GIS-Based Surface Runoff Modeling and Analysis of Contributing Factors; 
A Case Study of the Nam Chun Watershed, Thailand

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A GIS based Surface Runoff Modelling and Analysis of Contributing Factors; A Case Study of the Nam Chun Watershed Thailand

by

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Abstract

Changes in land use/cover have lead to increased water erosion in the Nam Chun watershed and flooding in lower areas. Deforestation and the use of heavy machinery for farming in the area are causing problems of soil degradation. One implication of this is that there is an increase in surface runoff as a result of land use management practices. In order to identify areas that require attention, it is necessary to quantify the volume of runoff taking these changes into account. Due to the spatial and temporal variability of the factors involved in surface runoff, the application of a modelling scheme in a GIS environment provides an efficient approach to determine areas of concern.

Three surface runoff models were applied including; (i) the index method, (ii) the SCS curve number method and (iii) a semi physical approach to assess the distribution of surface runoff in the watershed employing the dynamic modelling language of PCRaster. The first two were empirical based whereas the third one was more a more physical approach, based on equations derived from various sources to account for the different components involved in the process of surface runoff. All three methods took into considerations the effects of different land use/cover types in their predictions of surface runoff.

The semi-physical approach was found to be more suitable for this study because of its strong physical basis. The predictions attained through this approach revealed that areas of agricultural practice were resulting in increased surface runoff. The results were checked against measured surface runoff data collected from the field. Sensitivity assessments were carried out to identify parameters that have the most impact on the surface runoff predictions. Saturated hydraulic conductivity and surface roughness were the parameters to which the model was most sensitive and resulted in high percentage changes on the surface runoff predictions. On the other hand, interception store had a relatively lower effect on the predictions. Scenarios were also generated which gave interesting results. They showed that increasing agricultural activities in the watershed could lead to extremely high surface runoff rates. The influence of this was observed in the discharge pattern of the Nam Chun watershed which showed a high percentage increase when comparing it to the results of the surface runoff simulation using field data.

On the whole the modelling results showed that areas of agriculture practice are resulting in higher rates of surface runoff. This was further substantiated by assessments done on certain soil physical properties that contribute to surface runoff from the main land use/cover classes of the watershed namely forest areas, grasslands and corn fields. The study showed that land management practices, especially in cornfields influences soil properties which induces high surface runoff. Overall the results indicated that areas of agriculture practice are resulting in the generation of high surface runoff and should thus be areas of concern in the watershed that require the implementation of adequate conservation measures.
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<th>Full Form</th>
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<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>EUROSEM</td>
<td>European Soil Erosion Model</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization</td>
</tr>
<tr>
<td>HBV</td>
<td>Hydrologiska Byråns Vattenbalansavdelning</td>
</tr>
<tr>
<td>LDD</td>
<td>Land Development Department, Min of agriculture and cooperatives Thailand</td>
</tr>
<tr>
<td>RMMF</td>
<td>Revised Morgan Morgan and Finney</td>
</tr>
<tr>
<td>SHE</td>
<td>Systeme Hydrologique Europeen Model</td>
</tr>
<tr>
<td>TOPMODEL</td>
<td>Topographic Index Model</td>
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<td>USDA</td>
<td>United States Department of Agriculture</td>
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1. INTRODUCTION

1.1. Background

The area of land estimated to be suffering from some form of degradation stands, at just below 2 billion hectares of the world’s land mass, making it a serious global concern challenging the well-being of mankind (Barrow, 1994; Scherr and Yadav, 1996). The pressures of an increasing world population combined with insufficient agricultural production have resulted in measures that have further accelerated the processes of land degradation. Deforestation, poor agricultural management practices and the use of marginal lands for cultivation purposes are notable examples of measures being implemented (Eswaran et al., 2001; UNEP, 2000). Every year, from 5 up to 10 million hectares of land is reported to be degraded; the consequence of this has had a direct impact on the lives of about 15% of the world’s population (Eswaran et al., 2001; Scherr and Yadav, 1996).

Water erosion accounts for about 56% of the total land area estimated to be degraded, making it a major factor contributing to the process of land degradation (Swai, 2001). Certain areas in the world experience a reduction in food production by up to 50% as a result of soil erosion and desertification (Eswaran et al., 2001). This, not only undermines the economic growth, but also threatens the food security of a country.

The problems instigated by water erosion are not restricted to onsite problems. They extend further to low lying areas where transported soil particles are deposited. On site, water erosion depletes nutrient content of soils and diminishes soil depth. It damages soil structure leading to a decline in infiltration capacity, surface sealing and crusting which in combination further increase the loss of soil. Transformed soil particles can be deposited in reservoirs and streams not only polluting water bodies, but also filling them up and reducing their capacity to carry water which, can consequently result in severe floods (Schwab et al., 1981; White, 1997).

Soil erosion by water is closely related to rainfall and runoff. In general terms, it can be defined as the detachment and transport of soil particles from one area to another by rainfall and running water respectively (White, 1997). In most cases, intense runoff is also capable of detaching soil particles making surface runoff a major causal factor in the process (Schwab et al., 1981).
Erosion is a natural process but only when it takes place without the pressures of land use/cover changes which hasten, the rate at which it occurs. Alterations in land use/cover particularly affect the physical properties of soils which are closely related to infiltration characteristics. This in turn influences the runoff pattern in a catchment. An increase in the volume of runoff generated subsequently affects the amount of soil that is eroded. The consequences of changes in land use/cover on the rate of erosion can be assessed indirectly by studying runoff and its distribution in a catchment. In order to achieve this, it is necessary to quantify the volume of runoff taking these changes into account (DeRoo et al., 2000; Dingman, 2002; Green et al., 2000; Rientjes, 2004).

1.2. Statement of the Problem

Problems of land degradation have significantly intensified over the last decade in Thailand as a result of population pressures (Shrestha, 2003). High population growths have brought on severe damages to the environment. Among these damages, deforestation and forest degradation rank at the top. Forest stands are continuously being encroached for expansion of agricultural fields, logging purposes, for fuel wood and for the construction of roads and dams without the implementation of proper conservation measures. Additionally, poor land management practices including farming on steep slopes and marginal lands have further aggravated the problem. Erosion and flooding have become the two main land degradation problems, affecting the economy of the country as well as the lives of many (Shrestha, 2003).

