agricultural practices in steeper slope cause soil erosion in the area. No conservation practice is applied by the farmers except that they left the crop residues (maize stem) after harvesting the crop. The left over crop residues protect the soil during rainy days minimizing soil erosion.

Figure 3-3: Slash and burn practice (first) and newly invaded degraded forest area (second

4. Research methodology

The principal aim of this study is to perform a detailed study in a small and representative sub-watershed within a relatively bigger watershed to explore the possibility to validate the performance of an erosion model as well as to develop a knowledge based GIS model (applicable in data poor situation) to map the spatial pattern of soil erosion in the whole watershed. Nampong sub-watershed is selected for the purpose of detailed study as it has similar type of landscapes, land cover and other characters as compared to the whole watershed. The research is intended to evaluate the performance of an erosion model in different spatial and temporal scale. In addition, a detailed assessment of soil loss in relation to the land cover, slope and some of the topsoil properties (e.g. clay and silt content, organic matter content and crusting index) is carried out in the sub-watershed. Finally, the result of the runoff and erosion modeling in the sub-watershed is applied in a GIS environment to develop a qualitative knowledge based model to map the erosion susceptibility in the whole watershed area. Therefore, the study is conducted in three main methodological steps: (1) Mapping topsoil properties using geostatistical techniques, (2) detailed assessment and modeling of runoff and soil erosion in the representative sub-watershed; and (3) up-scaling the results from the sub-watershed to predict the discharge in the whole watershed quantitatively and to map the spatial pattern of soil erosion qualitatively.

4.1. Mapping Topsoil properties

Topsoil properties such as clay, silt and organic matter content are important physical properties that can be related with spatial pattern of soil erosion. Beside particle size and organic matter content, soil crusting index is also an important indicator of overland flow. Crusting index is calculated from the particle size data and organic matter content for every sample location by following equation (FAO, 1983):

Crusting index = $$\frac{(1.5\times finesilt + 0.75\times coarsesilt}{\%clay + 10\times\%OM}$$ **Equation 4-1**

For the purpose of topsoil mapping, topsoil (0-20cm) samples were collected from the sub-watershed in a regular grid of 200 m spacing. Similarly, some samples were collected from the whole watershed area by systematic random sampling scheme based on soil mapping units (landforms), and accessibility of the area (Freese, 1984). Geostatistical techniques are applied to map the topsoil distribution in the area. For the geostatistical analysis a closer sampling density is required (Yemefack et al., 2005). Therefore, both the regular grid sample data of the sub-watershed and random sample data of whole area are combined. Whole dataset is divided randomly into calibration and validation data set. Altogether 98 samples are used as calibration data set and 15 samples are used as the validation dataset (Annex 2 and 3).

For the mapping of the soil properties, exploratory data visualization as well as variogram analysis is done to understand the spatial pattern of the soil properties. Linear relationship of organic matter and crusting index with land cover types and the relationship of particle size in relation to the lithology types is analyzed. Finally, regression kriging with auxiliary information such as land use/cover map and lithology map is performed to map soil properties in the whole watershed area. The detailed of the procedure is explained in the following section.

4.1.1. Exploratory data analysis:

Exploratory data visualization is an important step before applying inferential statistics. It gives some impression of how the sample data are distributed in the population (Snedecor and Cocharn, 1980). For this purpose, summary parameters such as minimum, maximum, mean, standard deviation of the soil properties are calculated. For the further exploration of the distribution of soil properties, histogram and post plots are visualized by using geostatistical software R.

4.1.2. Variogram Analysis

Computation of variogram also known as semivariogam is a common way of visualizing spatial dependence. An experimental variogram estimates the average semivariance of all the point pairs in a bin separated by certain vector by the formula:

$$\bar{\gamma}(X_i, X_j) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [Z(X_i) - Z(X_j)]^2 \qquad \textbf{Equation 4-2}$$

Where, $\bar{\gamma}(X_i, X_j)$ is the average semivariance of point pairs in a bin. X is the geographic location and Z(X) is its attribute value and m(h) is the number of point pairs separated by the vector h.

An experimental variogram has some important features known as sill, nugget and range which explain the local spatial dependence. Sill is the maximum semivariance that reflects the variability in the absence of spatial dependence. Nugget is the semivariance as the separation approaches to zero and reflects the unexplained variability of the spatial structure and range is the separation distance at which the sill is reached and reflects the distance at which there is no evidence of spatial dependence (Rossiter, 2007). Experimental variogram are computed with g-stat package in R-software and fitted with some theoretical model to explain the local spatial dependence of the soil properties. Corresponding partial sill, nugget and range of the fitted variogram are computed. The ratio of the nugget to the total sill gives the proportion of the total variance that is not explained by the variogram model; its converse is the variance explained by the model. Total unexplained variance of a model expressed in percentage gives the measure of degree of spatial dependency.

NSR (Nugget to Sill Ratio) = $$\frac{C_o}{C_o + C_s} \times 100$$ **Equation 4-3**

Where, C_o is the nugget and C_s is the partial sill.

0-25% of the NSR value is the indicative of strongly structured spatial dependence; 25-75% indicate moderately structured spatial structure and the ratio >75% indicate the weak structured spatial dependence associated with high degree of unexplained variability (Sumfleth and Duttmann, 2007).

4.1.3. Analyzing Ancillary regional variables:

Linear relationships of soil properties such as OM and crusting index with regionalized categorical variable are visualized by box plot diagram using statistical software SPSS and the significance is tested by computing linear model in R software. Similarly, assuming that lithology is a strong factor to determine the soil texture, linear relationship of clay and silt with lithological category is also computed. Such association is necessary for interpolating at unknown location with ancillary information such as in case of Regression Kriging and Kriging with External Drift (Hengl, 2003).

4.1.4. Regression kriging

Ordinary kriging has the limitation that it can predict within the grid size of sample points. To predict the target variable at unknown location, geostatistical techniques of ‘universal kriging’ (UK), ‘Kriging with external drift’ (KED) and ‘Regression Kriging’ (RK) are used. If the predictor variable also known as auxiliary information is known to all grid nodes and correlated with the target variable, UK, KED or RK can be used to improve the spatial prediction depending upon the properties of auxiliary information (Hengl, 2003). In UK, trend is modelled by coordinates. In KED and RK instead of coordinates, drift is defined externally by some auxiliary information. To predict the target variable at unknown location with external drift (auxiliary information) the relation between the target variable and the auxiliary information (predictor) should be linear. In our case, silt and clay are mapped using RK with fitted variogram parameter with lithological map as auxiliary drift factor whereas, OM and crusting index are mapped by using RK with fitted variogram parameters and landcover map as drift factor. The predicted map are exported to ArcGis in tiff format and clipped to the study area for the further analysis. Necessary lithology map is digitized in ILWIS (Annex-11). Geology map (1:50000) of the year 2002 available from LDD, Thailand, along with rock identification during field study was the basis for the digitization.

4.1.5. Validation of prediction

The success of any model and its prediction must be judged by how well it meets its objectives or requirements. The accuracy of predictions is usually tested by comparing predicted with measured values and applying some measure of goodness of fit. In our case, before calibrating the variogram model for regression kriging, 15 sample points are randomly separated from the total data set keeping 98 samples in calibration dataset. We keep 98 points for calibration as the variogram modelling needs large dataset, at least 100 for better performance (Rossiter, 2007). Those 15 points are used to validate the prediction. The predicted values in each validation point are extracted by using point extraction tool of ArcGIS. Residuals are calculated and plotted in EXCEL spreadsheet. To test the goodness of fit mean error (ME), also known as bias, and Root Mean Square Error (RMSE) are calculated (Snedecor and Cocharn, 1980).

Mean Error or bias is the average of the absolute error given by:

$$\textbf{ME} = \frac{\sum (X_{obs} - X_{pred})}{n} \qquad \textbf{Equation 4-4}$$

And Root Mean Square Error (rmse) is calculated by

$$\textbf{RMSE} = \sqrt{\frac{\sum (X_{obs} - X_{pred})^2}{n-1}} \qquad \textbf{Equation 4-5}$$

4.2. Soil erosion modelling

4.2.1. The revised Morgan, Morgan and Finny (MMF) model

The MMF model is an empirical model used to estimate average soil loss and runoff at field level. This model was selected because of its strong physical base, easier to understand and requiring few parameters as compared to other physical models (Morgan, 2005; Shrestha et al., 2004; Vigiak, 2005). The model is recently revised by incorporating flow detachment part of the runoff. The new version presented an improved physical basis with enlarged guidelines for model inputs and with proper flow accumulation and can be used in a watershed scale also (Morgan, 2001). The revised version of the model is used in our study. The model explains the erosion process in two phases: water phase and erosion phase.

Water phase

In water phase, rainfall kinetic energy and volume of overland flow is calculated. Average rainfall is converted into the effective rainfall (ER), which is the fraction (0 to 1) of average rainfall that is not intercepted by the vegetation canopy. The effective rainfall is split into direct throughfall (DT), which directly reaches into the ground without intercepted by the vegetation canopy, and leaf drainage (LD), which is intercepted by the canopy and reaches the surface by stemflow or by dripping from the leaves. The division is the function of canopy cover (CC, fraction between 0 and 1).

The kinetic energy of the direct throughfall (KE_{DT}) is a function of rainfall intensity (I, mm/h) and the DT (Table 4-1). Similarly the kinetic energy of the leaf drainage (LD) is the function of plant height and leaf drainage portion of the effective rainfall (Table 4-1). The total of the two kinetic energies determines the splash detachment (F) of soil particles. In each field, the volume of overland flow (Q) is calculated in terms of saturation excess runoff: surface runoff is generated when daily rainfall exceeds the soil moisture storage capacity (Table 4-1).

Erosion phase

The volume of overland flow (Q) is then used to calculate the detachment of soil particles by the overland flow (H) and the transport capacity of the flow (Table 4-1). Total detachment (J) is the sum of splash detachment and flow detachment and the average soil loss in each element is the minimum of total detachment and transport capacity of that element. A detail overview of various equations and parameters used in the model are presented in the Table 4-1.

Flow accumulation

The model is designed for field scale, therefore, for the application of the model in the area larger than field size requires the introduction of some mechanism of the runoff generated in each cell along the slope. Morgan(2001) suggested to divide the catchment into elements of homogenous character regarding soil, slope and land cover. The elements are then arranged in a cascading sequence to represent how runoff passes over the land surface from one element to another. The total runoff (Q_i) in element (i) is the sum of the runoff generated on that element and the runoff received from the element upslope. This accumulated runoff is than used to calculate the flow detachment and transport capacity in that element (i). The total material detached in that element is the sum of the materials detached in that cell and the influx of detached materials from the upslope element. Detached materials from the upslope are directed to the downslope in the same way. Similarly the total runoff accumulated at the outlet (peat) will give the total runoff generated from the catchment which should represent the discharge at the stream outlet of the catchment. A digital elevation model (DEM) can be used to accumulate flow providing the influx flow map (Hengl et al., 2003)

In order to accumulate the runoff, hydrology tool of spatial analyst tools in ArcGIS software is used in which the accumulation is performed based on the flow direction. Digital elevation model (DEM) is first used to determine the flow direction and the flow accumulation is done by providing the runoff map as input weight raster along with the flow direction map. Accumulated flow map is used as input overland flow map in the erosion phase of the model to calculate the detachment by overland flow and transport capacity of the overland flow. When using accumulated flow map for the erosion phase of the model, there will be over estimation of flow detachment along the stream lines due to accumulated flow in the stream (Vigiak, 2005). Therefore, it is important to mask out stream line from the accumulated flow map. In the sub-watershed, streams are within 200 to 300 meter from the ridges. Therefore, a user defined threshold value of 6 cells (30 m) is used to extract the drainage network in the sub-watershed. After extracting the drainage line, Boolean operation ("iff….True, 0, 1") in ILWIS is used to mask out the drainage line. The final flow accumulation map is generated by multiplying the flow accumulated map with Boolean map of value zero and one.

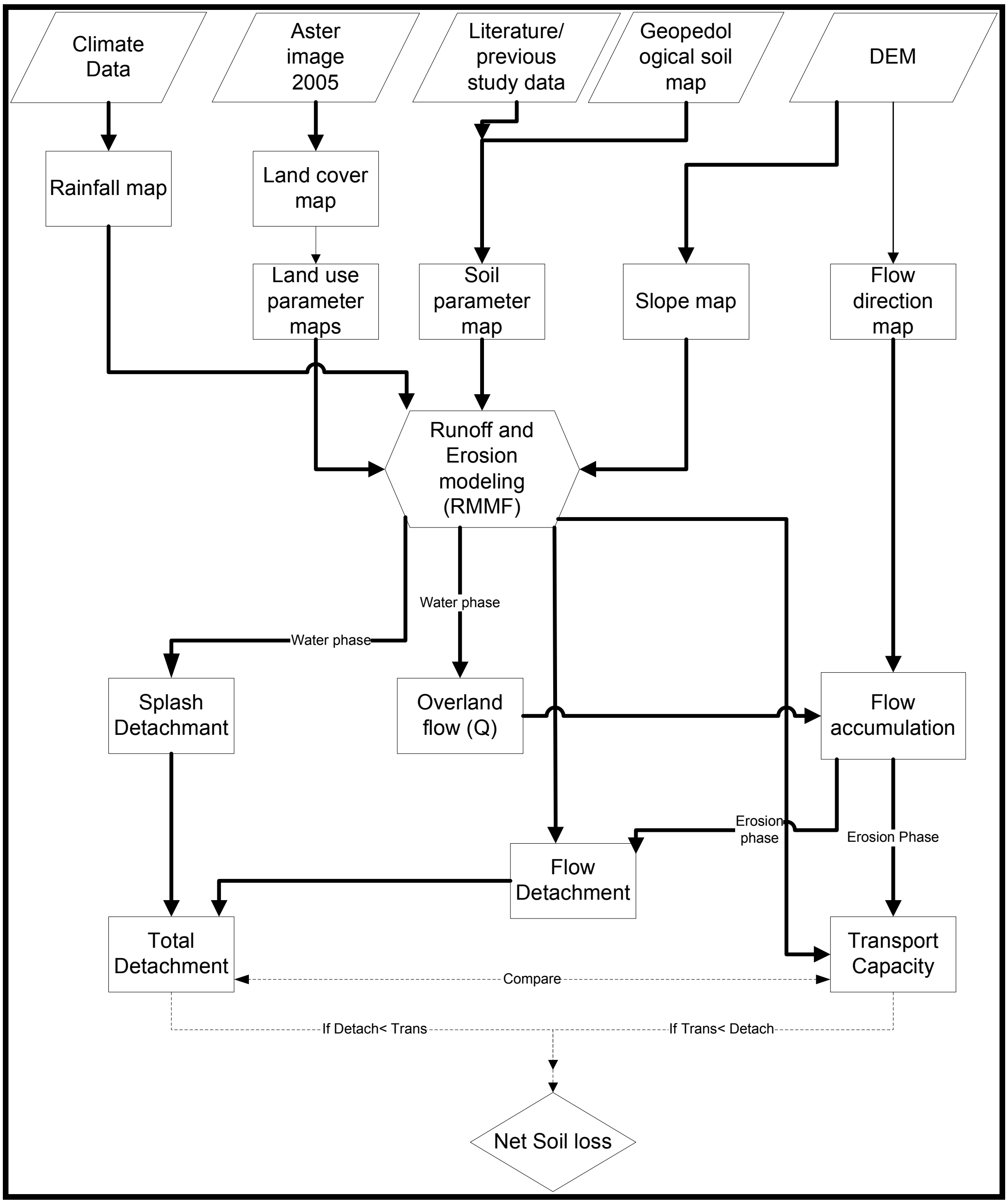


Figure 4-1: Flow diagram of RMMF model with flow accumulation.

Table 4-1: Operating functions for the RMMF model after (Morgan, 2005)

Eq No.	Equation	**Parameters**
Water Phase		
1	Effective rainfall (mm) $ER = R(1\text{-}A)$	R= Average annual rainfall (mm), A= Proportion (0-1) of rainfall intercepted by crop cover CC= Percentage canopy cover expressed as a proportion between 0 to 1 I= Typical value for the intensity of erosive rain (mm h^{-1}) PH= Plant height MS= Soil moisture content at field capacity (wt %), BD= Bulk density of top soil (mg m^{-3}), EHD= Effective hydrological depth of soil (m), E_t/E_0= Ratio of actual to potential evapotranspiration. R_n = Number of rain days per year.
2	Leaf drainage (mm) $LD = ER \times CC$	
3	Direct through fall (mm) $DT= ER\text{-}LD$	
4	Kinetic energy of DT(J m^{-2}) $KE(DT)=DT(11.9+8.7\log I)$	
5	Kinetic energy of LD (J m^{-2}) $KE(LD)=LD((15.8\text{-}PH^{0.5})\text{-}5.87)$	
6	Kinetic Energy of rainfall $KE= KE(DT)+KE(LD)$	
7	Volume of overland flow (mm)$Q= R \exp(-R_C/R_0)$ where, $R_C=1000\times MS\times BD\times EHD\times (E_t/E_0)$^0.5 And, $R_0= R/R_n$	
8	Splash Detachment (kg m^{-2} y^{-1}) $F = K\times KE \times 10^{-3}$	
Erosion Phase		
9	Flow Detachment (kg m^{-2} y^{-1}) $H= ZQ^{1.5}\times \sin S\times(1\text{-}GC) \times 10^{-3}$ Where, Z = 1/0.5 COH	K = Soil detachability index (g J^{-1}) defined as the weight of soil detached from the soil mass per unit of rainfall energy. S= Slope steepness (^{0}), GC = Percentage ground cover (proportion between 0 and 1) COH = Cohesion of the surface soil (kPa) as measured by a torvane under saturated condition. C= Crop cover management factor; combines the C and P factors of the Universal Soil Loss Equation.
10	Total soil detachment(kg m^{-2} y^{-1}) $J = F + H$	
11	Transport capacity of overland flow (kg m^{-2} y^{-1}) $G= CQ^2\times \sin S\times 10^{-3}$	
12	Soil loss = Minimum(J,G)	

4.2.2. Model Parameterisation

Preparation of Base Maps

Before running erosion model in a GIS environment, base maps such as landuse/cover map, soil map, rainfall map, slope map are necessary. Land use map in the sub watershed is prepared by using supervised classification of ASTER image of April 2005. The accuracy of the land cover classification map is assessed by ground truth data collected during field work. For the whole Namchun watershed, landuse/cover map prepared by (Suriyapiasit, 2008) is used (Annex-13). Landuse/cover classification consists of five classes such as dense forest, degraded forest, agricultural crops, grass land and orchard. Similarly, soil map prepared by Solomon (2005), available in digital form is used. Geopedological soil map has 19 mapping units in four broad landscapes such as Plateau, High Mountain, Low Mountain and Valley (Figure 4-2). Similarly, DEM is used to produce slope map of the area.

Rainfall is an important input parameter for the erosion model. Field measured rainfall data is used to produce rainfall map of the sub-watershed and watershed for the month of September. Average annual rainfall and rainy days are calculated from the available secondary rainfall information from 1987 to 2007 of Kao Khor area (Similar nearby area) to be used for the annual modelling. Because of the lack of spatial rainfall information, we assume a uniform rainfall throughout the area.

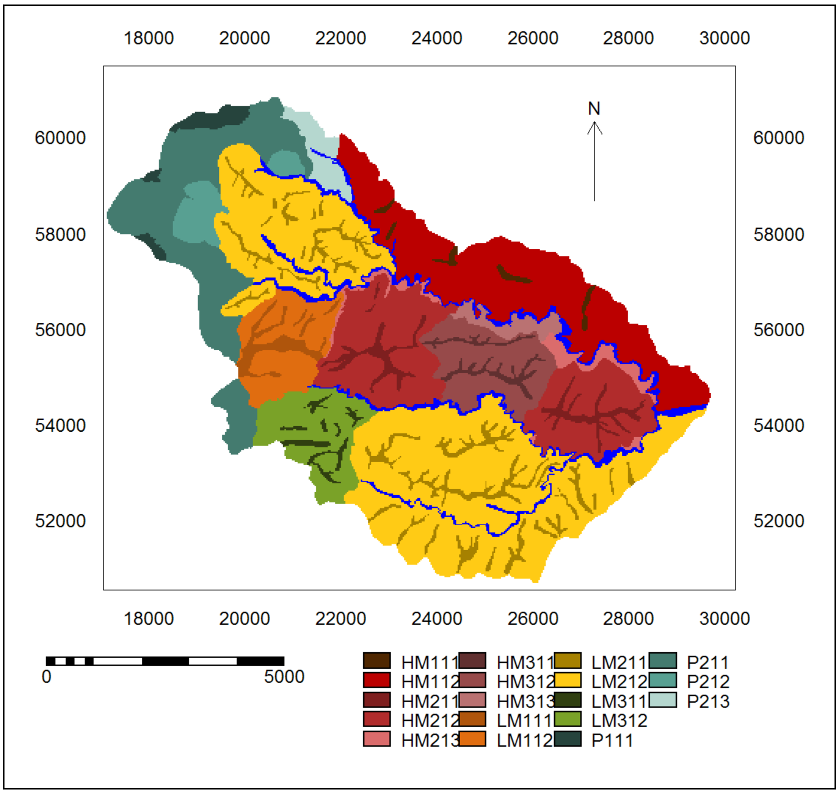


Figure 4-2: Geopedological soil map of Namchun, after (Solomon, 2005).

Preparation of Parameter maps

Secondary data of landuse parameters such as crown cover, ground cover, plant height and soil parameters such as soil bulk density and moisture content at field capacity of the area is available from the previous year study. A total of 58 sample data for landuse parameter and 52 samples for soil parameter is compiled by Amare Kassa (2007). Available secondary data is analyzed on those parameters to parameterize the model.

We compute one way analysis of variance (ANOVA), to test the statistical significance of the difference between the means of the landuse/cover parameters and soil parameters in different landuse/cover and soil mapping units respectively. After significance test, if the parameters are significantly different in different mapping units (land cover in case of land use parameters and soil mapping units in case of soil parameters); a linear modelling is applied to calculate the values of the parameters. Other parameters necessary for the model are taken from literature. Guide values of the parameters provided in Morgan (2001; 2005) are used. Parameters used in the model are presented in the annex-4. Landuse parameters and soil parameters are entered into the corresponding attribute table of the base maps and attribute maps are produced for each of the parameters as input map for the model by using ILWIS software.

4.2.3. Modelling Runoff and Erosion

After finalizing the model parameterization runoff and erosion are modelled in the sub-watershed for the month of September to compare the model predicted values with the field measured values. Runoff is also modelled for the whole Namchun watershed for the month of September. Here we compare the model predicted discharge value with the value obtained from the regression equation 4-10, by using the rainfall data of September. Gauged discharge data of the whole Namchun watershed for the water year 2004 and 2005 was available from the Royal Irrigation Department of Thailand (Annex-5). Therefore, for further evaluation of the model annually, runoff is estimated in the whole watershed for the water year 2005. As explained in section 4-2-1, flow accumulated runoff map is used in the erosion phase of the model to predict transport capacity and flow detachment.

Average annual soil loss is simulated in the sub-watershed to visualize the spatial pattern of soil loss in the area as well as to explore the association of soil loss with land cover, slope, and topsoil properties. For this purpose, the predicted soil loss values were extracted in the original sample point locations by using point intersection tool of ArcGIS. Similarly, DEM generated slope map is reclassified in five different slope class categories ($0\text{-}7^0$, $7^0 – 15^0$, $15^0 – 20^0$, $20^0 – 25^0$, $> 25^0$) reported as being suitable slope category for the tropical mountain areas (Sheng, 1972). Box plot visualization followed by one way ANOVA test is performed to test the significance of difference between means of soil loss in different slope class (Moore and McCabe, 2003). Similarly, Pearson's correlation analysis is performed to explore the relationships between the predicted soilloss with topsoil properties.

4.2.4. Validating Modelling Results

Validating Runoff

In order to validate estimated runoff by model, stream discharge was measured in the outlet of Nampong sub-watershed on a daily basis during fieldwork. The stream consists of a series of regular checkdams made of gabion box filled with stone and top surface finished with rough cement concrete. In between the checkdams, the water is stagnant, but across the slab the movement is quite faster. Therefore, measurements of discharge were carried out in one of the checkdam approaching to the stream outlet. The stream cross section was divided into four sections. Height of water in each section and the distance from the edge was recorded (Figure 4-3) daily to calculate the discharge by area velocity method. To measure the velocity, float method was used. In each section an average of five consecutive time measurements with a stop watch with 0.00 second precision was recorded. Velocity of water determined by float method is not the average velocity of the stream. As the velocity of the water is not the same at all places in the stream, which is slower at the sides and bottom, and faster on the surface. Taking 0.8 of the surface velocity as measured by the float gives an approximate value of the average velocity (Hudson, 1993). In each section the area is calculated by:

$$\textbf{Area } (A_n) = \frac{1}{2}(H_n + H_{n-1}) \times (L_n - L_{n-1}) \qquad \textbf{Equation 4-6}$$

Similarly, the discharge in each section is calculated by the equation:

$$\textbf{Discharge } (Q_n) = A_n \times V_n \qquad \textbf{Equation 4-7}$$

Where, V_n is the average velocity in the n^{th} section.

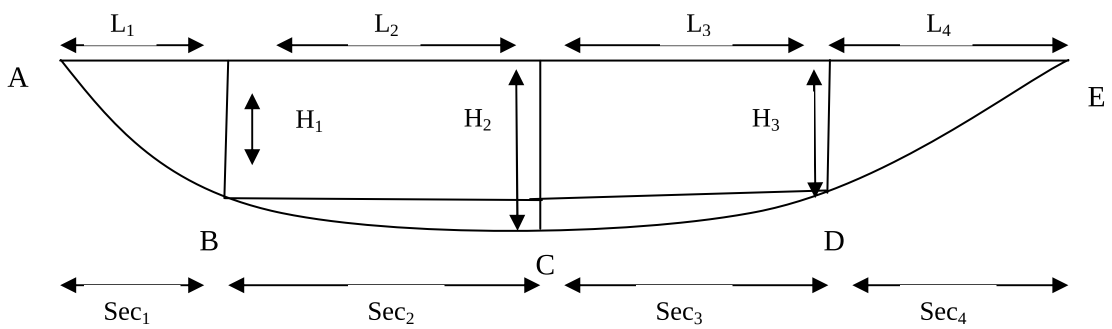


Figure 4-3: hypothetical cross section of stream for discharge measurement

To check the accuracy of the measured velocity, empirical formula to calculate the velocity, popularly known as manning formula is used which is given by (Hudson, 1993):

$$V = \frac{1}{n} R_h^{\frac{2}{3}} \cdot S^{\frac{1}{2}}$$

Equation 4-8

Where: V is the average velocity of flow in meters/second

R_h is the hydraulic radius in meters

S is the average gradient of the stream in m / m, and

n is a coefficient known as Manning's roughness coefficient.

The hydraulic radius is calculated by the formula:

$$R_h = \frac{A}{P}$$

Equation 4-9

Where: A is the area of the stream cross section (m^2) and

P is the wetted perimeter of the stream (m)

Uncertainty analysis is performed to analyze the uncertainty in discharge value with the uncertainty in height measurement.

In addition to measuring stream discharge from the sub-watershed of Nampong, gauged discharge data of the whole watershed of Namchun for the period 2004 and 2005 was also collected from the Royal Irrigation Department of Thailand (see annex5). To explore the relationship between monthly discharge and monthly rainfall, we plot a scatter plot fitted with linear trend surface in EXCEL (Figure 4-4). A linear regression equation produced from the trend showed a significant relation with R^2 value 0.74. We used that equation to calculate the total discharge of the watershed for the month of September 2007 with the rainfall data of September, 2007. The calculated value is used to compare the model simulated discharge of September, 2007 in the whole watershed.

From the regression analysis, the equation to calculate the monthly discharge is:

Discharge Q (m3/m) = 11558 × Rainfall + 66075 Equation 4-10

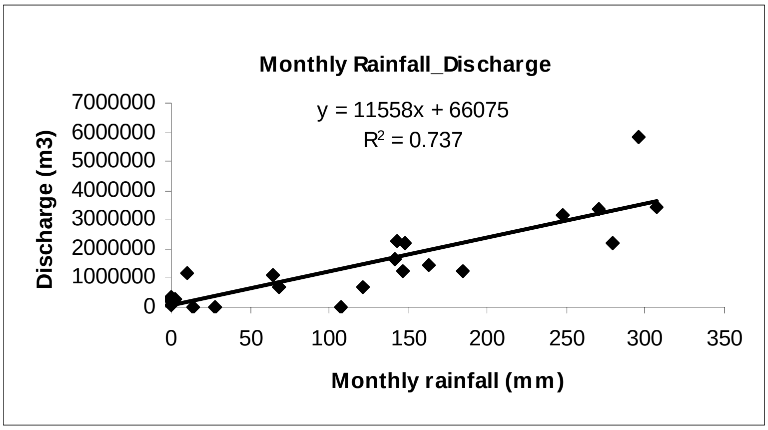


Figure 4-4: Scatter plot of monthly rainfall and discharge fitted with linear trend surface.

For the validation of the prediction the ratio between predicted value (discharge) and measured value is used. The percentage of predictions that are acceptable can be used as a measure of model's success. For the validation of a model, the ratio value between 0.5 and 2 can be considered acceptable (Morgan, 2005).

Validating Soil loss

Grab method was used to collect suspended sediment sample from the Nampong sub-watershed using water bottles of known volume. It has been recommended that the sample should be taken at the point where the suspended load is well mixed (Hudson, 1993). In our case we chose the location where there is a checkdam across the stream (Figure 4-5). A single sample during the flooded day was collected and allowed to settle. After the complete settlement, water is drained out; sun dried and weighed in an electric balance of 0.0000 gm precision.

4.3. Up-scaling runoff and erosion assessment from sub-watershed to bigger watershed

One of the objectives of this research is to explore the possibilities of up-scaling the results of the detailed assessment of runoff and soil erosion in a small and representative sub watershed to the whole watershed. Possibility of up-scaling the measured discharge, of the sub-watershed to that of the watershed scale, is explored with two different approaches. Similarly, based on the observed and analyzed pattern of soil loss in the sub-watershed, a decision rule is set and applied in a GIS environment to map the spatial pattern of soil erosion in the whole watershed qualitatively. Details of the approaches are explained in the following section.

4.3.1. Up-scaling discharge

Two different approaches of discharge up-scaling are tested in the study. Firstly, up-scaling is done by comparing the discharge ratio with the ratio of watershed total area with that of the sub-watershed. Here, we assume that the contributing area determines the overall flow in a catchment and if the soil properties and rainfall is similar then the ratio of the area of the watershed with the area of a nested sub-watershed can reflect the discharge ratio of the watershed to the sub-watershed. Therefore, the following equation is used to upscale the discharge:

$$\frac{Q_w}{Q_{sw}} = \frac{A_w}{A_{sw}} \qquad \textbf{Equation 4-11}$$

Where, A_w and A_{sw} are the total area of the watershed and that of the sub watershed.

In a second approach, it is assumed that landcover in a catchment determines the overall overland flow if other properties governing the runoff generation is considered to be similar. Thus area of each land cover type is multiplied by a runoff generation weight and the sum of the weighted area is calculated for the whole watershed as well as for the sub-watershed. For this purpose, average runoff data calculated by Prachansri (2007) is used. A weight factor is calculated by dividing the average runoff rate in each land cover type by the sum of runoff rates in all land cover types (see annex-7). Area of each land cover type in the watershed and in the sub-watershed is multiplied by the weight factor and the ratio of the sum of the weighted area of the watershed and sub-watershed is calculated. Finally, the up-scaling is done by using the following relation.

$$\frac{Q_w}{Q_{sw}} = \frac{\sum (L_i)_w \times W_i}{\sum (L_i)_{sw} \times W_i}$$ **Equation 4-12**

Where, $(L_i)_w$ and $(L_i)_{sw}$ are the area of the similar (i) land cover category in the watershed and sub-watershed and W_i is the runoff weight factor of the corresponding land cover type.

Equation 4-11 and 4-12 are used to up-scale the sub-watershed discharge to the watershed discharge and the results are discussed accordingly.

4.3.2. Up-scaling erosion pattern (Knowledge based modelling)

In order to up-scale the erosion pattern in the whole watershed knowledge based qualitative modelling is done. Qualitative erosion model requires different classified maps as input base maps. Therefore, for this purpose, DEM generated slope map is reclassified into five different slope classes as mentioned in previous section 4.2.3. Similarly, soil property maps are also reclassified into similar number of classes. For this purpose, soil property maps prepared for the area are imported into ArcGIS and reclassified into five classes (very high, high, moderate, low and very low) depending upon the value in a particular location (Annex-10). Result of the analysis of the relation of soil loss with soil properties, land cover and slopes, are used to set up the decision rules to be applied in a GIS environment. Based on the importance of different factors in causing soil loss, they are listed accordingly and a decision rule is set starting from least important factor and ending with high important factor. A qualitative domain, starting from very high to very low, is provided for the combination of any two factors based on the causal importance of those factors (refer two dimensional decision tables in Annex- 10). Developing decision rules is an important step in a qualitative modelling. Based on the causal strength of a factor in overall soilloss, factors are ranked accordingly (Shrestha et al., 2004). A two dimensional table is created in ILWIS by providing a qualitative domain value in between any two factors and a qualitative map based on that table is created. Once the qualitative map between two factors is generated, that map is used to generate another two dimensional table with another factor. Likewise, a final qualitative erosion map is produced in several steps.

4.4. Research procedure

4.4.1. Materials and software

1. **Materials:** Various materials used in this study are as follows:
   - ASTER image of April 2005
   - Digital Elevation Model (30m pixel size) available from LDD.
   - Digital geopedological map prepared by Solomon (2005).
   - Geological map (1:50,000) of the area available from the LDD (2002)
   - Hand held GPS (Global Positioning System)
   - Field equipment for soil sample collection such as spade, sample bag etc.
   - Stop watch
   - Electronic weighing machine
   - Laboratory apparatus and chemicals for soil analysis.
2. **Software:** Various software used in this study are: ArcGIS, ERDAS, ILWIS, Geostatistical software R, SPSS, Microsoft word and Excel etc.

4.4.2. Field Data Collection

Field work was carried out during September 2007. The field work was confined to collect necessary primary and secondary information required for the study. Following data were collected during the field study:

1. **Discharge and sediment measurement:** During the field work period, daily discharge measurement was done in the Nampong sub-watershed. As explained in section 4.2.4, daily heights of water and average velocity in different sections of the stream were measured (Figure 4-5). Similarly, during flooded period, suspended sediment samples were collected.
2. **Topsoil sample collection:** Topsoil samples (0-20 cm) were collected from the sub-watershed as well as from the whole watershed. In the sub-watershed, regular grid sampling in 200m grid spacing was done. Systematic random sampling based on soil mapping units and accessibility of the area was performed in the whole watershed (Freese, 1984) (Figure 4-6). A total of 58 soil samples from the sub-watershed and 68 samples from the watershed were

collected. In case of whole watershed, soil sample collection was carried in a team of four researchers.

3. **Rainfall measurement:** Daily rainfall was measured in the sub-watershed by using a temporary rain gauge. A calibrated beaker was used for this purpose.
4. **Training sample collection:** A number of training samples were collected for the image classification in order to produce land cover maps of the watershed and sub-watershed.
5. **Locating erosion features:** Erosion features such as rills, gullies, heavy sheet wash etc in the whole study area were located randomly by using hand held GPS. Such features as encountered during the field study were located.
6. **Secondary Data Collection:** Meteorological data were collected from Lom Sak as well as from Kao Khor stations. Runoff study data was also collected from the Forestry Department of the area. Gauged discharge data of the Namchun watershed was collected from the Royal Irrigation Department of Thailand. Similarly, DEM and geology map of the area were collected from the Land Development Department (LDD) of Thailand.

Figure 4-5 discharge measurement and soil sample collection in Nampong sub-watershed.