The Nam Chun watershed, situated in the North central part of Thailand, Petchabun Province (figure 3-1), has seen extensive land use/cover changes through human interventions in the past decades. The watershed that was once covered by forest, is now heavily under the influence of human activities. Deforestation on steep slopes and mechanised ploughing down slope for the cultivation of annuals and perennials, have become common practices all of which have had an impact on the soil (Shrestha, 2003). The few remaining forest stands in the area are mainly disturbed. The removal of the natural vegetation has exposed the soils to heavy tropical rainfalls (annual average of 1069mm concentrated mainly between the months of May and October). The area has a rugged terrain with very high relative relief altitudes varying from 240m to 1509m asl (Shrestha, 2003). The topographic features of the area and the climate compounded with poor farming techniques and depletion of forests have resulted in severe problems of land degradation in the watershed. Not only is the watershed losing large quantities of soil, thereby reducing its agricultural yield but the flood plain to which the watershed contributes is also faced with
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frequent problems of flooding. A case in point is the flood event of 2001 that claimed the lives of many and brought on extensive damage to property (ADPC, 2002; Saengthongpinit, 2004; Shrestha, 2003). One implication of these problems could be that the soil in the watershed is degraded as a result of catchment management practices resulting in increased rates of surface runoff. The study of the influence of different land use/cover types on surface runoff generation has therefore become a topic of consequence.

Several studies have been conducted to assess problems of land degradation by estimating soil loss from the watershed and its vicinity through the application of GIS based modelling techniques (Saengthongpinit, 2004; Yazidhi, 2003). This study will attempt to evaluate the impacts of different land use cover types on surface runoff by employing GIS based modelling techniques in order to identify the effects of soil degradation on its generation.

1.3. Objectives

The general objective of this research is to quantify the rate of runoff in the Nam Chun watershed taking into account the effects of different land use/ cover types. The Specific objectives of the research are the following:

- To quantify the rate of runoff in the Nam Chun Watershed through the application of GIS based modelling techniques
- To assess the applicability of different runoff modelling approaches
- To investigate the impacts of changes in land use/ cover on the rate of runoff
- To assess the effects of different land use/ cover types on certain soil properties related to runoff generation

1.4. Research Hypothesis

- A modelling approach is a suitable technique to quantify the rate of runoff in this study and assess the effects of land use/cover changes on its generation
- Land use/ cover types can result in reduced rates of infiltration due to changes in the physical properties of the soil in the watershed
- Changes in land use/ cover characteristics can influence the rate of runoff
1.5. **Research Questions**

- Which land use/cover types result in the generation of high surface runoff?
- Which land use/cover types result in the generation of low surface runoff?
- Can low infiltration rates be attributed to certain types of land use/cover types?
- What are the impacts of different land use/cover types on soil physical properties related to surface runoff generation?

1.6. **Structure of the Thesis**

The thesis is divided into 7 chapters. The first chapter identifies the research problem emphasising on the need for this study. The objectives, hypothesis and the research questions to be answered by this study are also given in this chapter. Chapter two discusses the background on the theoretical aspects of runoff with highlights on factors that influence it focusing on soils degradation problems. Various methods of modelling runoff are briefly specified in this chapter and finally a short description of the approaches employed in this study is given. In chapter 3, a description of the study area is given mentioning among others its location, climate, soil characteristics and geology. Chapter four introduces the modelling approaches implemented in this study. It gives detailed descriptions on the components used and specifies the data requirements of each approach. Following this the activities involved in attaining the required data for the modelling procedures are discussed. Chapter 5 discusses the procedures used in preparing the input maps and the parameterisation of the parameters required is mentioned. The results of the study are presented in chapter 6. This includes the results on the analysis of soil data and the model predictions relating them to different land use/cover types. Finally in chapter 7, conclusions on the results of the study are made. Limitations of the study are highlighted and some recommendations based on the study are given.
2. LITERATURE REVIEW

2.1. Runoff

The term runoff can be applied to stream or river discharge. It can also be employed in reference to the gravitational movement of a fraction of rainfall over the surface of land or as subsurface flow from an area peripherally bound by a water divide, towards a water body. Runoff is expressed in terms of volume per unit of time and its generation largely depends on the amount of rain water that reaches the earth’s surface (Rientjes, 2004; Schwab et al., 1981; Ward and Robinson, 1990).

Runoff in a catchment is generated by the portion of rainfall that remains after satisfying both surface and subsurface losses. Once these demands have been met, the remaining rainwater follows a number of flow paths to enter a stream channel. The course it follows depends on several factors including soil characteristics, climatic, topographic and geological conditions of a catchment (Ward and Robinson, 1990). Overland flow or surface runoff is the main flow path of runoff that can largely be influenced by human activities through catchment management practices. It is also the flow path of rainwater that triggers the process of soil erosion (Morgan, 1995).

2.1.1. Surface Runoff in a Catchment

Surface runoff refers to the portion of rainwater that is not lost to interception, infiltration, evapotranspiration or surface storage and flows over the surface of land to a stream channel (Morgan, 1995). During a rainstorm, a certain portion of rainfall is intercepted by vegetation canopy. What is left over falls directly onto the soil as throughfall (White, 1997). Intercepted rainwater either evaporates or in cases of heavy and continuous rainfall events, when canopy storage capacity is exceeded, intercepted rainwater falls to the ground as leaf drainage or stemflow (Morgan, 1995; Rientjes, 2004). The amount of rainwater that is lost due to interception depends on the vegetation cover and the rainfall pattern (Dingman, 2002). Rainwater retained in vegetation canopy that ultimately evaporates is referred to as interception loss (White, 1997).

Rainfall that is not lost to interception and reaches the soil surface either infiltrates into the soil, is stored in surface depressions or evapo-transpires. The remaining excess rainwater travels over land as surface runoff. Surface runoff occurs either when the soil is saturated from above or from
below. If the rate at which rain falls to the ground is higher than the rate at which it infiltrates into the soil and surface storage is full then, the excess water at the surface flows along its gravitational gradient as surface runoff. This is referred to as saturation from above or Hortonian overland flow. On the other hand, if the soil is already saturated due to previous rainstorm events and the infiltration capacity of the soil is zero, saturation from below occurs. In this case, most of the rain that reaches the ground is converted to overland flow after satisfying surface storage and no or very little water infiltrates into the soil (Dingman, 2002; Morgan, 1995; Ward and Robinson, 1990).

2.1.2. Soil Properties Influencing Infiltration

Infiltration rate refers to the rate at which water enters the soil during or after a rainstorm (Schwab et al., 1981; White, 1997). It plays a key role in controlling the amount of water that will be available for surface runoff after a rainfall event (Morgan, 1995). It involves several processes acting together including gravitational forces pulling the water down, attractive forces between soil and water molecules and the physical nature of soil particles and their aggregates (Dunne and Leopold, 1978; Morgan, 1995). A number of environmental factors govern the rate at which water infiltrates into soil. These include; the rate of rainfall, soil properties (including texture, soil porosity, organic matter content, structure of soil aggregates, soil depth and moisture carrying capacity of the soil), topography (slope), vegetation cover, and type of land use (Dunne and Leopold, 1978; Maidment, 1993; Schwab et al., 1981).