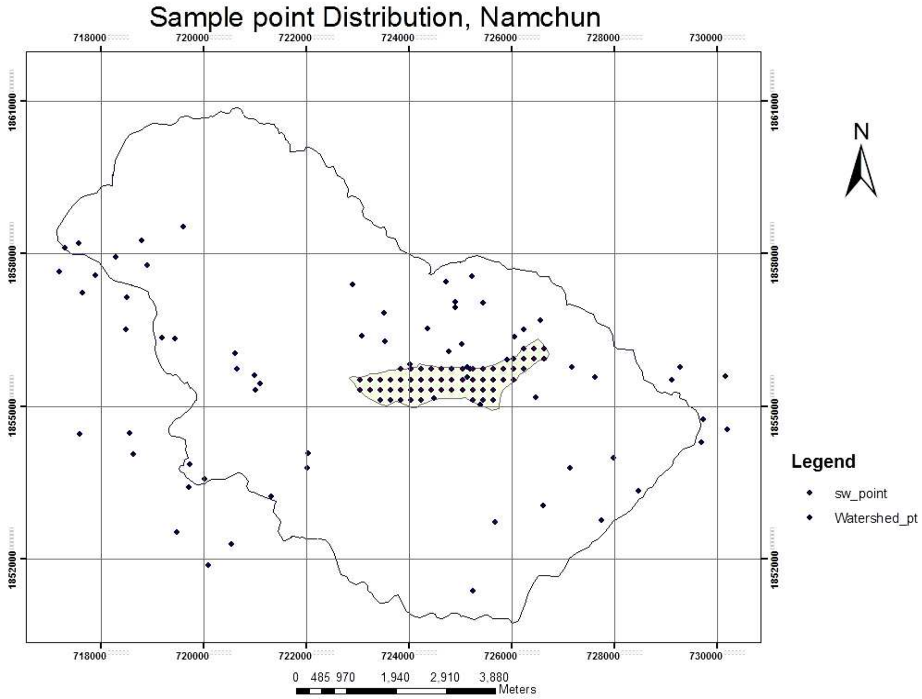


Figure 4-6: Distribution of sample points for soil sample.

4.4.3. Laboratory analysis of soil samples

Topsoil samples collected from the sub-watershed and from the watershed were brought to ITC soil laboratory for the particle size analysis and organic matter (OM) analysis. Pipette method for the particle size analysis (**Error! Reference source not found.**), and Walkley-Black procedure for the determination of OM was used following the standard of FAO and ISRIC laboratory analysis guidelines (Van Reeuwijk, 2002). For the quality control of the analysis, one random duplicate sample from the previous batch is analyzed in every next batch. A total of 126 soil samples (both from the sub-watershed and outside the sub-watershed) were analyzed.

Figure 4-7: Particle size analysis by pipette method.

5. Results and Discussions

5.1. Mapping Topsoil Properties

One of the objectives of the research is mapping of some topsoil properties to relate them with the spatial pattern of soil erosion in the area. The variability of soil properties, their relationship with regionalized variables like landuse/cover class and lithological factors are tested. Finally, interpolation was carried out using regression kriging to map soil properties in the study area. The prediction maps were validated with independent validation data set of 15 sample points

Regarding exploratory data visualization, topsoil clay content in the study area varies from 18 to 26 percent, with a mean of 22.1 and standard deviation of 2. Similarly silt has a range of 60 to 75 with average of 69.8 and standard deviation of 2.6. Organic matter varies from 0.2 to 4.3 percent with average of 1.8 and standard deviation of 0.8 (Table 5-1).

Table 5-1: Exploratory summary of soil properties in Namchun Watershed

	%CLAY	%SILT	%SAND	%OM	Crusting index
Min	18.1	60.3	2	0.2	1.3
Max	26.3	74.9	18.6	4.3	3.4
Mean	22.1	69.8	8.1	1.8	2.0
st.dev	2.0	2.6	3.6	0.8	0.42

The histogram of OM and clay content show a bimodal distribution where as the histogram of silt is slightly left skewed but symmetrical within the range of 65 to 75. Histograms of soil properties show normal distribution pattern (Figure 5-1). Similarly, the post plots of the properties show an impression of regionalized variation with cluster of high value and low value in some locations showing some degree of spatial dependence. Although the post plots give some impression of spatial dependence, the degree of spatial dependence can not be explained by those post plot diagrams.

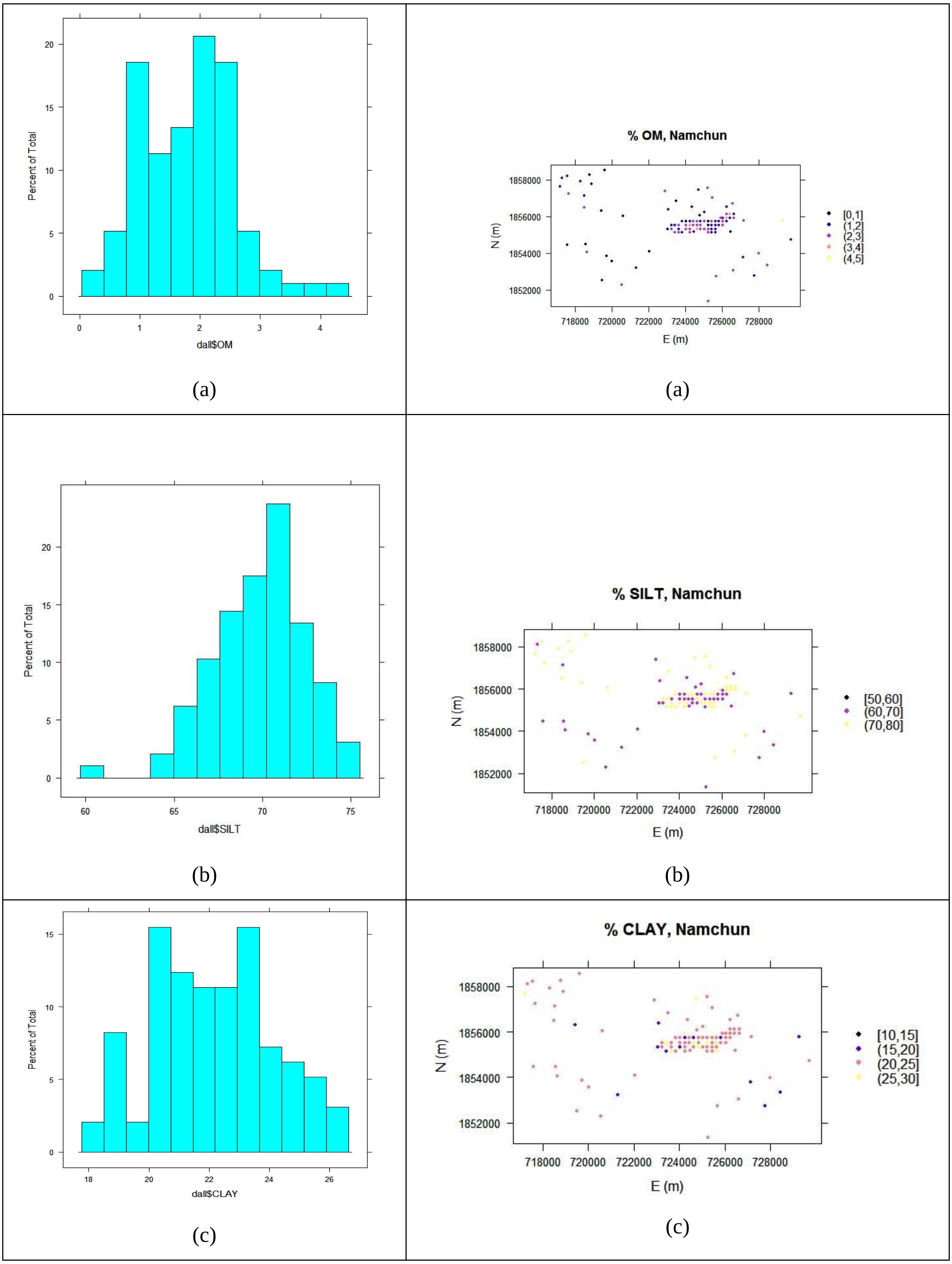
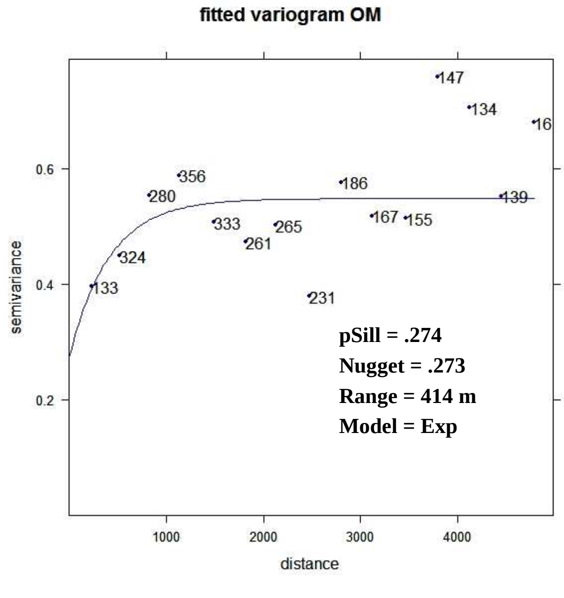


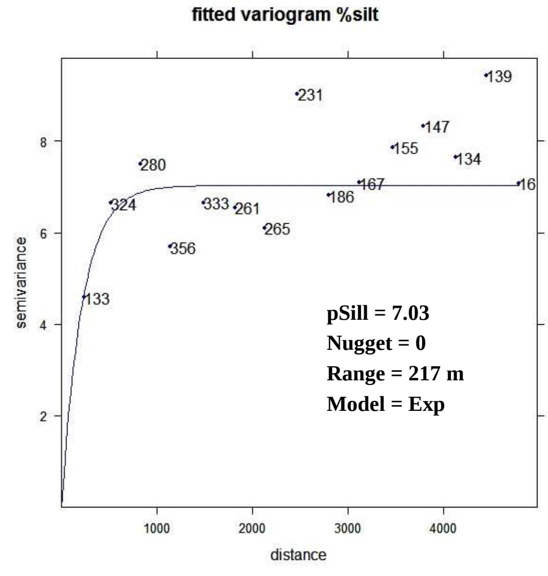
Figure 5-1: exploratory graphics of top soil properties (a) organic matter (b) silt content (c) clay content.

5.1.1. Variogram Analysis

The variograms of soil properties with their corresponding parameters such as nugget, sill and range are presented in Figure 5-2. It shows that the spatial autocorrelation is very high in case of clay as compared with other properties as the range is very high for clay. There is short range local spatial dependence in case of other soil properties except clay. Exponential model fitted to the experimental variogram provide satisfactory fit for the soil properties other than clay. In case of clay the model is unbounded linear with very high range. The ratio of nugget to the total sill represents the unexplained variability and the converse of that is the total variability explained by the model. In our case, the explained variability of the fitted models are 0.5 for OM., 1, for silt, 0.67 for clay, and 0.53 for crusting index. The unexplained variability (NSR in equation 4-7) are 50% for OM., 0% for silt, 33% for clay and 47% for crusting index which shows very strong spatial structure for silt followed by clay. Crusting index and organic matter has moderate structured spatial dependence. Yemefack et al.(2005) also found similar result for clay with unbound linear relation with very long range In southern Cameroon. The long range spatial dependency of clay may be because of its regionalized dependency with soil forming factors along with local factors such as land cover and local farming practice. Yemefack et al.(2005) have concluded that landuse practices have significant influence in topsoil variation. Strongly structured spatial dependence of soil properties are usually caused by intrinsic factors such as soil forming factors (Sumfleth and Duttmann, 2007). Therefore, very strong spatial structure of clay and silt is attributed to the theory of soil genesis. Whereas moderate structure of OM is attributed to land management factor such as land husbandry and cover management.



(a)



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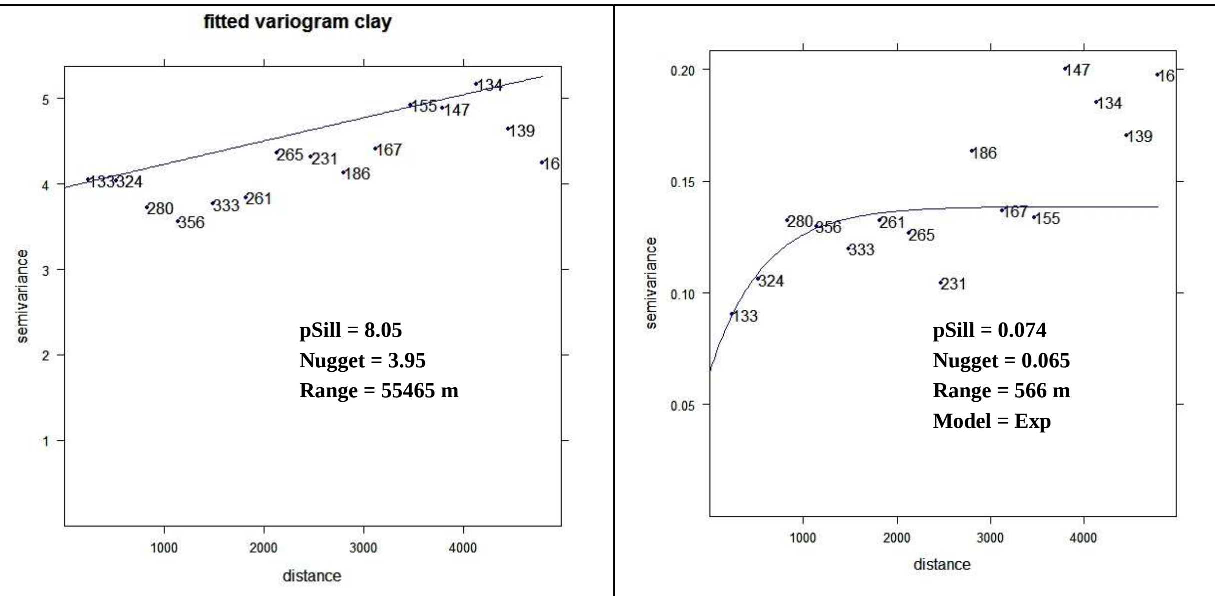


(c) (d)

Figure 5-2: Fitted variogram models with parameters (a) OM (b) Silt (c) Clay (d) Crusting Index

5.1.2. Analysis of Linear Regional Dependency of soil properties

Box plots were generated to visualize the distribution of different soil properties in different landuse/cover and lithology types (Figure 5-3). From the figure, it can be visualized that the distribution of mean values are different in different categorical factors but we can not conclude about the significance of the difference and the variability explained by the relation from the box plots.

Test of linearity of OM and crusting index with land cover types revealed a significant relation with probability of 1.295e-10 for OM and 3.071e-10 for crusting index. Similarly there is a significant linear relationship of clay and silt with lithology types with probability of 0.02267 and 0.02047 respectively. The variability explained by the relationship (adjusted R^2) is 40% for OM, 39%, for crusting index, and 11%, for clay and silt.

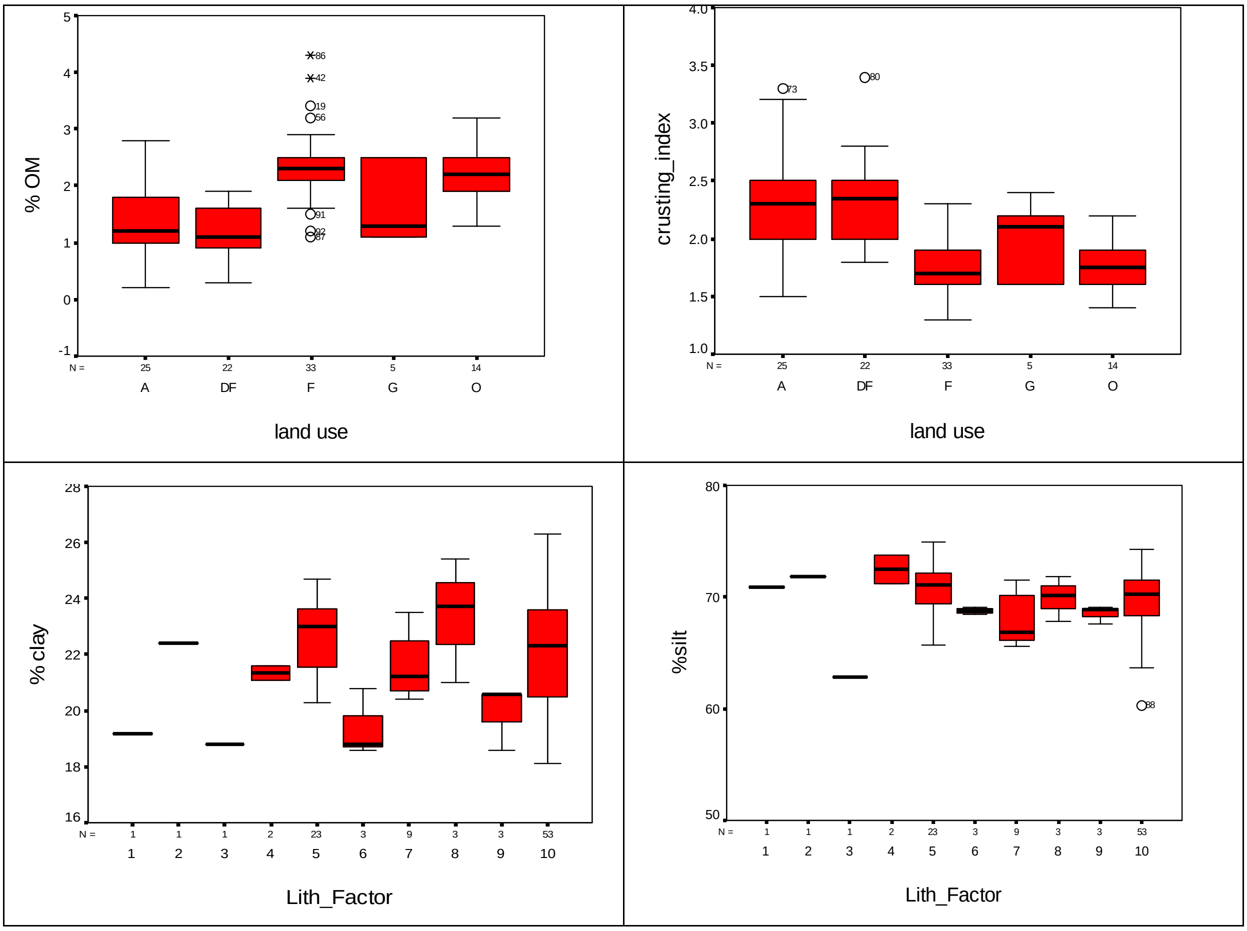
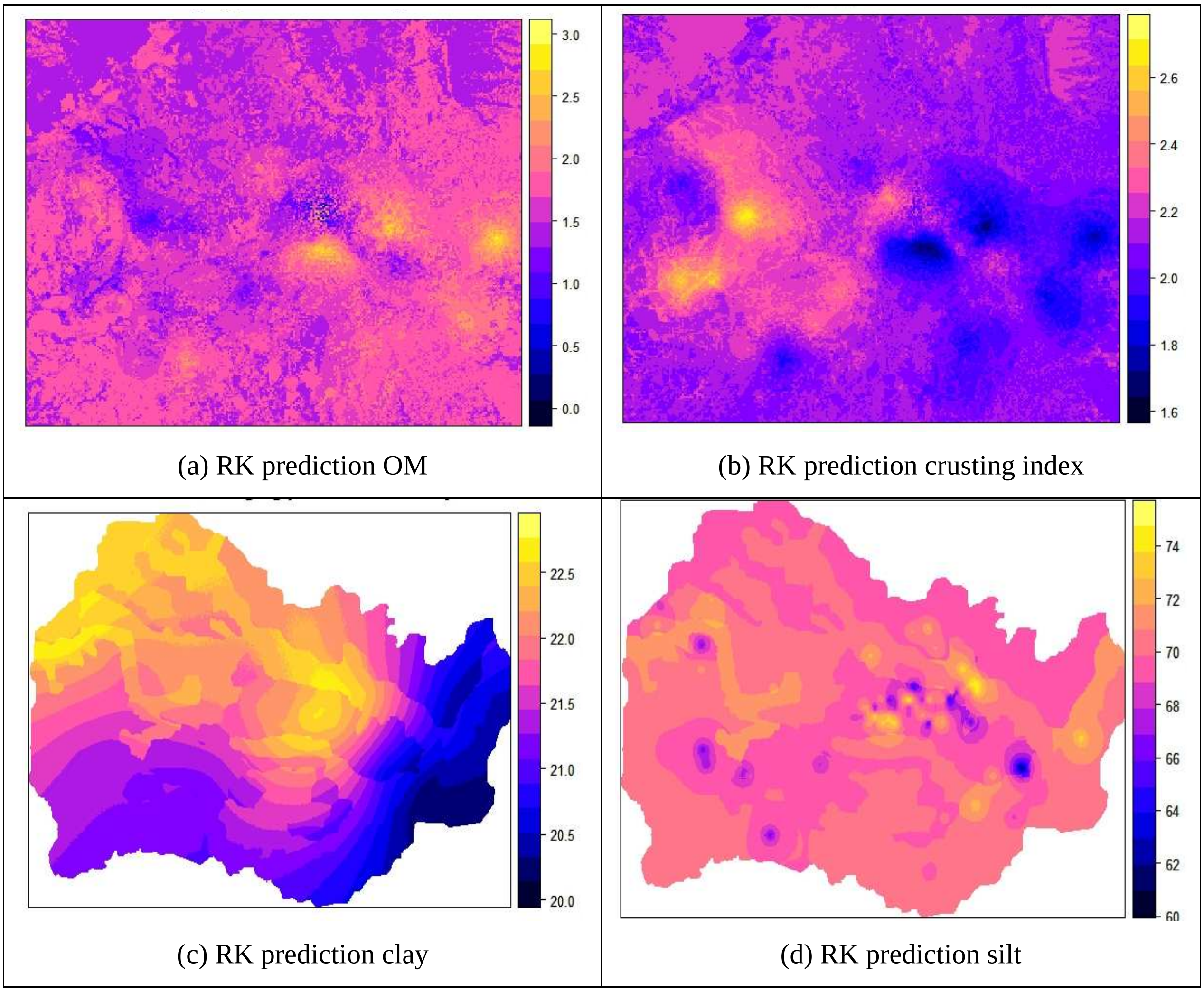


Figure 5-3: Box plots showing regional dependence of soil properties (Lith_ factors 1-10 are lithology types (Annex-11); Landuse A= Agriculture, DF= Degraded forest, F= Dense forest, G= Grass land and O= Orchard).

OM and crusting index are best explained by regional factors of soil variation than clay and silt. Significant but low association of clay and silt with lithology type may be attributed to the fact that the soil formation in the humid tropics is often so advanced that the relationship between rock and soil properties are no longer clearly distinguishable (Yemefack et al., 2005), and that may be the case in this region too.

5.1.3. Regression Kriging

The interpolation maps of topsoil properties by regression kriging are presented in Figure 5-4. The range of predicted value in case of clay is very short as compared to other soil properties. If we compare the predicted value range with the corresponding range in calibration data set, the prediction variation is quite fair for other soil properties except for clay.



(a) RK prediction OM

(b) RK prediction crusting index

(c) RK prediction clay

(d) RK prediction silt

Figure 5-4: Regression Kriging maps of (a) organic matter (b) Crusting Index (c) % Clay and (d) % Silt.

Residuals of OM reveal that there is over prediction of 1.5% in some location; where as the residuals of crusting index shows that there is under prediction up to 1.5. Similarly, there is over prediction of up to 6% in case of silt and in case of clay there is uniformity in over prediction and under prediction (Figure 5-5). Table 5-2 shows mean error (ME) and root mean square error (RMSE) of predictions. Silt prediction has high value of ME (1.33) where as predicted clay has high RMSE (5.88) value. Our results revealed that organic matter and crusting index are predicted with reasonable accuracy as compared to clay and silt.

Long ranged strong spatial structure along with less explained variability of lithology type for clay might be the possible causes of high prediction error in case of clay (section 5.1.2).Very strong spatial structure of clay and silt is attributed to many intrinsic soil forming factors. Topsoil texture is variable in space and time and is influenced strongly by various soil forming factors, both externally and internally (FAO, 1998). Therefore, to improve the accuracy of prediction all the governing intrinsic factors should be analyzed and accounted properly. Multi-linear regression models, taking into account of all the forming factors, might give better results in mapping these soil properties. Because of the limited time for the research, we could not focus on this aspect.

Table 5-2: Mean Error and RMSE of soil property prediction

	Silt	OM	Clay	Crusting index
ME(bias)	1.33	0.36	0.73	0.18
RMSE	2.49	0.61	5.88	0.55

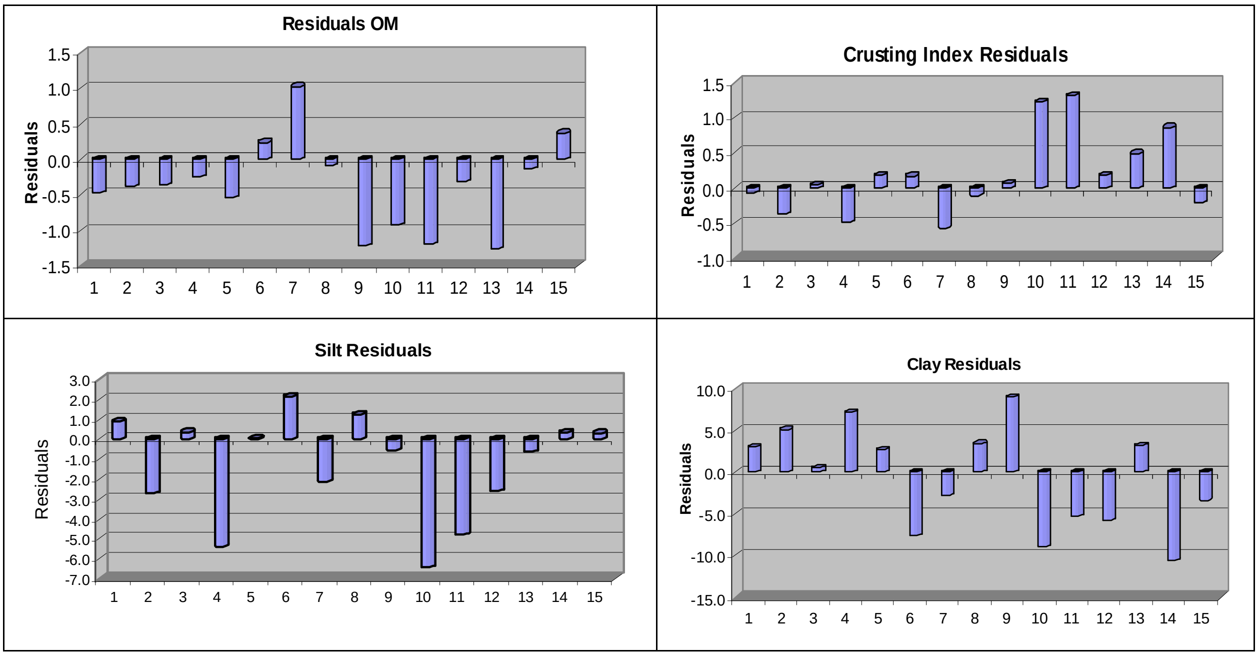


Figure 5-5: Residuals of prediction.

Table 5-3 summarises the distribution of different soil properties in different landscape units. High Mountain areas have in general higher organic matter content (average OM content 1.9%) whereas plateau landscapes have low organic matter content. Similarly, Plateau area have high crusting index as compared to other landscapes. However, the variation in silt content is not much significant in different landscapes. In Namchun Watershed, High Mountain areas are characterized as having dense forest where as plateau and Low Mountain areas are cultivated as well as the forests is degraded as compared to high mountain area. Therefore, the distribution of high organic matter and low crusting index in case of High Mountain can be justified.

Table 5-3: Distribution of soil properties in different landscapes

Landscape	Organic Matter		Silt		Crusting Index	
	Average	St dev	Average	St dev	Average	St dev
High mountain	1.9	0.23	69.6	1.1	2	0.1
Low mountain	1.6	0.15	70.2	0.4	2.2	0.1
Plateau	1.4	0.15	70.1	0.8	2.3	0.1
Valley	1.7	0.2	70.5	0.7	2.1	0.1

5.2. Modelling Runoff and Erosion

5.2.1. Model parameterisation

Landuse/cover classification

Landuse/cover classification of the sub-watershed is done in five land cover classes: Dense forest, degraded forest, Agriculture, Grassland and Orchard (Figure 5-6). The classification accuracy is tested with the ground truth data collected during field work which shows an overall classification accuracy of the landuse/cover map of the sub-watershed of 72% (Table 5-4). Landuse/cover areas of each class in the sub-watershed are presented in Table 5-5.

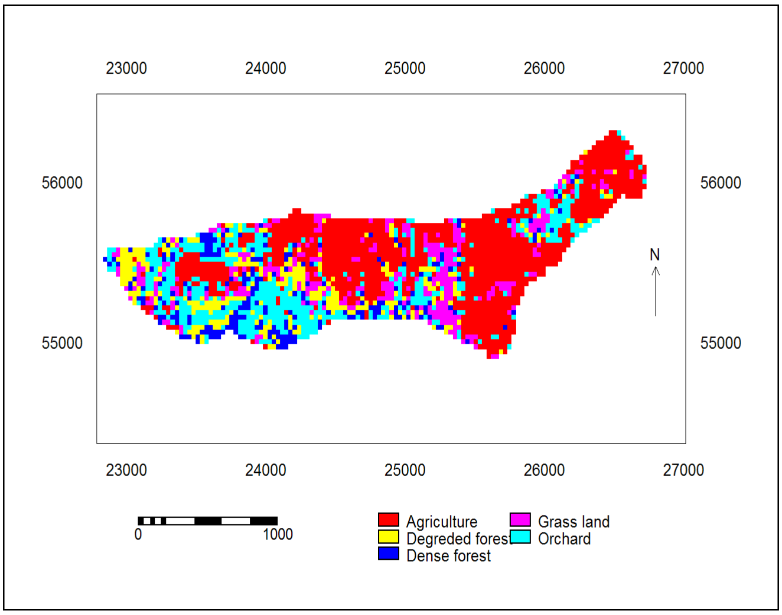


Figure 5-6: Landuse/cover maps (a) Namchun Watershed (b) Nampong sub-watershed

Table 5-4: Confusion matrix showing classification accuracy of Nampong sub- watershed

ACCURACY TOTALS

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Unclassified	0	0	0	---	---
densfor	10	7	7	70.00%	100.00%
degfrl	9	7	6	66.67%	85.71%
agir5	9	15	8	88.89%	53.33%
gras3	7	7	5	71.43%	71.43%
orch2	8	7	5	62.50%	71.43%
Totals	43	43	31		

Overall Classification Accuracy = 72.09%

Table 5-5: Area under different land cover

Landcover types	Area (ha.)	%
Dense forest	20.7	8.8
Degraded forest	25.9	11.0
Agriculture	106.1	45.2
Grass land	32.2	13.7
Orchard	49.9	21.3
Total	234.9	100.0

Preparation of parameter maps

One way ANOVA test reveals that, landuse/cover parameters (plant height, crown cover and ground cover) are significantly different in different landuse/cover classes; however there is no statistical significance of the difference between the means of soil parameters (moisture content at field capacity and soil bulk density) in different soil mapping units (Tables 5-6 and 5-7).

Table 5-6: One way ANOVA of landuse parameters with landuse classes

		Sum of Squares	df	Mean Square	F	Sig.
Plant height	Between Groups	3094.988	4	773.747	32.688	.000
	Within Groups	1254.565	53	23.671		
	Total	4349.553	57			
Crown cover	Between Groups	3.491	4	.873	34.332	.000
	Within Groups	1.347	53	.025		
	Total	4.838	57			
Ground Cover	Between Groups	1.028	4	.257	8.996	.000
	Within Groups	1.515	53	.029		
	Total	2.543	57			

Table 5-7: One way ANOVA of soil parameters with soil mapping units

		Sum of Squares	df	Mean Square	F	Sig.
MS	Between Groups	.141	11	.013	1.864	.075
	Within Groups	.275	40	.007		
	Total	.415	51			
BD	Between Groups	.136	11	.012	.624	.798
	Within Groups	.791	40	.020		
	Total	.927	51			

Results of linear modelling of land use parameters with landuse/ cover types revealed that it is possible to use linear model to calculate the values of these parameters because we get the adjusted R square of 69%, 70% and 39% for plant height, crown cover and ground cover respectively (Annex-14). The values of landuse parameters based on the linear equations are presented in Table 5-8. Other parameter values for the model literature data were used. Guide values of the parameters provided in literature are used for the purpose (Morgan, 2001; Morgan, 2005). Parameters used in the model are presented in annex-4.

Table 5-8: landuse parameter calculated by linear equation

Land use/cover	PH	CC	GC
Dense forest	19.4	.82	.92
Degraded forest	14.95	.35	.72
Agriculture	1.8	.49	.68
Grass land	1.5	.93	.96
orchard	7.3	.31	.62

5.2.2. Modelling runoff and erosion in the Nampong sub-watershed

Runoff and erosion modelling in the month of September

The total discharge in the sub-watershed as simulated by the model is 118181 m^3 (Table 5-9). Agriculture area has highest runoff (72.2 mm/m^2) followed by orchard and grass land, whereas; dense forest has lowest runoff (4.2mm/m^2).

Table 5-9: Model simulated discharge of September

Land use/cover	area	Av. Runoff (mm/m^2)	Total discharge (m^3/month)
Dense forest	195300	4.2	820.3
Degraded forest	254700	11.3	2878.1
Agriculture	1035900	72.2	74792.0
Grass land	293400	43.1	12645.5
Orchard	467100	57.9	27045.1
Total	2346400	Total simulated	118181.0
		Measured	224104
		Ratio	0.53

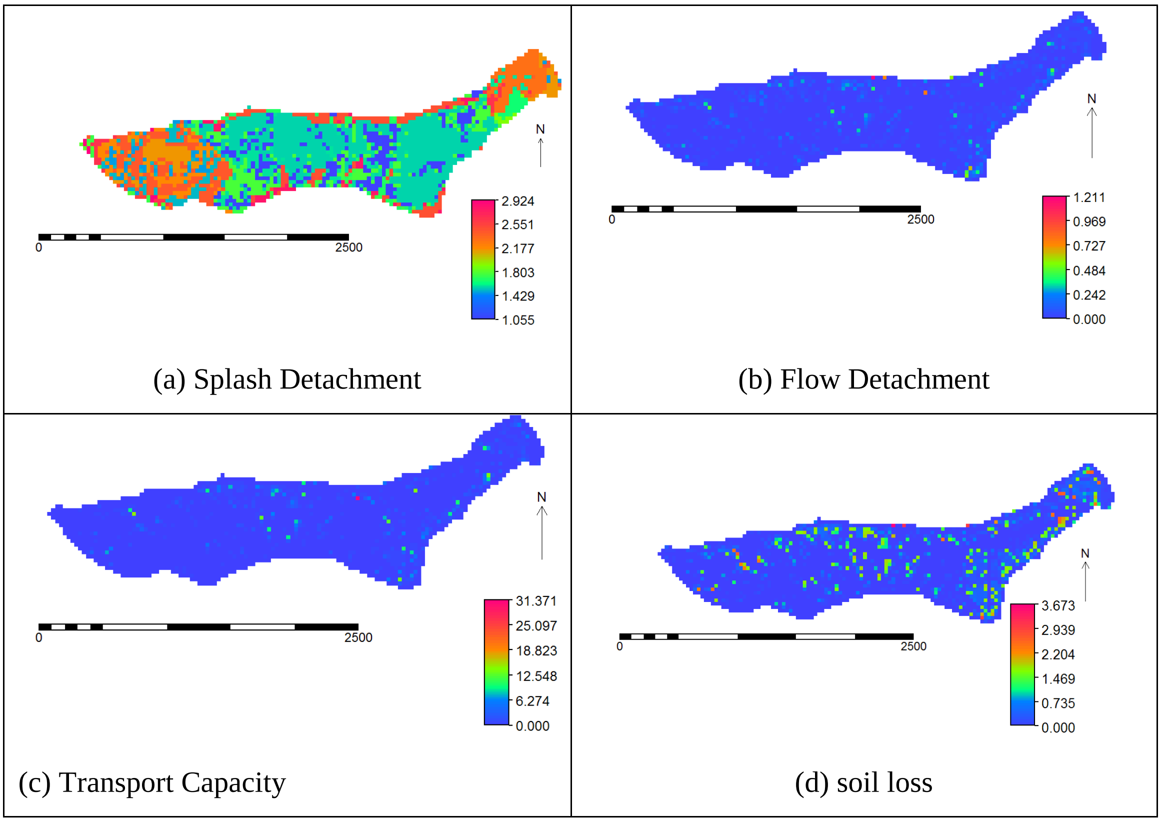
Table 5-10 summarises the results of model simulated values of flow detachment, splash detachment, transport capacity and net soil loss for the month of September in the sub-watershed. Splash detachment is more significant than flow detachment. Only in few locations in steep slopes, flow detachments seemed to be prominent. In a study in Tanzania, Vigiak(2005), have also reported the similar results where the flow detachment is less significant than splash detachment. Monthly soil loss ranged from 0 to 3.673 with an average of 0.426 kg m^{-2} m^{-1} for the month of September, 2007(Figure 5-7). Dense forest has minimum soilloss where as agricultural area and orchard have high soil erosion rate (Table 5-11).