The most important soil properties that influence the rate of infiltration, as mentioned above, are the physical properties of the soil. The size of the particles that make up the soil, the extent of soil particle aggregation and the way in which the aggregates are arranged are properties of the soil that make it a porous permeable medium through which water can flow (Dunne and Leopold, 1978; Hillel, 1980; Schwab et al., 1981). These properties vary extensively both spatially and temporally, and are a consequence of the geology and geomorphology of an area. They can also be influenced through catchment management practices (Brady and Weil, 1996; White, 1997).

Hydraulic conductivity of the soil refers to the soils ability to conduct water down its profile. It largely determines the amount of water that can pass into the soil and therefore it is directly proportional to the infiltration rate (White, 1997). During a rain fall event, rainwater reaching the surface of the earth is drawn into the soil through pores by a suction gradient and a gravitational head gradient. If the soil at the start of a rainfall event is dry then, the suction head gradient
becomes the strongest force pulling the water into the soil. As the soil fills up with water however, the suction head force decreases and the gravitational head gradient becomes the driving force conducting water down the soil profile. With continued saturation of the soil, the rate at which water moves into the soil approaches the saturated hydraulic conductivity. Under such conditions, if the rainfall intensity is greater than the rate at which the soil accepts water, ponding occurs at the surface. Further input of rainwater causes the capacity of surface storage to be exceeded resulting in surface runoff (Hillel, 1980; White, 1997).

Both soil structure and texture influence the hydraulic conductivity of soils (Hillel, 1980). In general, soils with high clay content have lower saturated hydraulic conductivity values whereas coarse textured soils such as sandy soils have higher values because of the larger pore space between the soil particles. As such, the infiltration rate of clayey soils is much lower than that of sandy soils. The infiltration rate can range from approximately 5mm/h for clay soils to 200mm/h for sandy soils (Morgan, 1995). In terms of soil structure, the extent of the soils porosity and the arrangement of soil aggregates determine the hydraulic conductivity of soils. Porous soils with stable aggregates have higher saturated hydraulic conductivity values than soils that are compact and dense (Hillel, 1980).

2.1.3. Land-use and Land-Cover Changes in relation to Surface Runoff

As previously stated, in the conversion of rainfall to runoff, there are a number of stages in the hydrologic cycle that rainwater goes through before runoff is generated in a catchment. These different stages result in different losses from the total rain, reducing the amount of water that will be available for overland flow. Through catchment management practices, man has had considerable influence over certain aspects of these stages. This has brought notable differences in the rate at which surface runoff is generated. An increase in the rate of runoff consequently increases the amount of soil that is eroded resulting in problems of land degradation (Morgan, 1995).

Soil compaction brought about as a result of changes in land use/cover practises in a catchment disrupts the natural arrangement of soil particles and their aggregates. This disruption causes soil particles to be more closely packed which reduces soil porosity, increases soil bulk density and destabilizes soil aggregates (Hillel, 1980; Schwab et al., 1981). This in turn causes a decline in the hydraulic conductivity of soils which directly influences the rate at which rain water infiltrates into the soil. In addition to hydraulic conductivity, other hydraulic properties of the soil including
suction head and soil moisture deficit which are functions of soil porosity and closely related to infiltration characteristics of the soil can also be affected as a result of a disruption in soil structure (Green et al., 2000; Hillel, 1980; Schwab et al., 1981).

Vegetation serves as a protective layer over soil surface and also increases its infiltration capacity. Removal of vegetation due to changes in land use/cover exposes the bare soil. When rain drops to the ground and hits the soil directly, soil particle detachment takes place. Freely flowing water then may cause fine particles to clog pore spaces provided by soil aggregates. This, results in the formation of a thin compact layer on the soil surface referred to as surface crusting which prevents water from passing into the soil (Hillel, 1980; Schwab et al., 1981; White, 1997). The formation of a surface crust at the surface greatly reduces the infiltration capacity of the soil, which ultimately increases the amount of water available for surface runoff.

Vegetation cover is also important in serving as a barrier to reduce flow velocity of surface water. It also has an important role in maintaining the structure of the soil. Plant roots increase the pore space along the lines occupied by roots and dead leaves provide litter that keeps up the organic content of the soil which strengthens soil aggregates and maintains good soil structure. Clearing of vegetation reduces the effect of roots and input of organic matter into the soil contributing to a reduction in the infiltration capacity of the soil (Schwab et al., 1981).

2.1.4. Surface Runoff in relation to Soil Erosion

Runoff is not in itself a form of land degradation but it is one of the major causes of land degradation problems, of which the main ones are erosion and flooding. Furthermore, the rate at which runoff is generated can be increased because of land degradation problems. Runoff on the one hand is an essential process in that it maintains water level in lakes and rivers preventing them from drying out and providing fresh water on which many living beings including humans largely depend. If however the rate of runoff is increased as a result of catchment management practices it can result in severe land degradation problems (Dunne and Leopold, 1978; Maidment, 1993; Schwab et al., 1981)

Areas having shallow and compact soils ensuing from a combination of poor farming techniques, exploitation of marginal lands, deforestation and excessive erosion are susceptible to higher rates of runoff. High runoff rate leads to an increase in soil erosion by running water. On the other hand, areas with deeper, more porous soil structures that are densely vegetated contribute to a reduction in the amount of water available for runoff which results in reduced rates of erosion
Land use/cover changes that increase runoff rates therefore ultimately influence the rate at which soil loss occurs. Soil loss brings about problems of soil degradation which in turn further aggravates problems of runoff.

### 2.2. Runoff Modelling

There are several approaches to quantify the volume of runoff. One would be to gauge a stream channel and measure its discharge pattern. But this, will not give adequate information on the effects of changes in management practices (such as soil, land-use and land-cover changes) on the rate at which runoff is generated from different areas in a catchment. Due to the spatial and temporal heterogeneity of the factors involved in runoff at catchment scale, a modelling approach to simulate the physical processes of runoff would be ideal to study the effects of changes in a catchment on its generation (Beven, 2000; Dingman, 2002).

The mathematical description of all runoff models are simplifications of the actual process of runoff in nature. Some models are more simplified than others but at the base of each model, there is a mathematical description that simplifies the factors that are being considered and that enables models to make quantitative predictions (Beven, 2000; Rientjes, 2004). Factors involved in the process of runoff, such as soil characteristics, vary extensively over small distances. It is impossible to account for each variation in space in a mathematical model. For this reason, average values are taken for sets of variables that share similarities. All models whether empirical, physical or combinations of the two are therefore based on many assumptions (Beven, 2000).