Table 5-10: RMMF estimated monthly values of erosion in Nampong SW (Kg$m^{-2}m^{-1}$), September

Erosion Process	Range	Mean
Flow Detachment	0 - 1.21	0.04
Splash Detachment	0.06 - 2.92	1.98
Transport Capacity	0 - 31.37	0.84
Net soil loss	0 - 3.67	0.43

Table 5-11: Soil loss in SW (September)

Land use/cover	Area (m^2)	Av.soil loss kg/m^2/month	Total soil loss t/m
Dense forest	195300	0.038	7.4
Degraded forest	254700	0.146	37.2
Agriculture	1035900	1.707	1768.3
Grass land	293400	0.812	238.2
Orchard	467100	0.838	391.4
Total			2442.6



(a) Splash Detachment

(b) Flow Detachment

(c) Transport Capacity

(d) soil loss

Figure 5-7: RMMF output maps of September 2007.

Modelling average annual soil erosion in the sub-watershed

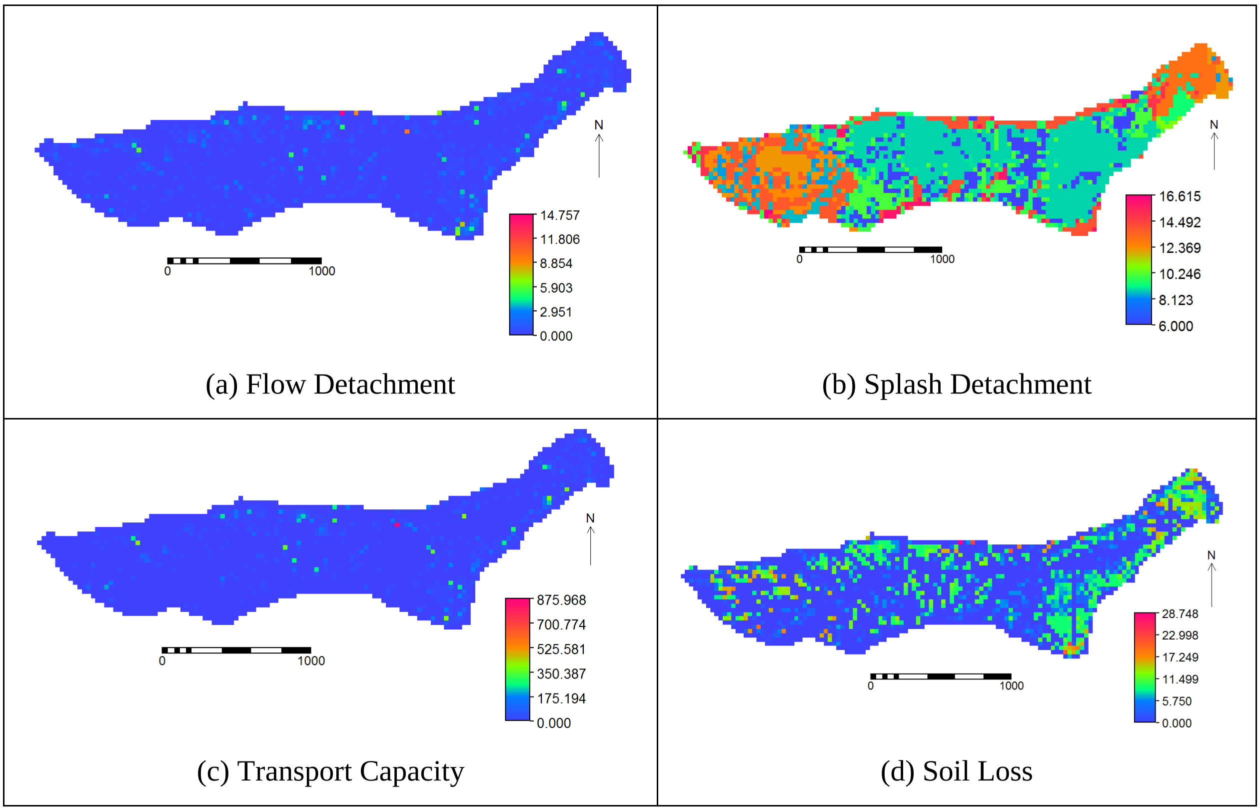
Table 5-12 summarises the model simulated average annual values of flow detachment, splash detachment, transport capacity and net soilloss in Nampong sub-watershed. Annual soil loss ranged from 0 to 28.7 kg m^{-2} y^{-1} with an average of 4.8 kg m^{-2} y^{-1}. Agriculture field has high value of average annual soil loss (11.9 kg m^{-2} y^{-1}), followed by orchard and grass land. Whereas, dense forest area has very low rate of annul soil loss (Table 5-13). In a study in Tanzania, Vigiak (2005) reported average annual soil loss of <0.01 kg m^{-2} $y^{-1}$to 13.5 kg m^{-2} y^{-1} with mean annual rainfall of 1000 mm. In

Nampong, as the average annual rainfall is 1377 mm, the obtained soil loss is close to the values in literature.

Table 5-12: RMMF estimated annual values of erosion in Nampong SW ($Kgm^{-2}y^{-1}$)		
Erosion Process	Range	Mean
Flow Detachment	0 - 14.7	0.56
Splash Detachment	6 – 16.6	11.3
Transport Capacity	0 – 875.9	23.7
Net soil loss	0 – 28.7	4.8

Table 5-13: Average Annual soil loss

Land use/cover	area	Av.soil loss kg/m2/year
Dense forest	195300	1.029
Degraded forest	254700	3.93
Agriculture	1035900	11.921
Grass land	293400	5.792
Orchard	467100	10.287



(a) Flow Detachment

(b) Splash Detachment

(c) Transport Capacity

(d) Soil Loss

Figure 5-8: Maps of annual flow detachment, splash detachment, transport capacity and soil loss in Nampong sub-watershed.

The estimated rate of soil loss in the area is quite high. High rate of soil erosion can be justified by analyzing structural stability of the soil in the area. The structural stability of the soil is calculated as(FAO, 1993) :

$$S = \frac{\%OM \times 100}{\%clay + \%silt} \qquad \textbf{Equation 5-1}$$

With the critical value range as follows:

S<5 = Severe prone to physical degradation,

5 < S < 7 high hazards of physical degradation

7 < S < 9 low hazards of physical degradation

9 < S no physical degradation

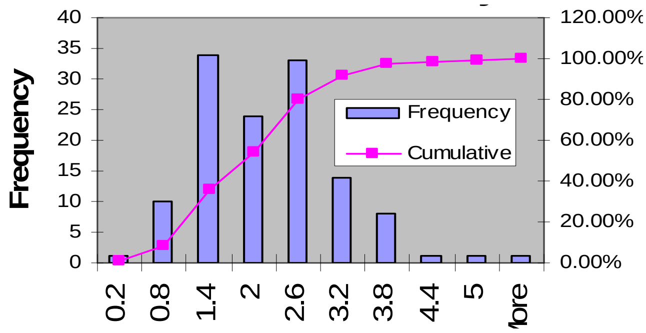


Figure 5-9: Structural stability of the topsoil in the area.

The calculated values of structural stability is less than 5 with an average value of 1.9 (Figure 5-9). According to the above mentioned critical range, the soil in the study area can be categorized as severe prone to physical degradation. Soils with low structural stability are prone to surface crusting giving increased runoff and erosion.

Further justification of the higher rate of average annual soil loss can be made by analyzing some of the topsoil properties in the area. It is reported that topsoils having more than 25 % silt content and less than 35 % sand content are characterized as prone to surface crusting and sealing (FAO, 1998). In Namchun area as the average silt content is around 70 % with only around 8 % of sand content (Table 5-1). Soils of the area are highly susceptible to surface crusting and sealing leading to high runoff and erosion. Also the high rate of soilloss in the area can be attributed with the restricted fraction of clay in the area. Evans (1980) has indicated that soils with a restricted clay fraction, between 9 and 30 percent, are the most susceptible to erosion. In Namchun area, the range of clay content is in between 18%-26 % (Table 5-1); therefore the soils of the area are highly erodible.

5.2.3. Validation of the modelling results

Discharge measurement

Rainfall and discharge measured during fieldwork period in the subwatershed is shown in figure 5-7. The highest discharge of approx. 30,000 m^3/day was estimated for 10 September 2007 and the lowest estimated discharge (baseflow) was approx. 5000 m^3/day. A total of 224,104 m^3 (100,046 m^3/km^2) of discharge is estimated for the month of September in the sub-watershed and is around 39% of the total monthly rainfall (Figure 5-10).

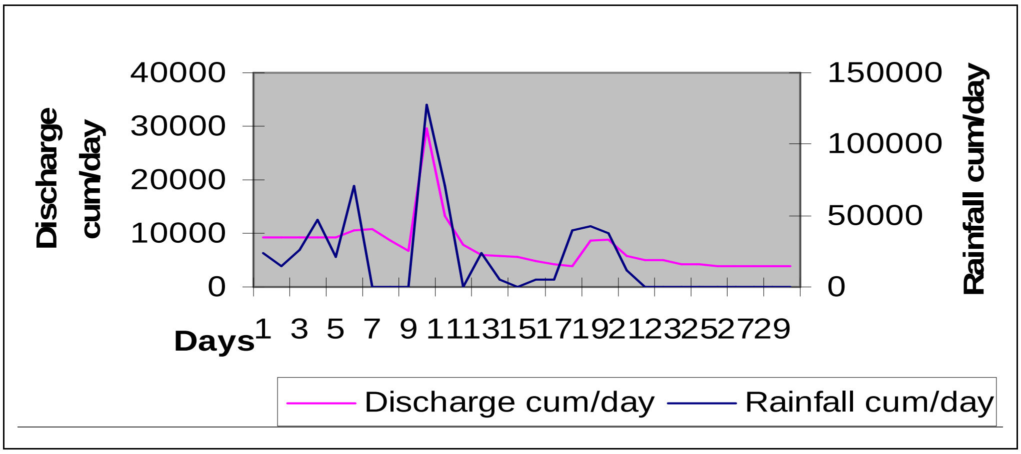


Figure 5-10: Discharge hydrograph and daily rainfall of September 2007, Nampong sub-watershed.

To examine the accuracy of velocity measurement by float method, Manning's formula was used to calculate the velocity of the stream by using the literature value of Manning's n for the rough cement concrete 0.014 (Edwards, 2007). Discharge calculated by using Manning's equation (equation 4-3, 4-4) is about 8.4% higher than the discharge obtained by measured velocity. By Manning's formula, over estimation of discharge is observed during pick flow whereas there is under estimate during baseflow (Figure 5-11).

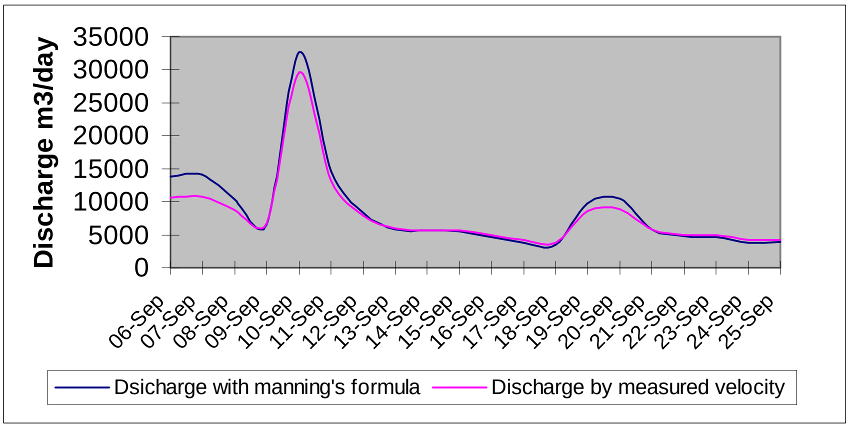


Figure 5-11: Discharge hydrographs with manning's formula for velocity and by measured velocity.

The effect of uncertainty in depth measurement in overall discharge measurement was also analyzed. It is found that ±1 mm uncertainty in depth measurement lead to ± 2% uncertainty in discharge (Figure 5-12). Therefore, height of water (depth) has significant effect in measured discharge. In Nampong stream, the lowest water depth was 3 cm and the highest was 12.9 cm during peak flow in September. During peak flow, height measurement can be affected by turbulent movement of water resulting in over estimation of discharge.

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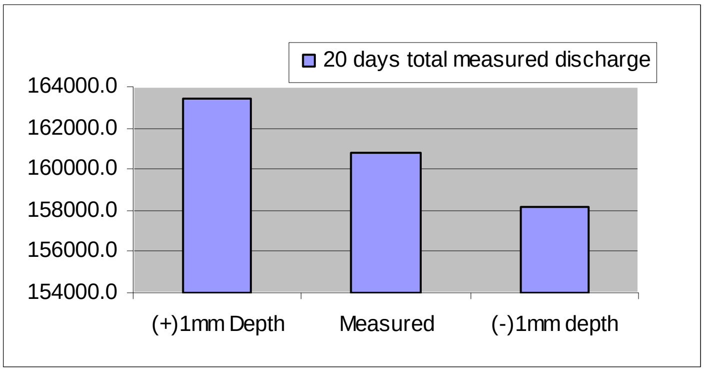

Figure 5-12: Effect of ±1mm uncertainty in depth measurement in total measured discharge.

In a runoff study conducted by Royal Forestry Department of Thailand in Nam Kek Watershed, Khao Khor District, the estimated runoff volume in the month of September were 131,399 m^3/km^2 for grassland,, 109,358 m^3/km^2 for dry evergreen forest and 87,466 m^3/km^2 for secondary forest (Annex-6). It shows that our measured discharge is close to the reported values in the area. Float method of measuring velocity of stream can measure discharge within accuracy of 10 to 25 percent (Buchanan and Somers, 1976). Therefore, the measured discharge can be considered as the true value and it can be used for the validation of the model.

Comparison of the results

The total measured discharge in September is 224,104 m^3. The ratio between predicted value by RMMF model and measured value is 0.53, which is within the acceptable range of 0.5 to 2 as prescribed by Morgan(2005). Model simulated discharge is less than the measured discharge. As we look at the uncertainty analysis of discharge measurement (section 5-1), with ± 1mm uncertainty in height measurement there is ± 2% uncertainty in discharge. During flooded time there might be unwanted error in height measurement due to the high turbulence of the flow giving rise to the over estimation of the discharge. Also the simulated discharge is for the surface runoff only. However, total discharge in a stream may be the accumulation of some sub-surface runoff flowing down the hill slope and the surface runoff. Therefore, it can be concluded that the simulated discharge can represent the actual runoff in the area.

Sediment measurement

Water samples with suspended sediment were collected from the Nampong stream. From the collected samples suspended sediment (g/l) was measured. The value of the suspended sediment of a day is plotted against the discharge of the day (l/s). A linear trend surface is fitted, which shows a significant relation with R^2 value of 0.93 (Figure 5-13). Obtained regression equation is used to calculate the suspended sediment load for the month of September. A total of 136.3 tons (0.6 t/Ha) of suspended sediment was estimated in Nampong sub-watershed for the month of September, in 2007.

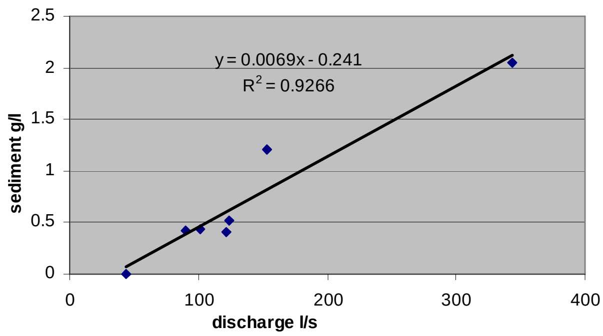

Figure 5-13: Linear regression between discharge and suspended sediment.

A tentative map of global sediment yield provided by Walling (1994), has reported a tentative suspended sediment of 250-500 t km^{-2} y^{-1} for Thailand. As the September falls within the main rainy months in Thailand (Figure 3-2), the measured suspended sediment seems to be reasonable.

Comparison of the results

A total of 2442.6 tons of soil loss was predicted by the model in the sub-watershed for the month of September 2007 (Table 5-11). The measured suspended sediment in the stream for September is 136.3 tons, which is only around 6% of the total soil loss. Suspended sediment does not represent total soil loss. In Nampong stream, as already mentioned, several check dams are made to control the gully formation in the stream bed, which causes a lot of deposition of the sediment before reaching to the stream outlet. This might be the case of less measured suspended sediment yield in the stream. After making comparisons of several suspended sediment yields and total erosions in the catchment of several African drainage basins, Walling (1994) has reported an average of 10% sediment delivery ratio. Therefore, the delivery ratio of 6% in our study can be considered reasonable

Validation of the model performance in higher spatial scale

For the further validation of the model in higher spatial scale, we simulated the monthly (for September 2007) and annual (for water year 2005) runoff in the whole watershed. Total rainfall in sub-watershed for September is also used for the whole watershed and the total rainfall and rain days during water year 2005 is used for the annual modelling. Because of the lack of rainfall data in near by locations we assumed a uniform rainfall throughout the watershed. The result of the model simulated discharge is presented in the Table 5-14. The regression equation 4-10 is used to calculate the discharge of September 2007. The calculated discharge for the month September is 2871202 m^3, which is considered as a measured discharge for September 2007. The ratio of predicted to measured discharge for September is 1.08. The total gauged discharge of the water year 2005 is 19388160 m^3 (Annex-5) and the ratio of predicted and measured discharge is 0.81 (Table 5-14). In both the cases, the ratio is within the acceptable range (Morgan, 2005), and the predicted discharges are very close to the measured discharge. Our study revealed that RMMF model can be used to predict monthly and annual discharge with reasonable accuracy.

Table 5-14: Model simulated discharge of Namchun

Land use/cover	Area (m^2)	Sep-07		Annual 2005	
		Av. Runoff ($mm/m^2/month$)	Total discharge ($m^3/month$)	Av. Runoff ($mm/ m^2/year$)	Total discharge ($m^3/year$)
Dense forest	4899600	4.6	22538.2	16.9	82803.2
Degraded forest	15200100	12.3	186961.2	50.9	773685.1
Agriculture	15301800	75.5	1155285.9	395.3	6048801.5
Grass land	9260100	45.6	422260.6	223.6	2070558.4
Orchard	21672900	60.8	1317712.3	309.2	6701260.7
Total	66334500		3104758.2		15677108.9
Calculated by equation 4-10			2871202	Measured	19388160
Ratio			1.08	Ratio	0.81

5.2.4. Analyzing spatial variability of predicted soil loss

To look at the spatial variability and relationship of predicted soil erosion with topsoil properties, predicted annual soil loss values of the sub-watershed are extracted in the original sample points. We check the statistical significance of difference in average soil loss in different slope class. We compare the mean using one way ANOVA. Result of the one way ANOVA revealed that soil loss is significantly different in different slope classes (Table 5-15). Furthermore, Soil loss map is crossed with slope class map using ILWIS software to calculate the average soil loss in different slope classes. Steep to very steep slopes (>25 degree) are found to have more soil loss as compared to others (Table 5-16).