Increasing the complexity of a model by emphasizing more on the physical basis of environmental processes does not necessarily improve the performance of the model. Making a certain model more physical based implies that the input parameters are also increased and are more complicated to attain (Deursen, 1995; Pfeffer, 2003). Most parameters are obtained through measurements or observations and are rarely free of error. This error introduced into the model when the parameters are processed contributes to the overall inaccuracy of a model (Deursen, 1995). On the other hand, the use of simpler empirical models also has its own drawbacks. Simple models tend to generalize details of environmental processes. This may result in the loss of both spatial and temporal information (Beven, 2000; Deursen, 1995). As a result, there is no perfect model currently in existence that can fully explain all details involved in runoff and simulate the process as it occurs in nature.
However, there are many types of runoff models available today and through the application of a suitable modelling approach, useful information on if and where there are problems can be identified (Beven, 2000; Deursen, 1995; Ward and Robinson, 1990). Although a challenging task, once a suitable model for a particular catchment has been identified and surface runoff is simulated, taking into account changes in land use/cover, the predictions of the model can be very useful. It can help in identifying areas that contribute to higher rates of runoff. This information can be used to execute changes in catchment management practices in an effort at reducing the rate of surface runoff in the long run diminishing problems of land degradation. The selection of a suitable model should therefore depend very much on the objectives of a study but additional factors such as availability of data, money, and time should also be taken into account (DeRoo et al., 2000).

2.2.1. Runoff Model Classification

Runoff models can broadly be classified into two classes: lumped or distributed; and deterministic or stochastic (Beven, 2000; Ward and Robinson, 1990) models.

Lumped modelling approaches consider a catchment to be one unit and a single average value representing the entire catchment is used for the variables in the model. The predictions obtained from such models are single values (Beven, 2000). In the distributed modelling approach, models make predictions that are spatially distributed. The spatial variability of model variables are simulated by grid elements (grid cells), that can either be uniform or non-uniform (Rientjes, 2004). Not only one average value over the entire catchment is considered but values of parameters that vary spatially are locally averaged within each grid elements. Model equations are solved for each element or grid square and depending on the spatial variability of a certain parameter different values are used for each grid elements (Rientjes, 2004). Such type of models make predictions that are distributed in space allowing to assess the effects of changes in a catchment (such as land use/cover) on the rate at which runoff is generated (Beven, 2000).

Stochastic models (also known as probabilistic models) consider the chance of a hydrological variable occurring (Ward and Robinson, 1990). Both the input and output variables of stochastic runoff models are expressed in terms of a probability density distribution. In a stochastic modelling approach, uncertainty or randomness in the possible outcome of the model is permitted because of the uncertainty that is introduced by the input variables of the model (Beven, 2000; Rientjes, 2004).
Deterministic models on the other hand focus on the simulation of the physical processes involved in the transition from precipitation to runoff. Most runoff models use the deterministic approach in simulating the process of runoff. In this case, only one set of values per variable are input into the model and the outcome is also one set of values. At any time step, the expected outcomes from a deterministic modelling approach are single values (Beven, 2000; Rientjes, 2004; Ward and Robinson, 1990). Deterministic models can further be divided into black box, conceptual and physical based runoff modelling approaches (Rientjes, 2004).

2.2.2. Modelling Approach with PCRaster

Most runoff models in existence today do not give the user full control over how each stage of a complex process such as runoff is simulated. Generally, environmental researchers are not expert programmers and their use of a modelling approach is restricted by the design of a particular model (Dijck, 2000). Changing certain components, that are not satisfying or that require data that might not be obtained for a particular research, is not possible in standard models (DeRoo, 1999).

PCRaster provides ideal conditions for modelling environmental processes such as surface runoff (Burrough et al., 2005). It links a dynamic environmental modelling language to a GIS. The modelling language of PCRaster is specifically developed for the modelling of environmental process. It can easily be used by environmental researchers to construct dynamic environmental models that are adapted to particular problems being studied (Burrough et al., 2005; Dijck, 2000). Whilst the GIS portion of the system allows the storage, manipulation and visualisation of large data sets, the dynamic modelling language provides operators specifically designed for modelling environmental processes taking into account their spatial (distributed modelling) and temporal variability (Burrough et al., 2005; DeRoo, 1999; DeRoo et al., 2000; Deursen, 1995).

The integrated idea behind PCRaster allows for a more flexible and adoptable approach. It offers the researcher the freedom to focus on the processes deemed most relevant for a particular study and for which sufficient input data are available (Burrough et al., 2005; DeRoo et al., 2000; Pfeffer, 2003). Models designed in PCRaster can range in complexity from very simple empirical based models to more complex physical based approaches.
2.2.3. **Empirical Based Models**

Black box models involve the simulation of empirical relations through the use of regression equations that are developed after long-term field observations. They make use of regression coefficients derived from observation rather than from the theoretical or physical background of natural process (Rientjes, 2004). The simplest case of such runoff models are index models. Index models assume there is a constant loss rate from the total rain falling in a catchment before surface runoff occurs or that a certain constant fraction of the total rain falling in a catchment becomes surface runoff (Beven, 2000; Maidment, 1993). Such types of models are still widely used and are simple ways of obtaining approximate runoff estimates (Beven, 2000). However to ensure that their predictions coincide with the reality on the ground, it is necessary to have long term data on climate and discharge pattern of a catchment.

The U.S soil conservation Curve Number Method is another simple empirical method for estimating the amount of rainwater available for runoff in a catchment (USDA, 1986). The method was developed by the U.S Department of Agriculture and Natural Resources through the analysis of runoff volumes from small catchments in the US. The initial abstraction values determined by the curve numbers were developed for different soil types and land-use practices (USDA, 1986). The main assumption of the curve number approach is that the ratio of the actual runoff to the potential runoff (rainfall minus an initial abstraction) is equal to the ratio of the actual retention to the potential retention. This assumption has no physical basis making the approach entirely empirical based (Beven, 2000). The advantage of this approach is that it is not data demanding and very simple to use. Its predictions can be useful in identifying weather problems exist (Deursen, 1995). However very little quantitative information is available on how the curve number values were developed and their application to conditions for which they were not developed may lead to questionable results (DeRoo et al., 2000).

2.2.4. **Physical based models**

Physical runoff models involve the use of equations that represent the physical basis underlying environmental processes (Pfeffer, 2003). These equations are based on the laws of conservation of mass, energy and momentum (Rientjes, 2004). In physical based modelling approaches, the characteristics and properties of real world processes are included through the use of mathematical equations that are derived based on the physics of the processes involved. Thus, such types of models are complicated and demanding in their data requirement (Dingman, 2002;
Rientjes, 2004). However the results they give are considered more reliable because of their physical basis and their application is not restricted to areas for which they were created.

A wide range of physical based rainfall-runoff models are available today. The use of physically based models such as HBV, TOPMODEL and the SHE have the disadvantage that they require a large number of parameters to run them and most of the parameters required are obtained through calibration making such approaches expensive and time consuming (DeRoo et al., 2000; Dingman, 2002). With the use of the dynamic modelling language of PCRaster, it is possible to construct a spatially distributed physical based surface runoff model that uses measurable input parameters (DeRoo et al., 2000). Through the integration of equations developed for describing the mechanisms of the components involved in the transformation of rainfall to runoff a hydrological model that satisfies the purposes of a particular study and that uses measurable input parameters that are attainable within the time span of a study can be designed (DeRoo et al., 2000; Pfeffer, 2003)
3. STUDY AREA

3.1. Location

The study area, Nam Chun sub-watershed, is situated in the province of Petchabun in the central part of Thailand which is about 400kms due north of Bangkok (Figure 3-1). It lies between the latitudes 16°44’ and 16°48’ North and longitudes 101°02’ and 101°09’ East. The watershed covers a total area of about 67km² and it is part of the larger river basin of the Pa Sak River which flows from the northern part of the country to the south. Farmers living clustered in small villages populate the area. Most of these villages are reachable by roads that branch out from the main road that cuts across the watershed. These roads are however restricted to locations where people reside making areas with steeper high mountains, inaccessible.

![Figure 3-1: The study area in the Phetchabun Province of Thailand](image)

3.2. Climate

Owing to its geographical location, the area is characterised by a tropical climate that is influenced by north eastern and south western monsoons. It has three distinct seasons; a dry and cool winter, a hot spring and a wet hot summer period that starts in May and lasts until October. The average number of rainy days in a given year is estimated to be 120, most of which falls in the rainy season period (May to October). The area experiences an annual average rainfall of 1120mm with maximum rainfall in one month reaching as high as 230mm.
3.3. Geology and Geomorphology

The area forms part of the central highlands, which is a hilly area that lies in the central part of Thailand. The Cenozoic, Mesozoic and Palaeozoic eras note the formation of the main geological features of the area. The upper portion of the catchment is dominated by uplifted sedimentary rocks of the “korat” group of rocks that formed in the Mesozoic era. This group of rocks comprises of conglomerates, sandstone, shale, mudstone and argillaceous limestone. The lower portion of the area is characterised by quaternary colluvial and alluvial terrace deposits (Hansakdi, 1998; Kunda, 2004).

The area exhibits a complex physiography having three main landscapes: the high plateaus that form part of the north-western tip of the catchment, a heavily dissected mountainous area that dominates a large portion of the catchment and a low-lying narrow valley (Figure 6-2). The area has high altitudinal variation ranging from a minimum of 240m in the valley bottom to a maximum of 1509m above sea level in the plateau landscape.
3.4. Soils

The soils in the area are characterised by high clay content and can be categorised in the silt loam to silt clay textural classes. The soils in the central highlands of Thailand are classified under the great groups such as the ustifluvents, paleustalfs, haplustalfs, kandiustox, haplusterts, haplustolls, haplustults and paleustults (Vijarnsorn and Eswaran, 2002). The soil moisture regime in the area is Ustic.

3.5. Vegetation and Land Use

The watershed is characterised by six major land use/cover types. These include forest, degraded forest, maize plantation, mixed crop, orchard and extensive grassland areas. Deciduous trees of the teak species dominate the forest areas. However much of the previous forest area has been encroached and a large portion is today mixed with bamboo plants and grasslands. Such areas are therefore classified as degraded forests.

The principal annual crop in the area is maize and it is found predominantly in the south-western part of the study area. Maize cultivation is mainly done on sloping areas. The mixed crops mainly consist of annuals such as mungbeans and coriander but in some areas, varieties of vegetables are also grown. Much of the upper part of the catchment is covered by fallow grasslands dominated by the grass species *Impecata cylindica*. Much of this area was previously used for maize cultivation.
4. MATERIALS AND METHODS

4.1. Materials Used

- The following materials were used for the study:
- Black and White aerial photographs taken in 19and with a scale of 1:25,000
- Aster Images with 9 different bands obtained in January 2004
- Ortho-photo mosaic of the study area obtained from the Land Development Department, (Thailand) with a scale of 1:25,000
- A digital contour map with contour intervals of 20m in mountainous areas and 10m in flat areas
- A digital land-use/land-cover map acquired from the Land Development Department, (Thailand) at a scale of 1:25,000
- Equipments used in the office include; stereoscope, anaglyph, transparencies, coloured pencils
- The software’s used were; ILWIS for producing input maps for PCRaster, PCRaster for writing up model scripts and simulating runoff, HanDBase for construction of a database that was used in the collection of data, Microsoft Excel for statistical analysis, Microsoft Visio for the production of flow charts and Microsoft word for writing up the thesis.
- Sampling equipments used in the field include; GPS receiver (Garmin XL12), sample collecting bags, squeezing bottle, measuring tape, compass, floating bottle, rope, stop watch, measuring cylinder, beaker, funnel, bucket, hand penetrograph, infiltration ring, hammer, soil sample rings, core sampler, spade, auger, field knife, altimeter, stop watch, pH meter, Munsel colour chart, FAO Guidelines for soil description, Field Book for Describing and Sampling Soils, hand held computer and a field notebook
4.2. Modelling Runoff

Runoff is a dynamic process that is dependant on factors that vary both spatially and temporally. In order to evaluate the rate at which it is generated and how different factors in a catchment affect it, a modelling design in a GIS provides an ideal environment. Such an approach allows the storage, integration, analysis, and maintenance of large environmental data sets. It provides an efficient, cost effective technique that offers possibilities to investigate factors that influence the rate of runoff over a large area. The information attained can be used to simulate the effects of certain decisions on catchment management practices to prevent for instance excessive runoff that may lead to a number of problems. See also chapter 2. This study therefore considers, a modelling approach in a GIS environment as the most effective method to assess the rate at which runoff occurs over the study area and the factors that influence it.

PCRaster, an open source, GIS software developed by the PCRaster research and development team in the Department of Physical Geography, Faculty of Earth Sciences at Utrecht University in the Netherlands (Burrough et al., 2005) was selected for use in this study. Through the use of PCRaster’s dynamic modelling language, a researcher is able to integrate equations from different sources that describe the mechanisms of the components involved in surface runoff generation. It allows the researcher to select modelling approaches that are not only suited for the objectives of a particular study but also, approaches that require input parameters that are obtainable or measurable within the time span of a study. This was a particularly important reason for selecting PCRaster for this study as, surface runoff modelling had not been done in the area before (imposing restrictions on the use of existing data) and, the data collection period of the study was limited (imposing restrictions on the amount of data that can be collected). In addition, since the main aim of this research was to assess the impacts of changes in land-use and land-cover on the rate of surface runoff, the application of a spatially distributed modelling approach, which PCRaster offers, was imperative to meet the objectives of the study.

Three different modelling approaches were used in PCraster to model runoff in the Nam Chun watershed. The first and second methods were empirical based approaches that describe the runoff process based on empirical assumptions. The first one was selected because of it can easily be employed and it provides an indication of whether there is a problem that needs further investigation. The second approach was also selected because of its simplicity in its data requirement but also because of the fact that it considers the influence of land use/ cover changes in the derivation of the parameters (CN) used to compute excess precipitation. The third approach
was more physical based and involved the integration of equations, from different sources, that describe the different components involved in the runoff process. This approach was selected because of its physical basis. Its predictions are based on the physical laws that govern the surface runoff process and thus its results are likely to be more accurate and because it also considers the effects of land use/cover changes on the generation of surface runoff. The following sections give brief descriptions on the methods employed.