Table 5-15: one way ANOVA between soil loss and slope class

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	244.092	4	61.023	4.000	.007
Within Groups	701.771	46	15.256		
Total	945.862	50			

Table 5-16: Average Soil loss per slope class

slope class	average soil loss ($kg/m^2/y$)
0-7 degree	9.8
7-15 degree	8.9
15-20 degree	10
20-25 degree	10.7
>25 degree	11.8

Before analyzing the relationships of model predicted soilloss with topsoil properties, sample points having zero soil loss values are removed. It is because while modelling erosion we have masked out the stream and channel by providing zero value of overland flow. A total of 25 sample points, with values more than zero, are used in the analysis (Annex-9).

Pearson's correlation coefficient analyses revealed a positive correlation of annual soil loss with crusting index and sand content in the area. Similarly, there exists a negative correlation between organic matter content, clay and silt content (Table 5-17). We got satisfactory correlation for organic matter, silt, sand and crusting index but the correlation coefficient of other properties are quite less. It might be attributed to the strong spatial structure of the soil properties like silt and clay in the study area. We found negative correlation between silt and soil loss which might be due to high crusting index value and also our total soil detachment is mainly govern by splash detachment rather than flow detachment and silt is quite resistant to splash detachment.

Table 5-17: Correlation of soil loss with different soil properties

	OM	Silt	Sand	Clay	Crusting Index
Pearson Correlation	-0.47	-0.30	0.28	-0.09	0.25

5.3. Up-scaling runoff and erosion assessment from sub-watershed to bigger watershed

5.3.1. Up-scaling discharge

Ratio of the total area of the watershed and that of the sub-watershed is 29.4 and the ratio of the sum of weighted landuse/cover category (weight by runoff factor) of the watershed and sub-watershed is 20.92 (Annex-7). The up-scaled discharge is compared with the model simulated discharge of the watershed and the ratio of the model predicted discharge and up-scaled discharge is computed.

It is found that the up-scaling by equation 4-12 (sum of weighted land cover area ratio) is more reliable with the goodness of fit of 0.66 between reference discharge and the up-scaled discharge (Table 5-18). This might be attributed to the fact that the runoff characteristics of the different land cover categories are considered in this approach. Our study revealed that it is possible to validate a model performance in a bigger watershed with the measurement in a representative sub-watershed.

Table 5-18: Comparison of the different up-scaling approaches

Measured sub-watershed discharge for the month September m^3	Simulated (RMMF) September discharge of the watershed (m^3)	Measured value up--scaled by over all area ratio (29.4)	Measured value up--scaled by sum of weighted land use/cover ratio (20.92)
224104	3104758	6617622.3	4688903
Goodness of fit	**ratio of simulated and up-scaled values**	**0.47**	**0.66**

5.3.2. Up-scaling erosion pattern

Slope class map and land cover map along with classified soil property maps were used to develop a qualitative erosion pattern map. Regarding the topsoil texture, distribution of silt is the major factor controlling the texture in the area (section 5-1-3, Figure 5-4); therefore, only silt map is used for the purpose. Classified base maps, two dimensional decision tables and intermediate maps are presented in annex- 10. Figure 5-14 shows the final qualitative erosion pattern map of the whole Namchun watershed produced in a GIS environment. Around 30% of the area is classified as high to very high susceptible to soil erosion, where as around 35% of the area is classified as moderately susceptible to soil erosion. Plateau and Low Mountain landscapes were classified as relatively high prone to soil erosion as compared to High Mountain and Valley landscapes (refer geopedological soil map in Figure 4-2).

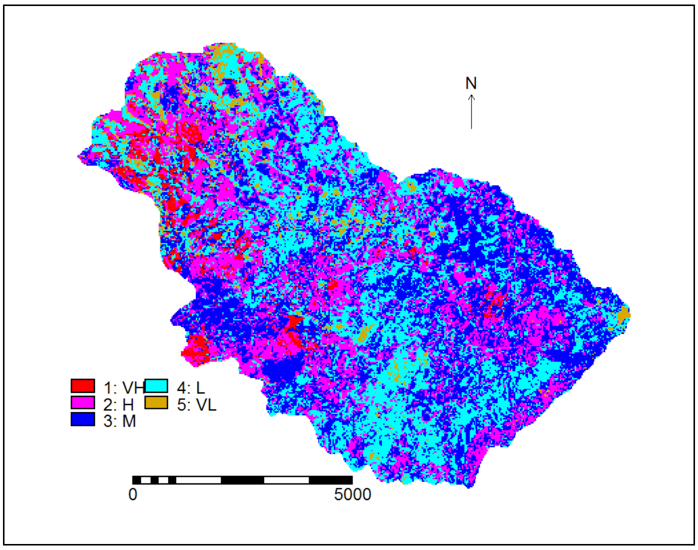

Figure 5-14: Qualitative erosion susceptibility map based on erosion causing factors

Validation of the qualitative erosion map

For this purpose, the GPS locations of erosion features such as rills, gullies and sheet erosions, collected during fieldwork were used. The erosion feature locations were overlaid on the erosion susceptible map. Most of the points are found to be located in the range of moderate to very high susceptible area (Figure 5-15).

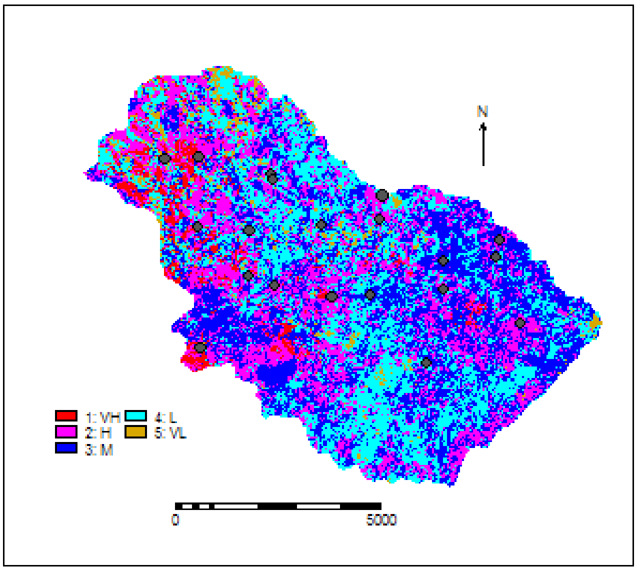

Figure 5-15: Susceptibility map with the field observed location of erosion features.

Detailed study of erosion in small spatial scale to understand the process and underlying causes can add to develop a knowledge based GIS model to map the spatial pattern of soil erosion in a bigger area. The quality of a knowledge based map is more dependent on the quality of the input maps of causal factors. Furthermore, a careful analysis of casual factors and setting decision rules based on the strength of the factors can produce erosion pattern map with a reasonable accuracy. The technique can offer a better alternative for the analysis of spatial pattern of soil erosion in a data poor situation because it is simple, flexible and in full control of the user. Also factors that are specific to a certain region can be accompanied in this approach.

6. Conclusions and Redommendations

6.1. Conclusions

Based upon the results and discussions in previous sections, it is possible to draw the following conclusions:

- Topsoil clay content has long-range spatial autocorrelation as compared to other soil properties. Similarly, silt content and clay have very strong spatial structure where as organic matter and crusting index has moderate spatial structure. Strongly structured spatial dependence of soil properties are usually caused by intrinsic factors such as soil forming factors. Therefore, very strong spatial structure of clay and silt is attributed to the theory of soil genesis.
- There exists a significant relationship between organic matter and crusting index with land cover types. Similarly, there is a significant relationship between silt and clay content with lithology types. The explained variability of organic matter and crusting index by land cover type is higher than the explained variability of silt and clay content by lithology type. Significant but low association of clay and silt with lithology type may be due to the advanced soil formation process in humid tropics.
- High Mountain areas are mapped with high organic matter content where as plateau landscapes have low organic matter content. Similarly, Plateau area have high crusting index as compared to other landscapes. However, the variation in silt content is not much significant in different landscapes.
- Float method of velocity measurement and grab method of sediment sampling can measure discharge and sediment with a reasonable accuracy in the area. There is not much difference between the measured discharge by float method and by Manning's formula.
- RMMF model can predict monthly as well as annual discharge and soil loss with reasonable accuracy. The ratio between predicted discharge and the measured discharge shows an acceptable goodness of fit in different temporal and spatial scale (monthly and annually in the sub watershed and in the watershed).
- Soil loss is significantly different in different land cover types and slope classes. Agriculture area has very high soil erosion followed by orchard. However, the soil loss is less in dense forest area. Similarly, steep to very steep slopes have high soil loss as compared to other slope classes.

- There is a positive correlation of annual soil loss with crusting index and sand content whereas a negative correlation between organic matter, clay and silt content in the area. Correlation with clay is significantly low as compared to other properties.
- It is possible to up-scale the measured discharge of the representative sub-watershed to the watershed scale. The ratio of the sum of the weighted land cover areas in the watershed and sub watershed (weight according to runoff characteristics of different land cover types in the area) to up-scale the sub watershed discharge is more reliable as compared to the overall area ratio.

Validation of a model performance in a bigger watershed is not straight forward but needs a lot of resources and sophisticated techniques to generate the data needed for the validation. Therefore, the approach of validation of a model from the data generated in a small and representative catchment is important in data poor conditions. Erosion models are region and scale specific. Adoption and modification of a model is therefore necessary before applying to a new location. Furthermore, models require a lot of input parameters which are not readily available in most of the data poor situation. In such case, detailed study of erosion in small spatial scale to understand the process and underlying causes can add to develop a knowledge based GIS model to map the spatial pattern of soil erosion in a bigger area. The technique offers the possibility to prioritise factors responsible for soil erosion and assess erosion hazard. The model is simple and flexible and under the full control of the user. Such models can offer widespread applicability in data poor situation.

6.2. Limitations

The main limitation of the study was the availability of rainfall data. Rainfall data was available from only one location which can not represent the spatial variability of the rainfall. Also the extrapolation of the result to the watershed scale is based on the study in a single sub-watershed. Because of the limited field time it was not possible to generate data from more than one sub-watershed. Study in more than one sub-watershed can reveal better generalization of underlying causes and processes of soil erosion in the area.

6.3. Recommendations

Detail study in more than one sub-watershed can give better insight knowledge of erosion processes in the area and consequently can improve the reliability of the upscaling approaches. We attempted to validate the model performance with the measured discharge and sediment of the sub-watershed. However, the measurement of discharge is confined only for the month of September and the sediment sampling is done only for few flooded days during September. September belongs to the period of high rainfall in the area. We could not measure the discharge during dry period of the year due to limited time for the field. Therefore, further study regarding this aspect can produce better insight knowledge of the variability of the discharge in the area.

While applying regression kriging to map topsoil particle size distribution, we have used lithology type as an ancillary variable. However, topsoil properties are the function of several soil forming factors. A multi-linear regression model taking into account of all soil forming factors can be a better alternative to model such soil properties. Also, geostatistical techniques were used to map the distribution of topsoil properties. Application of geostatistical techniques in soil mapping is limited with the necessity of high amount of sampling density. Combination of remote sensing techniques with some field measurements can be a better alternative for the topsoil mapping in a larger geographical area. Further study regarding this aspect may develop a cost effective approach for the study of soil erosion in relation to topsoil properties in relatively larger scale.

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List of Annexes

Annex: 1: Measured discharge and sediment, September 2007, Nampong SW

Date	discharge m^3/s	discharge m^3/day	Remarks
Sep-01	0.106	9174	average of 6-9
Sep-02	0.106	9174	average of 6-9
Sep-03	0.106	9174	average of 6-9
Sep-04	0.106	9174	average of 6-9
Sep-05	0.106	9174	average of 6-9
Sep-06	0.122	10536	
Sep-07	0.124	10728	
Sep-08	0.101	8720	
Sep-09	0.078	6712	
Sep-10	0.343	29660	
Sep-11	0.153	13250	
Sep-12	0.091	7837	
Sep-13	0.069	5963	
Sep-14	0.066	5687	
Sep-15	0.065	5602	
Sep-16	0.056	4878	
Sep-17	0.048	4155	
Sep-18	0.044	3823	
Sep-19	0.099	8563	
Sep-20	0.102	8832	
Sep-21	0.067	5786	
Sep-22	0.058	4988	
Sep-23	0.057	4922	
Sep-24	0.049	4210	
Sep-25	0.049	4269	
Sep-26	0.044	3823	Base flow
Sep-27	0.044	3823	Base flow
Sep-28	0.044	3823	Base flow
Sep-29	0.044	3823	Base flow
Sep-30	0.044	3823	Base flow
Measured suspended sediment			
Date	sediment g/l	Remarks	
06-Sep-07	0.4112		
07-Sep-07	0.5254		
08-Sep-07	0.4367		
10-Sep-07	2.0485		
11-Sep-07	1.2060		
12-Sep-07	0.4208		

Annex 2: Calibration data set for soil property with lab value

UTM-X	UTM-Y	%CLAY	%SILT	%SAND	%OM	Crusting index
722038	1854079	20.6	67.6	11.8	0.8	2.6
718791	1858263	23.4	72.1	4.5	0.9	2.5
719607	1858535	22.7	70.1	7.2	1	2.4
718906	1857766	21.5	71.9	6.6	1	2.5
720019	1853565	20.6	68.9	10.5	1	2.5
719730	1853853	22.2	66.9	11	1	2.3
727178	1855776	23	71	6	2.2	1.8
725917	1855920	23.6	71.2	5.2	2.5	1.6
720625	1856037	24.7	71.1	4.3	0.5	2.6
724787	1856072	20.6	64.2	15.2	0.8	2.5
726241	1856508	21.3	74	4.7	1.9	2
726567	1856697	20.3	69.7	10	2.4	1.8
725451	1857035	21.8	71.2	7	2.2	1.8
722897	1857397	21.4	69.9	8.7	2.4	1.7
725221	1857545	21.1	72.3	6.6	2.2	1.8
718286	1857925	23.2	71.1	5.6	1.2	2.3
717565	1858208	21	70.1	8.9	1.2	2.4
726241	1856124	21.6	70.1	8.2	2.8	1.6
726441	1856124	21.2	73.9	4.9	3.4	1.5
726641	1856124	23.1	74.9	2	1.6	2.1
726041	1855924	23.5	66.2	10.3	1.9	1.8
726241	1855924	24.4	71.3	4.4	3.2	1.4
726441	1855924	24.2	70.5	5.3	2	1.8
726641	1855924	23.7	74.2	2.2	2.1	1.9
723841	1855724	23.2	71.1	5.7	1.9	1.9
724041	1855724	20.1	66.3	13.5	1	2.4
724241	1855724	18.9	67.4	13.7	1.2	2.4
724441	1855724	24.3	71.1	4.5	2.6	1.6
724641	1855724	18.7	74.3	7	2.3	1.9
724841	1855724	20.4	69.9	9.7	1.6	2.1
725041	1855724	21.4	67.1	11.6	2.2	1.7
725241	1855724	23	72.4	4.6	0.7	2.6
725441	1855724	24.1	70.3	5.6	2.7	1.5
725641	1855724	22.6	71.2	6.3	1.1	2.3
725841	1855724	19.8	63.7	16.5	1.3	2.2
726041	1855724	22.4	67.5	10.2	2.2	1.7
726241	1855724	22.4	67.9	9.7	1.7	1.9
723241	1855524	23.6	71	5.5	1.3	2.2
723441	1855524	26.3	71.5	2.2	1.8	1.8
723641	1855524	21.1	66.6	12.3	2.1	1.7

UTM-X	UTM-Y	%CLAY	%SILT	%SAND	%OM	Crusting index
724041	1855524	20.5	68.3	11.2	2.4	1.7
724241	1855524	21.9	67.3	10.8	3.9	1.3
724441	1855524	22.7	70	7.3	2.1	1.8
724641	1855524	25.4	68	6.6	2.5	1.5
724841	1855524	23.6	70.5	5.9	2.3	1.7
725241	1855524	25.4	68.8	5.8	0.8	2.3
725441	1855524	20.5	68.6	10.9	1.1	2.4
725641	1855524	25.2	69.4	5.4	1.6	1.9
725841	1855524	22.9	67.2	10	1.6	2
726041	1855524	20.3	67.8	12	2.2	1.8
723041	1855324	20	68.5	11.5	1	2.6
723241	1855324	22.5	68.5	9	2.4	1.7
723641	1855324	23.4	73.8	2.9	1.7	2
724041	1855324	18.9	73.1	8	2.9	1.7
724241	1855324	24.9	71.6	3.5	2.4	1.7
724641	1855324	23.2	68.6	8.2	3.2	1.4
724841	1855324	25.2	69.8	5	2.5	1.6
725041	1855324	24.5	71.7	3.8	2.4	1.6
725241	1855324	24.7	70.6	4.8	2.3	1.7
725441	1855324	20.3	70.6	9.1	1.1	2.6
725641	1855324	21.9	71.2	6.9	1.8	2
723441	1855124	19.1	71.6	9.3	2.2	2
723641	1855124	26.2	70.4	3.4	2.1	1.6
723841	1855124	23	73.2	3.9	1.8	2
724241	1855124	22.3	73.7	4.1	2.1	1.9
725241	1855124	20.6	65.6	13.9	2.5	1.6
725441	1855124	23	71.9	5.1	1.6	2.1
725641	1855124	25.1	71.9	3	1.3	2.1
721311	1853220	18.6	69.1	12.3	1.1	2.6
718516	1857130	20.4	66.1	13.5	1.2	2.2
718495	1856500	23.5	71.5	5	2.2	1.8
717588	1854450	20.7	69.1	10.2	0.6	3.2
718561	1854480	20.5	65.6	13.9	0.2	3.3
723083	1856380	18.1	68.9	13	1.5	2.3
726621	1853050	22.1	73.1	4.8	2.2	1.8
729741	1854740	21.6	73.7	4.7	1.7	2.1
718643	1854060	20.8	66.7	12.5	2.5	1.7
720536	1852290	22.5	65.7	11.9	2.8	1.5
719437	1856320	19.2	70.9	9.9	0.3	3.4
724364	1856530	21.4	69.2	9.4	0.9	2.5
723514	1856840	22.5	72.3	5.2	0.7	2.8