4.2.1. **Empirical Models**

**a) Index Method**

The first approach was a simple index model based on a certain constant loss from rainfall. It assumes that in each time step, a certain constant amount of rain falling infiltrates into the soil and the remaining becomes surface runoff. Rainfall was modelled in each time step as described in chapter 5. Infiltration values were assigned to the different soil textural classes occurring in the area based on the soil map. The infiltration values assigned to each class were arbitrary factors of the infiltration data collected in the field. The excess water or surface runoff was routed using the local drain direction map produced from the DEM as explained in chapter 5. The `accuthreshold` operator of PCRaster was used for this purpose. The operator describes the flow of water over a catchment after a certain loss, in this case infiltration defined by the soil map, has been satisfied in each time step. Rainfall, in each time step enters a cell as well as excess water coming from its upstream cells. The water that has entered the cell infiltrates into the soil until the infiltration threshold value imposed by the soil map is satisfied. Once the infiltration loss has been met then the excess water travels to its downstream cell following the local drain direction and the same procedure is repeated for all the time steps used. The script used to model runoff using this approach is presented in appendix 1.

**b) SCS Curve Number Method**

The equation used in the Curve Number method was derived based on observations made on rainfall-runoff data collected over a long period of time from different sites in the United States making the approach empirical based (Beven, 2000). The method was selected for this study because of its simplicity and the fact that it is not too demanding in terms of its data requirement. The availability of tabulated CN values (USDA, 1986), for a wide range of soil and land use/cover practices, considerably facilitated the application of this method.
The approach considers the time distribution of rainfall and initial rainfall losses to interception surface storage and, infiltration rate that decrease over a period of a rainstorm event (Gerlach et al., 2003). A certain amount of the rainfall will not contribute to runoff until the demands of the initial abstraction \((I_a)\) are met. So potential runoff becomes \(P - I_a\). Once water is available for runoff, an additional amount of water is retained in the catchment and this is equal to or less than the potential maximum retention \((S)\). Equation 4-1 summarises the relationship between rainfall, initial abstraction, the potential maximum retention and the additional water retained. The application of this method in the iterative environment of PCRaster results in surface runoff values that vary both spatially and temporally (Deursen, 1995).

The general equation of the method is as follows (USDA, 1986):

\[
Q = \frac{(P - I_a)^2}{(P - I_a) + S}
\]  
(4-1)

Where,

\(Q\) = runoff (inch)

\(P\) = rainfall (inch)

\(I_a\) = Initial abstraction (surface storage, interception, and infiltration, inch)

\(S\) = potential maximum retention (inch)

\(I_a\) can further be defined by the following empirical equation:

\[I_a = 0.2S\]  
(4-2)

Substituting equation 4-2 into equation 4-1 gives:

\[
Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}
\]  
(4-3)

\(P\) is a measurable quantity and can easily be obtained. However, \(S\) is difficult to determine. As a result, the runoff curve number is used to determine \(S\) based on the following relationship:

\[
S = \frac{1000}{CN} - 10
\]  
(4-4)
Where,

\[ CN = \text{runoff curve number} \]

The \( CN \) can be derived from tabulated values based on the soil condition, land use/cover and treatment of an area. The higher the \( CN \) value implies the higher the runoff potential. The initial moisture content of the soil can also be considered in the approach. Once the \( CN \) has been determined based on the land use/cover and soil type of an area, the following equation can be used to adjust the \( CN \) values for antecedent moisture content (TxDOT, 2004).

\[
CN_{adj} = \frac{23CN}{10 + 0.13CN}
\]

(4-5)

This equation was used for this study because the field work was conducted during the rainy season and the soil was wet during data collection. The script used to model runoff using the Curve Number method in PCRaster is presented in appendix 2.

### 4.2.2. Semi-physical modelling approach

The third approach involved the integration of different equations to model the various components involved in the process of surface runoff. The components of surface runoff that were considered important in this approach were

- interception by vegetation,
- infiltration into the subsurface,
- surface storage and
- routing of excess water.

Figure 3-1 below shows the overall structure of the model that was used to describe the mechanisms of surface runoff generation during a rainfall event. The rationale for the methods employed to model each component, the mathematical equations used to describe each process, the data requirements and how each input parameters were obtained, including data for model calibration, are discussed in the following sections of this chapter.
Figure 4-1: Flow chart showing the structure of the surface runoff model used
4.2.2.1. Interception

Interception was modelled by making use of the event-based interception modelling approach of the EUROSEM (Morgan et al., 1998). The reason this method was selected was because of its applicability in event based modelling and because it assumes a more dynamic approach. In addition to this, the parameters required for running the model could be retrieved from literature using land use/cover data collected in the field. Interception was modelled as follows (Burrough et al., 2005):

Rainfall is divided into two parts

1. a portion that falls directly on the ground

\[ DR = Pr(1 - Cov) \]  \hspace{1cm} (4-6)

2. a portion that falls on canopy

\[ Int = Pr \times Cov \]  \hspace{1cm} (4-7)

Where,

\( Int \) = intercepted rainfall (m/T)

\( Pr \) = rain (m/T) and

\( Cov \) = Percentage cover of the vegetation

An initial proportion of the intercepted rainfall (\( Int \)) is assumed to be stored on vegetation canopy and never makes it to the ground. This is referred to as interception store. Interception store (\( ICSt \)) for each time step is modelled as a function of the cumulative rainfall from the start of the storm using the exponential relationship proposed by Merriam (1973) as follows:

\[ ICSt = ICStM \times \left[ 1 - \exp\left(-\frac{Pcum}{ICStM}\right) \right] \]  \hspace{1cm} (4-8)

Where,

\( ICSt \) = Content of interception store (m)

\( ICStM \) = maximum content of the interception store for a given crop or vegetation cover (m) and

\( Pcum \) = Cumulative rain (m)
The values of $ICStM$ depend on the crop or plant species, the growth stage for annual crops and on the plant density. The amount of rainwater that goes to interception store is calculated in each time step using the following equation:

$$ToICSt = \frac{ICSt_{(t)} - ICSt_{(t-1)}}{T}$$

(4-9)

Where,

$ToICSt =$ Flux to interception store (m/T)

$ICSt_{(t)} = $ Content of interception store in current time step (m)

$ICSt_{(t-1)} = $ Content of interception store in preceding time step (m)

$T = $ Time step (s)

Throughfall refers to the amount of rain that falls on vegetation minus the portion that goes to interception store. Throughfall, in each time step is calculated as:

$$TF = Int - Cov * ToICSt * T$$

(4-10)