UTM-X	UTM-Y	%CLAY	%SILT	%SAND	%OM	Crusting index
726466	1855170	23.7	65.7	10.6	0.6	2.5
728465	1853341	18.6	68.8	12.6	2.7	1.7
729283	1855760	19.8	69.8	10.5	4.3	1.3
724726	1857450	26	71.1	3	1.1	2.1
727989	1853993	21.1	60.3	18.6	2.4	1.5
727148	1853789	18.2	71.8	10	1.6	2.3
724482	1855161	22	69.6	8.3	1.6	2
727759	1852758	18.8	68.4	12.8	1.5	2.2
725031	1856220	24.5	69.1	6.4	1.2	2.1
724364	1856530	22	69.2	8.8	2	1.8
719479	1852520	21.2	70.4	8.4	1.1	2.4
717194	1857644	25.4	71.8	2.8	1.1	2.2
717306	1858104	23.7	67.8	8.5	1.3	2.1
725256	1851370	20.8	69.1	10	2.2	1.8
725689	1852730	21.6	70.5	7.9	2.6	1.6
717643	1857230	22.4	71.8	5.8	2.4	1.7

Annex 3: Validation data set for soil property with lab values and predicted values

UTM-X	UTM-Y	CLAY	SILT	SAND	OM	CRUST	silt_pred	om_pred	clay_pred	crust_pred
721006	1855327	24.9	71.3	3.8	1.3	2.1	70.4	1.8	21.9	2.2
721100	1855437	27.0	67.7	5.4	1.4	1.8	70.4	1.8	21.9	2.2
727628	1855563	22.1	70.8	7.1	1.6	2.0	70.4	2.0	21.6	2.0
720990	1855610	29.3	66.1	4.6	1.5	1.7	71.5	1.7	22.2	2.2
720625	1856037	24.7	71.1	4.3	0.5	2.6	71.1	1.0	22.1	2.4
723543	1856277	14.4	71.4	14.2	1.7	2.4	69.3	1.5	22.0	2.2
724901	1856932	19.7	68.5	11.8	2.3	1.5	70.6	1.3	22.6	2.1
724907	1857046	25.6	70.8	3.6	1.3	2.0	69.6	1.4	22.2	2.1
720101	1851875	30.1	69.1	0.8	0.6	2.1	69.7	1.8	21.2	2.0
725389	1855037	13.4	63.5	23.1	0.9	3.2	69.9	1.8	22.4	2.0
720654	1855740	16.9	66.8	16.2	0.3	3.6	71.6	1.5	22.2	2.3
729121	1855510	14.6	66.7	18.7	2.1	2.0	69.3	2.4	20.5	1.8
726050	1856360	25.6	70.7	3.7	1.0	2.3	71.3	2.3	22.5	1.8
717897	1857567	12.0	71.6	16.4	1.4	3.0	71.3	1.5	22.6	2.1
719719	1853410	17.8	69.3	12.9	2.0	2.0	69.0	1.6	21.2	2.2

Annex 4: Landuse and soil parameters used in RMMF model

Source (Amare Kassa, 2007; Morgan, 2001)

Land use parameters

Land cover	A	Et_Eo	C	CC	GC	PH	EHD
Dense forest	0.25	0.9	0.002	0.82	0.91	19.4	0.2
Degreded forest	0.25	0.8	0.01	0.35	0.5	14.95	0.16
Agriculture	0.25	0.5	0.2	0.49	0.37	1.8	0.08
Grass land	0.35	0.65	0.08	0.93	0.95	1.5	0.1
Orchard	0.2	0.7	0.05	0.31	0.5	7.3	0.08

Soil parameters

SMU	MS	BD	K	COH
HM111	0.25	1.3	0.7	10
HM112	0.25	1.3	0.21	10.5
HM211	0.25	1.3	0.73	7.7
HM212	0.25	1.3	0.61	9.6
HM213	0.25	1.3	0.47	10.6
HM311	0.25	1.3	0.7	3
HM312	0.25	1.3	0.44	10.3
HM313	0.25	1.3	0.66	10
LM111	0.25	1.3	0.33	11
LM112	0.25	1.3	0.54	10.5
LM211	0.25	1.3	0.75	6.5
LM212	0.25	1.3	0.67	8
LM311	0.25	1.3	0.5	10
LM312	0.25	1.3	0.14	11.7
P111	0.25	1.3	0.28	11
P211	0.25	1.3	0.29	9.8
P212	0.25	1.3	0.5	10
P213	0.25	1.3	0.5	10

Annex 5: Gauged discharge data of Namchun, for the water year 2004 and 2005

(Source: Royal Irrigation Department, Thailand)

Discharge, in Cubic Meter per Second, Water Year April 1, 2004 to March 31, 2005

Date	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	annual
1	0.5	0.5	1.1	0.4	0.7	0.5	0.4	0.2	0.1	0.1	0.1	0	
2	0.5	0.5	1.1	0.4	0.7	0.6	0.4	0.2	0.1	0.1	0.1	0	
3	0.6	0.5	1.1	0.4	0.6	0.6	0.4	0.2	0.1	0.1	0.1	0	
4	0.6	0.9	0.9	0.4	0.6	0.5	0.3	0.2	0.1	0.1	0.1	0.1	
5	0.7	0.6	0.8	0.3	0.5	0.5	0.3	0.2	0.1	0.1	0.1	0	
6	0.6	0.7	0.7	0.4	0.5	0.5	0.3	0.2	0.1	0.1	0.1	0	
7	0.6	1.3	1.1	0.3	0.5	0.5	0.3	0.2	0.1	0.1	0.1	0	
8	0.9	1.3	1.8	0.4	0.5	0.5	0.3	0.2	0.1	0.1	0.1	0	
9	0.7	0.9	0.8	0.4	0.5	0.7	0.3	0.2	0.1	0.1	0.1	0	
10	0.5	0.7	1	0.3	0.6	0.7	0.3	0.2	0.1	0.1	0.1	0	
11	0.5	0.8	5	0.3	0.8	0.7	0.3	0.2	0.1	0.1	0.1	0	
12	0.5	0.7	1.7	0.4	1	0.6	0.3	0.2	0.1	0.1	0	0	
13	0.4	0.6	0.8	0.4	0.9	2.1	0.3	0.2	0.1	0.1	0	0	
14	0.4	1.3	5.2	0.3	0.7	1.3	0.3	0.1	0.1	0.1	0	0	
15	0.4	0.8	3.3	0.4	0.6	2.6	0.3	0.1	0.1	0.1	0	0	
16	0.4	0.8	2.6	0.3	0.6	1.5	0.3	0.1	0.1	0.1	0	0	
17	0.5	0.8	2.3	0.4	0.6	0.7	0.2	0.1	0.1	0.1	0	0	
18	0.4	0.9	1.6	0.4	0.5	0.6	0.2	0.1	0.1	0.1	0	0	
19	0.4	0.8	0.9	0.3	0.6	3.5	0.2	0.1	0.1	0.1	0	0	
20	0.7	0.7	0.6	0.3	0.6	0.5	0.2	0.1	0.1	0.1	0	0	
21	0.9	1.3	0.5	0.4	0.7	0.9	0.2	0.1	0.1	0.1	0	0	
22	0.5	0.9	0.5	0.5	0.7	0.5	0.2	0.1	0.1	0.1	0	0	
23	0.8	0.8	0.6	0.4	0.7	0.7	0.2	0.1	0.1	0.1	0	0	
24	0.9	0.7	0.5	0.5	0.6	0.7	0.2	0.1	0.1	0.1	0	0	
25	0.6	0.7	0.5	0.5	0.6	0.6	0.2	0.1	0.1	0.1	0	0	
26	0.5	0.8	0.5	0.6	0.6	0.6	0.2	0.1	0.1	0.1	0	0	
27	0.5	0.7	0.4	1.5	0.6	0.5	0.2	0.1	0.1	0.1	0	0	
28	0.5	0.8	0.4	0.8	0.5	0.5	0.2	0.1	0.1	0.1	0	0	
29	0.5	0.8	0.4	0.7	0.5	0.5	0.2	0.1	0.1	0.1		0	
30	0.5	1	0.4	0.6	0.5	0.5	0.2	0.1	0.1	0.1		0	
31		1.1		0.7	0.5		0.2		0.1	0.1		0	
Total	17	25.7	39.1	14.4	19.1	25.7	8.1	4.3	3.1	3.1	1.1	0.1	160.8 CMSDAY
Mean	0.6	0.8	1.3	0.5	0.6	0.9	0.3	0.1	0.1	0.1	0.04	0.003	
Max	0.9	1.3	5.2	1.5	1	3.5	0.4	0.2	0.1	0.1	0.1	0.1	5.2 CMS
Min	0.4	0.5	0.4	0.3	0.5	0.5	0.2	0.1	0.1	0.1	0	0	0.0 CMS
Runoff	1.47	2.22	3.38	1.24	1.65	2.22	0.7	0.37	0.27	0.27	0.1	0.01	13.89 MCM

Discharge, in Cubic Meter per Second, Water Year April 1, 2005 to March 31, 2006

Date	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual
1	0.1	5.7	0.7	0.2	0.6	0.7	0.8	0.2	0.2	0.1	0	0	
2	0.1	0.6	0.3	0.1	48:00.0	0.5	0.8	0.2	0.2	0.1	0	0	
3	0.1	0.4	0.3	0.1	1.3	0.6	1.1	0.2	0.2	0.1	0	0	
4	0.1	0.3	0.3	0.1	1.8	0.7	0.8	0.2	0.2	0.1	0	0	
5	0.1	0.2	0.3	0.3	1.2	0.5	0.6	0.2	0.2	0.1	0	0	
6	0.1	0.1	0.3	0.4	1.4	8.5	0.6	0.3	0.2	0.1	0	0	
7	0.1	0.1	0.2	1.4	0.8	3.6	0.6	0.2	0.2	0.1	0	0	
8	0.1	0.1	0.2	0.4	0.7	2.2	0.5	0.3	0.2	0.1	0	0	
9	0.1	0.1	0.5	0.3	0.6	2.9	0.5	0.3	0.2	0.1	0	0	
10	0.1	0.1	0.3	0.3	0.5	2.9	0.5	0.3	0.2	0.1	0	0	
11	0.1	0.1	0.3	0.3	0.5	1.7	0.5	0.2	0.1	0.1	0	0	
12	0.1	0.2	0.9	1.1	0.9	4.7	0.5	5.5	0.1	0.1	0	0	
13	0.1	4.3	0.2	3.1	1.4	2	0.5	0.5	0.1	0.1	0	0	
14	0.1	5	1.4	1.1	0.7	2.1	0.4	0.4	0.1	0.1	0	0	
15	0.1	0.2	0.3	6.3	0.6	1.4	0.4	0.3	0.1	0.1	0	0	
16	0.3	0.2	0.2	1.4	0.7	1.2	0.4	0.3	0.1	0.1	0	0	
17	0.4	0.1	1	0.6	0.6	1.3	0.3	0.3	0.1	0.1	0	0	
18	0.3	0.1	2	3.9	0.6	2.3	0.3	0.2	0.1	0.1	0	0	
19	0.2	0.1	0.9	1.1	1.1	2	0.3	0.2	0.1	0.1	0	0	
20	0.2	0.1	0.5	0.7	0.9	5.3	0.3	0.2	0.1	0.1	0	0	
21	0.1	0.2	0.6	5.8	1.5	2.9	0.3	0.2	0.1	0.1	0	0.1	
22	0.4	3.2	0.3	1.1	2.4	2	0.3	0.2	0.1	0.1	0	0	
23	0.2	7.2	0.3	1	1.2	1.5	0.3	0.2	0.1	0.1	0	0	
24	0.2	0.6	0.3	1.2	0.7	1.4	0.3	0.2	0.1	0.1	0	0	
25	0.3	0.3	0.6	1.1	0.6	1.2	0.3	0.2	0.1	0.1	0	0	
26	2.4	0.2	0.4	1	0.5	4.2	0.3	0.2	0.1	0.1	0	0	
27	0.5	0.2	0.3	1.7	0.5	3.2	0.2	0.2	0.1	0	0	0	
28	0.2	0.1	0.3	1.1	0.5	1.5	0.2	0.2	0.1	0	0	0	
29	0.2	0.2	0.2	0.8	0.4	1.2	0.2	0.2	0.1	0		0	
30	0.2	0.2	0.2	0.7	0.3	1	0.2	0.2	0.1	0		0	
31		5.7		0.7	0.4		0.2		0.1	0		0	
Total	7.6	36.2	14.6	39.4	26.6	67.2	13.5	12.5	4.1	2.6	0.00	0.1	224.4 CMSDAY
Mean	0.3	1.2	0.5	1.3	0.9	2.2	0.4	0.4	0.1	0.1	0.00	0.00	
Max	2.4	7.2	2	6.3	2.4	8.5	1.1	5.5	0.2	0.1	0	0.1	8.5 CMS
Min	0.1	0.1	0.2	0.1	0.3	0.5	0.2	0.2	0.1	0	0	0	0.0 CMS
Runoff	0.66	3.13	1.26	3.4	2.3	5.81	1.17	1.08	0.35	0.22	0	0.01	19.39 MCM

Annex 6: Ammount of water in stream from different land cover

(Source: Royal Forest Department, Thailand)

Amount of water in stream (Grassland) , Nam Kek watershed, Khao Khor District, Petchabun Province

Month	Amount of water in stream (m3)				water / area (m3/km2)
	1998-1999	1999-2000	2001-2002	mean	
April	0	2,114	1,112	1,075	1,887
May	12,665	45,825	66,933	41,808	73,347
June	25,146	23,587	28,950	25,894	45,429
July	29,368	26,057	38,275	31,233	54,795
August	41,141	52,057	67,426	53,541	93,932
September	68,308	97,931	58,452	74,897	131,399
October	22,946	36,842	30,595	30,128	52,855
November	9,789	14,424	8,304	10,839	19,016
December	1,976	3,574	2,744	2,765	4,850
January	0	1,151	952	701	1,230
February	0	189	36	75	132
March	0	0	0	0	0
Total	211,339	303,751	303,779	272,956	
(m3/km2)	391,368	543,421	584,235	478,871	
% per rain	22.4	30.8	31.0	28.1	

Amount of water in stream (Dry evergreen forest) , Nam Kek watershed , Khao Khor District , Petchabun Province

Month	Amount of water in stream (m3)					water / area (m3/km2)
	1998-1999	1999-2000	2000-2001	2001-2002	mean	
April	0	1,675	14,981	351	4,252	5,669
May	9,650	38,147	65,860	81,089	48,687	64,915
June	35,420	44,981	50,396	42,801	43,400	57,866
July	45,722	43,265	75,559	31,005	48,888	65,184
August	56,752	68,554	84,438	55,625	66,342	88,456
September	62,550	98,414	104,083	63,028	82,019	109,358
October	56,205	22,097	11,724	45,829	33,964	45,285
November	6,359	19,166	12,506	14,457	13,122	17,496
December	545	4,716	1,957	1,054	2,068	2,757
January	0	36	466	0	126	167
February	0	0	0	0	0	0
March	0	0	239	0	60	80
Total	273,203	341,051	422,209	335,239	342,926	
(m3/km2)	364,272	454,683	562,006	446,986	457,233	
% per rain	20.4	25.5	31.5	25.0	26.3	

Amount of water in stream (Secondary Forest) , Nam Kek watershed , Khao Khor District , Petchabun Province

Month	**Amount of water in stream (m3)**					**water / area (m3/km2)**
	1998-1999	**1999-2000**	**2000-2001**	**2001-2002**	**mean**	
April	0	1,046	1,750	1,050	962	1,232
May	36,214	37,162	46,571	67,546	46,873	60,094
June	27,828	29,845	32,321	35,210	31,301	40,129
July	30,828	35,979	79,400	25,480	42,922	55,028
August	24,657	62,857	34,194	60,117	45,456	58,277
September	53,966	75,063	109,803	34,062	68,224	87,466
October	10,191	10,818	74,642	22,025	29,419	37,717
November	5,279	7,782	13,183	6,052	8,074	10,351
December	1,234	1,133	2,199	998	1,391	1,783
January	0	153	567	47	192	246
February	0	0	0	0	0	0
March	0	0	202	0	51	65
Total	190,197	261,838	394,832	252,587	274,864	352,388
(m3/km2)	243,842	335,494	505,208	323,768	352,078	
% per rain	17.1	19.5	23.5	19.8	20.0	

Annex 7: Calculation of weighted area of different land cover types

Average per pixel runoff adopted from Pranchansri (2007)

Land cover	Average Runoff $m^3/s/pixel$	Runoff weight factor	Area m^2		Weighted Area m^2	
			watershed	Sub-watershed	watershed	Sub-watershed
Dense forest	0.0133	0.014	4923200	206881	68067	2860
Degraded forest	0.0251	0.026	15303464	258979	399677	6764
Agriculture	0.4820	0.501	21868472	1061253	10955259	531647
Grass land	0.0452	0.047	15217275	322436	714460	15139
Orchard	0.3966	0.412	9237243	498982	3807089	205653
Total			66549654	2348532	15944552	762063
Ratio of the sum of weighted area = 20.92						
Ratio of the total area without weight = 28.34						

Annex 8: Average monthly climate data from 1987-2007, Kao Khor, Petchebun

(Source: Meteorological station, Forest Department, Kao Khor)

Rainfall												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987						245.60	119.65	289.70	426.24	104.32	54.35	-
1988	-	31.83	13.22	130.75	173.30	147.55	232.08	167.20	130.55	260.87	-	-
1989	102.75	-	78.85	111.95	334.80	190.80	117.40	214.80	229.10	179.50	0.70	
1990	-	10.60	188.40	45.00	375.80	218.15	241.60	187.40	203.50	201.00	14.20	-
1991	-	-	19.40	41.38	276.16	188.70	218.12	415.36	140.77	63.70	-	-
1992	23.50	31.83	0.00	6.98	98.17	209.14	207.58	342.58	255.86	71.34	0.00	11.74
1993	-	-	40.02	108.37	186.75	45.16	162.11	131.98	221.24	3.78	-	-
1994	0.00	13.79	133.40	49.34	252.70	224.54	27.02	320.97	210.04	69.26	12.84	61.76
1995	-	-	10.60	181.90	232.60	111.36	234.50	266.94	204.50	77.96	2.42	-
1996	-	75.70	52.80	174.90	173.30	258.10	86.30	286.00	280.10	149.00	146.00	-
1997	-	7.10	47.60	159.30	86.70	61.60	252.20	253.60	181.50	207.90	-	-
1998	-	5.20	25.00	61.50	451.80	192.90	176.30	231.60	184.40	86.00	54.80	-
1999	0.00	0.00	69.00	314.60	338.00	138.30	232.10	325.50	234.90	217.80	14.80	0.00
2000	0.00	0.00	19.50	320.20	454.60	336.10	211.00	229.40	332.70	155.80	0.00	0.00
2001	6.50	23.52	156.00	108.40	287.20	135.90	161.20	323.20	176.60	95.20	0.00	0.00
2002	22.40	15.60	34.30	131.80	406.60	173.30	89.30	441.50	523.20	118.90	18.70	0.00
2003	0.00	22.50	84.50	61.30	287.50	255.70	173.60	204.20	254.30	51.80	0.00	0.00
2004	70.80	50.00	19.00	163.00	279.80	270.00	146.90	141.00	147.50	68.50	0.00	0.00
2005	2.50	0.00	13.50	121.90	248.10	185.10	306.50	142.40	296.20	10.20	64.00	0.00
2006	0.00	28.10	107.00	292.10	242.00	162.40	212.60	163.20	220.90	143.00	18.90	0.00
2007	0.0	34.5	66.6	151.2	236.0	239.1	101.7	235.0				
Average	11.42	17.51	58.93	136.79	271.09	189.98	176.66	253.03	239.36	116.79	20.09	3.68