Where,

$TF = $ Throughfall (m/T)

$Int = $ rain falling on Vegetation (m/T)

$Cov = $ Vegetation Cover

$ToICSt = $ Flux to interception store (m/T)

$T = $ Time step (s)

The total amount of rain that makes it to the ground is the sum of direct rain and throughfall and is calculated in each time step using the following equation:

$$RainNet = TF + (Pr - Int)$$

(4-11)

Where,

$RainNet = $ net rain reaching the soil surface

$TF = $ throughfall (m/T)
Pr = rain (m/T)

\textit{Int} = rain falling on vegetation (m/T)

4.2.2.2. Infiltration

For modelling infiltration, the Green and Ampt infiltration modelling approach (Green and Ampt, 1911) was selected. It was considered suitable for this study firstly because it is based on the physical laws that govern the infiltration process. Additional to this the parameters used in the model are functions of soil structural properties that can be influenced by land management practices. This allowed the inclusion of information on the effects of certain management practices on soil through the soil properties incorporated in the model. Furthermore, for areas where data was not available, guide values derived taking into account the soil and land use/cover characteristics were used (Gerlach et al., 2003; Maidment, 1993; Smemoe et al., 2004),

The basic equation of the Green and Ampt model has the following form:

\[ f = \begin{cases} 
    K_s \left( 1 + \frac{\psi \theta}{F} \right) & \text{if, } f < i \\
    i & \text{if, } f \geq i
\end{cases} \quad (4-12) \]

Where,

\[ f \] = infiltration rate (m/Time step)
\[ i \] = rainfall intensity (m/Time step)
\[ K_s \] = Hydraulic Conductivity
\[ \psi \] = average capillary suction in the wetted zone (m)
\[ \theta \] = soil moisture deficit (dimensionless equal to porosity-soil moisture content)
\[ F \] = the depth of rainfall infiltrated into the soil since the beginning of rainfall (m)

For each time step, infiltration rate \( f \) equals the rainfall intensity \( i \) reaching the ground until ponding occurs. Once ponding occurs (i.e when the rate at which rain falls onto the ground in greater than the rate at which it infiltrates into the soil which is also determined by accumulated rainfall \( F \) ) infiltration rate is calculated using equation 4-12. The values for \( K_s \), \( \psi \) and \( \theta \) were derived from literature values (see chapter 5).
4.2.2.3. Surface Storage

For modelling surface storage, the approach proposed in EUROSEM (Morgan et al., 1998) was selected. Surface roughness determines the volume of water that can be held on the surface as surface storage. The soil surface roughness is expressed by a roughness measure ($RFR$) as described in the EUROSEM documentation and Users Guide (Morgan et al., 1998). The RFR measure is the ratio of the straight-line distance between two points on the ground ($X$) to the actual distance measured over all the micro topographic irregularities ($Y$). It is calculated as follows:

$$RFR = \frac{Y - X}{Y} \times 100$$ (4-13)

This mean height is converted to a surface storage depth, $D$ using the following regression equation proposed by Auerswald (1992):

$$D = \exp(-6.66 + 0.27 \times RFR)$$ (4-14)

In each time step, the amount of water that goes to the surface storage is computed using equation 4-14. After interception and infiltration losses have been satisfied, surface storage is filled until it reaches its maximum storage capacity ($D$). Only then does water become available for runoff.

4.2.2.4. Evapotranspiration

Evapotranspiration was not considered separately for this study because it was assumed that the evapotranspiration taking place during a rainfall event will be accounted for by the interception and surface storage loss.

4.2.2.5. Routing of Excess Water

Routing of excess precipitation or overland flow was done by the kinematic wave operator, which is one of the transport functions available in PCRaster. It is very suitable for routing excess water in hilly catchments after a rainfall event over the local drain direction network. It incorporates surface and channel characteristics in each grid cell and considers the time it takes for a certain volume of water to travel to its downstream cell. Not all the water available in one time step in each grid cell is transferred to the next cell in the next time step all at once. It is a continuity equation that considers a storage and flow relationship. Thus a certain delay factor is introduced as the water is routed over a catchment (Chow et al., 1988). The kinematic wave equation ensures
that the travel time of excess surface water remains within the extent of the model time step. (Burrough et al., 2005; Chow et al., 1988)

The direction of flow in PCRaster is computed by making use of the DEM. The map that is produced is referred to as the Local Drain Direction Map (LDD). The movement of water from one grid cell to its down stream cell following the LDD is determined by change of the volume of stream flow per length of the channel or grid cell and by the change of the cross sectional surface of flow during each time step. The following equation is used to define the kinematic wave model (Burrough et al., 2005; WIT, 2001):

\[
\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q
\]  

(4-15)

Where,

\( Q \) = the streamflow through channel or grid cell (m\(^3\)/s)

\( x \) = Channel length through cell (m)

\( A \) = Cross sectional surface of flow

\( t \) = timestep used in model (s)

\( q \) = inflow into the channel or grid cell (m\(^3\)/s)

The cross sectional surface of flow can further be described by the following equation:

\[
A = \alpha Q^\beta
\]  

(4-16)

Where,

\( \beta \) = a coefficient having a value of 0.6

\( \alpha \) = a coefficient that is calculated using Manning’s \( n \), slope and wetted perimeter. It is calculated as follows:

\[
\alpha = \left( \frac{n}{\sqrt{\text{slope}}} \right)^\beta \ast P^{\frac{2}{5}}
\]  

(4-17)

Where,

\( n \) = Manning’s roughness coefficient (dimensionless)
\(\text{slope} = \text{tangent of the slope angle of the channel or grid cell}\)

\(P = \text{wetted perimeter (m)}\)

It is assumed that the channels in each grid cell have a rectangular channel profile and the wetted perimeter is calculated based on this using the following equation:

\[P = B_w + 2H\]  \hspace{1cm} (4-18)

where,

\(B_w = \text{Bottom width of streambed (m)}\)

\(H = \text{height of water level in channel or grid cell (m)}\)

With change in time and change in rainfall input, the height of the water level changes in each time step. The new water level is used to calculate a new wetted perimeter. In turn, this is used to recalculate the cross sectional surface parameter that is used to calculate the inflow into the stream in the next time step. The script used in this approach is presented in appendix 3.

4.2.3. Model Parameterisation

Environmental models depend on one or several types of input parameters as is the case with the model used for this study. Two types of parameters are involved in this modelling approach:

1. physical parameters giving information on the physical structure of the catchment including parameters derived from the DEM and
2. process parameters including interception, infiltration and surface storage

that in combination influence the amount of runoff that is generated from the rainfall data used as input in the model (Kirkby et al., 1987).