Rain days												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987						21	11	21	24	10	10	-
1988	-	5	4	13	19	16	25	23	11	16	-	-
1989	2	-	3	6	19	17	17	17	18	14	1	-
1990	-	4	10	5	21	18	17	15	21	16	4	-
1991	-	-	4	10	15	18	20	23	14	3	-	-
1992	5	5	-	2	9	11	13	16	12	5	-	1
1993	-	-	2	5	11	7	10	12	15	1	-	-
1994	-	5	5	5	9	12	4	15	11	3	1	3
1995	-	-	1	8	10	9	10	12	13	7	9	-
1996	-	2	2	11	12	9	8	14	10	7	9	-
1997	-	1	5	8	6	7	23	15	18	7	-	-
1998	-	2	3	9	14	8	12	12	10	7	2	-
1999	-	-	5	15	17	10	16	21	14	10	1	-
2000	-	-	1	14	16	20	14	12	16	11	-	-
2001	1	-	10	5	12	9	10	19	15	9	-	-
2002	2	1	4	7	17	14	10	22	18	7	1	-
2003	-	1	4	2	6	13	12	13	14	2	-	-
2004	4	2	1	8	17	12	10	12	11	1	-	-
2005	1	-	3	9	12	17	20	15	19	2	7	-

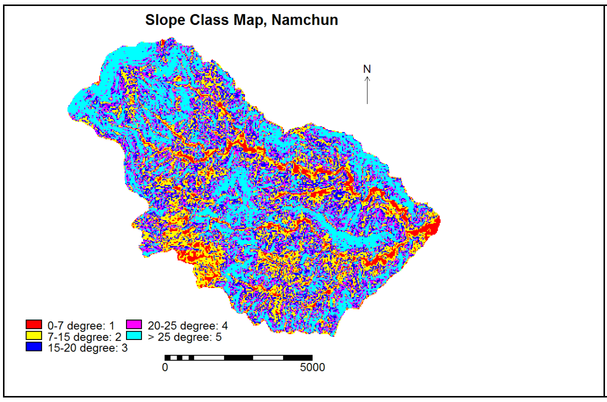
2006	-	4	5	15	15	13	16	14	18	8	2	-
2007	-	3	3	9	20	13	13	19				
Average	1	2	4	8	14	13	14	16	15	7	2	1

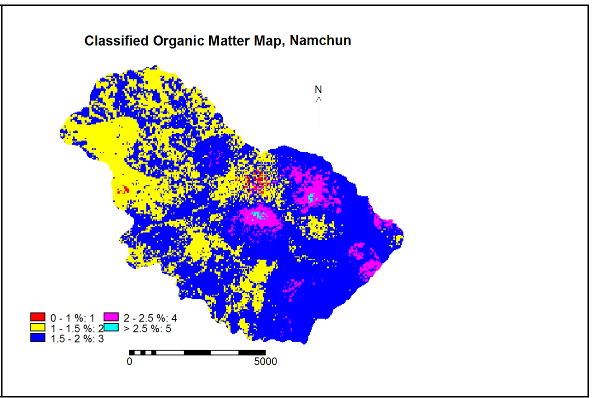
Mean monthly temperature												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987						25.81	25.32	25.31	24.96	24.45	23.88	18.16
1988	21.90	24.68	26.74	26.75	25.93	25.35	25.12	24.91	25.17	23.68	20.55	19.38
1989	22.25	22.39	24.49	27.12	25.73	24.54	25.39	25.22	25.17	24.67	22.88	20.57
1990	23.27	23.92	25.24	27.61	26.00	25.06	24.51	25.16	25.01	24.91	23.93	22.80
1991	25.25	24.93	27.57	27.99	26.64	26.55	25.27	24.29	25.19	25.52	23.14	22.20
1992	21.00	23.95	27.07	29.36	28.13	25.85	25.08	24.81	25.28	23.89	22.25	23.08
1993	23.31	24.20	26.89	27.50	27.41	27.23	26.65	25.35	25.61	25.48	24.63	22.19
1994	24.49	26.05	26.40	27.54	28.50	26.88	27.23	26.44	26.04	24.94	24.79	24.68
1995	23.70	23.97	28.49	29.40	29.59	27.34	26.73	26.28	27.08	26.90	24.94	22.61
1996	23.94	22.74	26.94	28.45	24.39	26.61	27.10	26.37	26.85	26.32	24.69	22.39
1997	23.05	25.90	27.70	26.95	28.20	28.05	25.45	26.10	25.75	26.90	25.60	25.65
1998	26.16	27.14	29.25	29.78	28.97	27.85	26.75	26.85	27.08	27.04	25.42	23.84
1999	24.83	29.68	28.38	27.34	26.29	25.98	26.38	25.75	25.91	25.86	24.86	20.42
2000	24.90	24.35	27.11	27.72	26.23	25.86	26.02	26.31	25.63	27.69	24.03	24.18
2001	25.40	26.21	26.13	28.68	26.38	25.18	26.21	25.92	25.60	27.03	22.41	23.89
2002	21.76	23.60	27.60	27.66	26.65	25.55	25.71	25.34	24.40	25.87	23.76	24.94
2003	22.90	25.71	27.02	28.56	28.16	26.20	26.47	26.33	25.82	26.44	26.06	22.20
2004	23.34	24.57	27.75	28.17	26.70	26.03	26.00	26.07	26.53	26.21	26.17	23.03
2005	23.98	27.70	26.86	28.44	27.95	26.15	25.98	25.66	26.00	26.95	25.43	22.98
2006	24.56	25.98	27.66	27.28	26.02	26.62	25.90	25.98	25.97	25.94	25.80	22.95
average	23.68	25.14	27.12	28.02	27.05	26.26	26.00	25.74	25.79	25.91	24.28	22.84

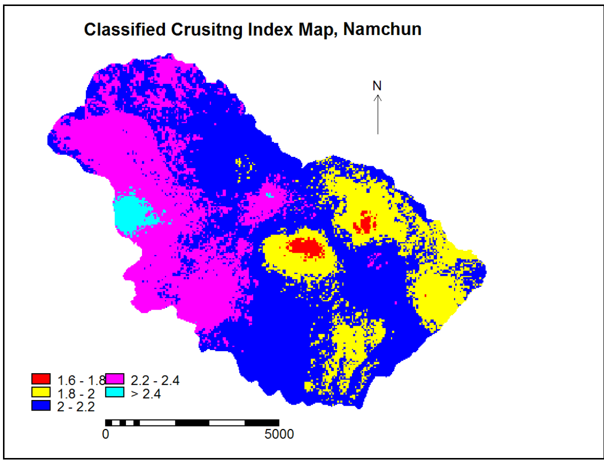
Annex 9: Sub-watershed points with values of soil properties and model predicted soil loss

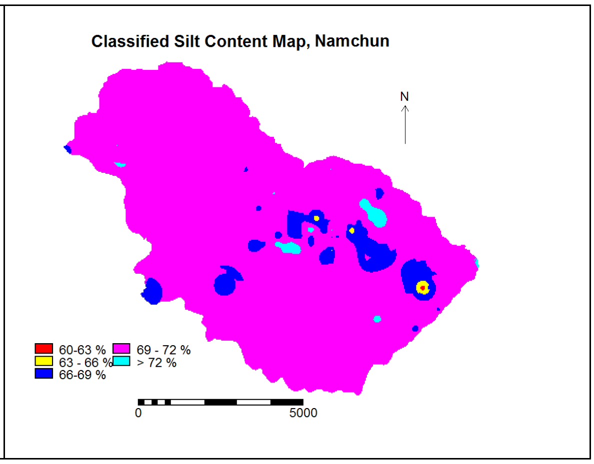
X	Y	CLAY	SILT	SAND	OM	CRUST	Soilloss (kg/m^2/year
726641	1856124	23.1	74.9	2.0	1.6	2.1	1.02
726041	1855924	23.5	66.2	10.3	1.9	1.8	4.20
724041	1855724	20.1	66.3	13.5	1.0	2.4	4.19
724241	1855724	18.9	67.4	13.7	1.2	2.4	9.24
724441	1855724	24.3	71.1	4.5	2.6	1.6	0.28
724841	1855724	18.4	71.8	9.7	1.6	2.3	0.03
725041	1855724	21.4	67.1	11.6	2.2	1.7	9.14
725441	1855724	24.1	70.3	5.6	2.7	1.5	0.03
725641	1855724	22.6	71.2	6.3	1.1	2.3	9.78
725841	1855724	19.8	63.7	16.5	1.3	2.2	1.06
726241	1855724	22.4	67.9	9.7	1.7	1.9	3.79
723641	1855524	21.1	66.6	12.3	2.1	1.7	0.01
724241	1855524	21.9	67.3	10.8	3.9	1.3	0.01
724641	1855524	25.4	68.0	6.6	2.5	1.5	0.09
725841	1855524	22.9	64.2	13.0	1.6	1.9	9.35
726041	1855524	20.3	65.8	14.0	1.2	1.7	9.24
723641	1855324	23.4	73.8	2.9	2.7	2.0	0.02
724041	1855324	18.9	73.1	8.0	2.9	1.7	0.01
724241	1855324	24.9	71.6	3.5	2.4	1.7	2.15
724841	1855324	25.2	69.8	5.0	2.5	1.6	9.24
725241	1855324	24.7	70.6	4.8	2.3	1.7	3.11
723441	1855124	19.1	71.6	9.3	2.2	2.0	1.68
723641	1855124	26.2	70.4	3.4	2.1	1.6	0.15
723841	1855124	23.0	73.2	3.9	1.8	2.0	1.40
724241	1855124	22.3	73.7	4.1	2.1	1.9	8.59

Annex 10: Classified base maps, two dimensional decision tables and intermediate maps for qualitative modeling



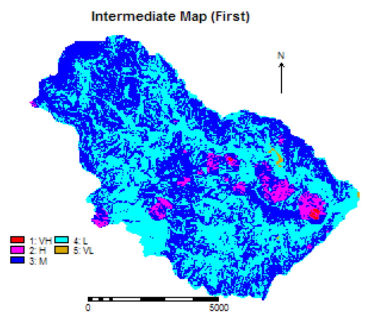






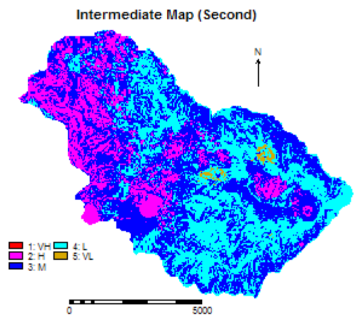
Two dimensional table and intermediate map between slope class and silt class

Silt Class /Slope	60-63 %	63 - 66 %	66 - 69 %	69 -72 %	>72 %
0 - 7 degree	H	M	M	L	VL
7 - 15 degree	H	M	M	L	L
15 - 20 degree	H	H	M	L	L
20 - 25 degree	VH	VH	H	M	L
> 25 degree	VH	VH	H	M	M



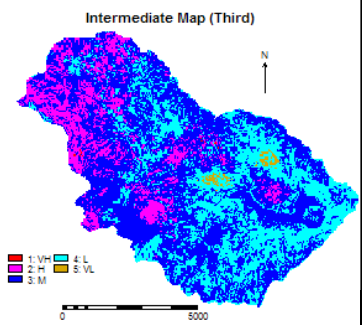
Two dimensional table and intermediate map between first map and crusting index

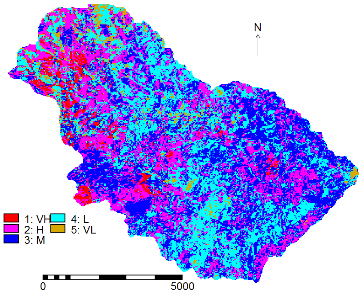
Crust class /class from 1	1.6 -1.8	1.8-2	2-2.2	2.2-2.4	>2.4
Very High	M	H	H	VH	VH
High	M	M	H	H	VH
Moderate	L	M	M	H	H
Low	VL	L	L	M	M
Very Low	VL	VL	L	L	M



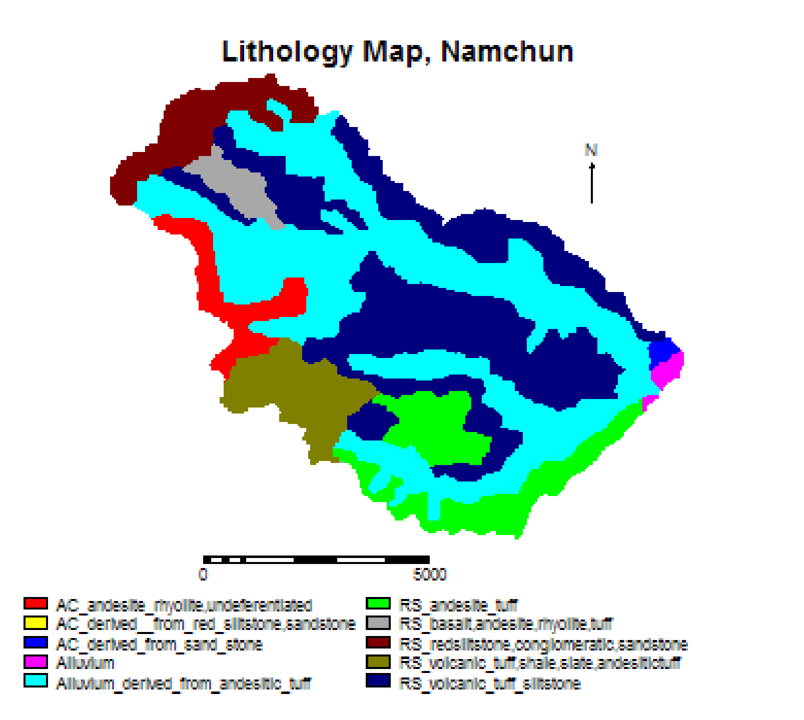
Two 'D table and intermediate map between second map and Organic matter

OM class /class from 2	0-1 %	1-1.5 %	1.5-2 %	2-2.5 %	>2.5 %
Very High	VH	VH	H	M	M
High	VH	H	M	M	L
Moderate	H	M	M	L	L
Low	M	M	L	L	VL
Very Low	M	L	L	VL	VL

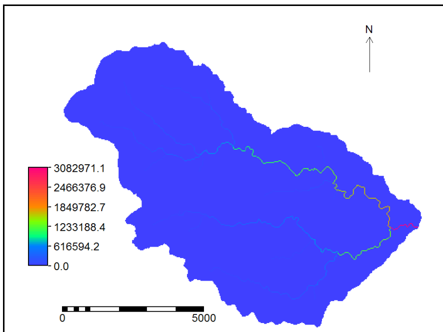


Final Two 'D table and intermediate map between third map and Land cover class						
Land cover class /class from 3	Dense Forest	Degraded Forest	Agriculture	Grass land	Orchard	Final map 
Very High	M	M	VH	H	VH	
High	L	M	VH	H	VH	
Moderate	VL	L	H	M	H	
Low	VL	L	M	L	M	
Very Low	VL	L	M	L	M	

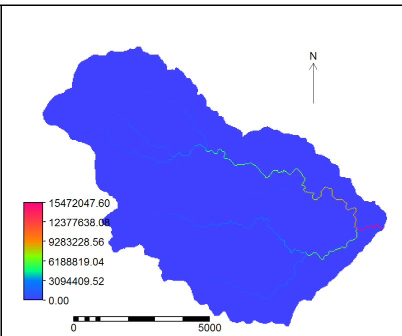
Annex 11: Lithology Map of the area (Digitized in ILWIS)



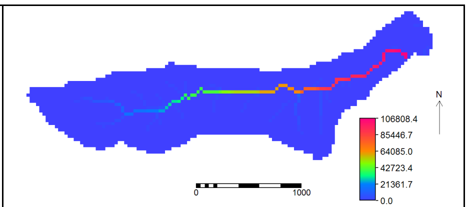
Annex 12: Flow accumulation maps of the watershed and sub-watershed



(a) September, 2007 Q (m^3)

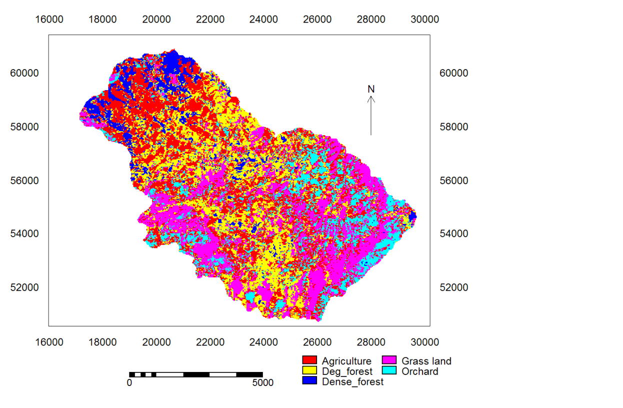


(b) Annual (2005), Q (m^3)



(c) Sub-watershed, September

Annex 13: Land use map and area of different land cover of the whole Namchun watershed (After Suriyapiasit 2008)



Land Cover type	area Ha	%
Dense forest	492.3	7.4
Degraded forest	1530.4	22.9
Agriculture	2186.9	32.9
Grass land	1521.7	22.9
Orchard	923.7	13.9
Total	6655	100.0

Annex 14: Linear model results with adjusted R^2 value of land use parameters

Land use/parameter	PH	CC	GC
Intercept	1.8	0.49	0.68
dense forest	17.6	0.33	0.24
degraded forest	13.2	-0.14	0.04
grass land	-0.3	0.45	0.28
orchard	5.5	-0.18	-0.06
Adjusted R2	69%	70%	36%