To define the mathematical equations used to describe the processes, the parameters need to be quantified. This is known as model calibration. In some cases these parameters are measurable in the field and these field values can be used for calibration purposes (Kirkby et al., 1987). In this study, this was not possible for most of the parameters due to lack of time and resources. Most of the parameter values used were derived from literature values using information on the soil and land use/ cover characteristics of the watershed. To check the model results, discharge measurements were taken at a sub-catchment for a rainfall event.
4.3. Simple Analysis of soil properties in relation to land use/cover

To supplement the modelling approach conducted in this study, certain soil properties that play key roles in the generation of runoff were assessed in relation to different land use and cover types. These soil properties include: organic matter content, porosity, bulk density infiltration rate and hydraulic conductivity of the soil (Dunne and Leopold, 1978; Hillel, 1980; Miyazaki et al., 1993; Schwab et al., 1981). To assess if any relationship exists between these properties and land use/cover characteristics of the watershed, a descriptive statistical approach was employed where statistical applications such as arithmetic mean, standard deviation were computed and relationships were established using a regression analysis.

Owing to various reasons, data was not collected from all land use/cover classes occurring in the watershed thus limiting the magnitude of detail in the study. Three classes were selected to see the pattern of the soil properties on different land-use/cover types including areas classified as forest, grassland, and crop fields. These were selected because they were considered to be representative of the major land use/cover classes (agriculture, pasture and forest) in the watershed. The results of this analysis are presented in chapter 5.

4.4. Study Outline

In order to meet the objectives of this study, the overall work was divided into three phases; the pre-fieldwork phase, the fieldwork phase and the post fieldwork phase. The Pre-fieldwork phase of the study involved; selecting a suitable research approach, gathering and organisation of available data from previous studies, acquisition of remotely sensed imagery, identification of methods and preparation of materials for field data collection, production of a geo-pedological map, and finally identification of data gaps. The fieldwork phase of the study-involved collection of data on the soils of the watershed, infiltration tests, collection of soil samples for laboratory analysis, collection of training samples for land use and land cover mapping, discharge measurements from strategic locations during rainstorms, cross sectional measurements of the river Huai Nam Chun, river height and river velocity measurements and gathering of climatic data. The third and final phase of the study involved modelling surface runoff using the three approaches discussed in the first part of this chapter and the assessment of the relationship of soil properties and land use/cover characteristics which are discussed in chapters 5 and 6.
Figure 4-2: Flow chart showing the research approach of the study
4.4.1. Field work Preparation

In this stage of the study, methods on how to collect primary data required for the study were outlined. These included methods on soil data collection, discharge measurements, land use and land cover assessments. Materials required for the collection of data were assembled and a database for entry of the field data was constructed. An example of the database created is shown in Appendix 4. Alongside this, previously collected data in the area was gathered in order to avoid repetitions in primary data collection.

Photo interpretations were also done during this stage by means of a stereoscope using aerial photos of scale 1:25000 from the area. A suitable legend was developed based on the geo-pedological approach proposed by (Zinck, 1988). The scale of the aerial photographs allowed the identification of geo-pedological units at a level of landscape, relief type and landforms based on the lithology of the area. The units considered representative of the soil landscape relationship were delineated and were later on revised based on field observations. The interpretations were digitized to produce a segment preliminary geo-pedological map.

A Digital Elevation Model (DEM) was produced using the contour interpolation function in ILWIS on an existing digitised contour map of the watershed. The map had contour intervals of 20m in higher and 10m in flat areas.

4.4.2. Field Work

The fieldwork stage of the study involved collection of primary and secondary data and took place from mid September to mid October. Primary data collection included collection of soil data, discharge measurements, land use and land cover data. Secondary data collection on the other hand involved visits to various offices including the metrological station in Lom Sak for climatic data and the Land Development Department (LDD) in Bangkok for information on the main land use practices and land cover characteristics of the watershed.
4.4.2.1. Primary Data Collection

(a) Soil Data

Before the actual task of soil sampling commenced, several reconnaissance trips were made to inspect the study area and ensure that the mapping units delineated on the geo-pedological map coincided with the reality on the ground. The soil pattern of the area was studied in relation to the landscape and the main soil types identified. The relation of the soils in the area with the mapping units was assessed in the field and based on this, new landform units were added onto the map and some units were merged.

The landform units delineated were used to account for the soil landscape relationship study (Farshad, 2003). Soil observations were mainly made from mini pits and in some cases by auguring. Soil descriptions were conducted based on the FAO Guidelines for Soil Descriptions (FAO, 1990). The data that was collected at each site was carefully entered into the database constructed for this purpose by making use of a hand held computer. An example of the data collection is shown in appendix 4. The information collected on the soils of the area was used in determining the suction head, soil moisture deficit and hydraulic conductivity values from literature required by the semi physical approach, CN values in the curve number method and finally infiltration capacity in the index method. In each of the different landscapes, soil sampling was done from representative sites in the land form units. A selective stratified sampling approach was followed for the collection of soil data wherein representative samples were taken from each mapping units recognized in the area.

Data on the Physical Properties of the Soil

For investigations on selected soil properties in relation to the main land use/cover types of the watershed, a clustered stratified sampling technique was employed. Units which exhibited proximity in the occurrence of the main land use/cover types of interest, units that had similar soil textural classes (to ensure that the influence of textural differences would not affect the results) and units that were accessible were selected for sampling. The main land use/cover types recognised in the watershed were cornfields, forest areas and grasslands. Slope position was also taken into consideration in the sampling procedure. At each location, on site infiltration, tests were conducted and samples for laboratory analysis on soil particle distribution, soil bulk density, soil particle density, soil organic matter content and soil hydraulic conductivity were collected. A total of 24 samples were analysed for each of the properties.
Infiltration Measurements

A standardised approach was applied at each of the sampling sites according to the method described in (USDA, 1999). An infiltration ring having a diameter of 23 cm was used to conduct the infiltration tests. At each site, the ring was hammered into the soil until it was firmly in the ground. An earth bund was constructed around the infiltration ring. A plastic sheet was placed over the infiltration ring and 1 inch of water (equivalent to 666ml based on the volume of the ring) was measured out in a measuring cylinder and poured over the sheet. The plastic sheet was then gently pulled out leaving the water in the ring, as can be seen in figure 4-3 below. Water was also added in the earth bund around the ring to prevent lateral flow of water. The amount of time it takes for the water in the ring to infiltrate into the soil was noted. The same test was conducted again at the same location and in each case; the second test was used for comparison with results from other locations as described in (USDA, 1999) Figure 4-3 shows the procedures followed.

The infiltration rate was then computed as (Franzluebbers, 2002)

\[
\text{Infiltration rate (cmh}^{-1}) = \frac{Q}{A \times T}
\]  \hspace{1cm} (4-19)

Where,

\[Q = \text{The quantity of water (cm}^3\)\]
\[A = \text{The area of the infiltration ring (cm}^2\)\]
\[T = \text{The time recorded (hour)}\]

Soil Sampling for bulk density, particle density, and hydraulic conductivity measurement

Soil samples for bulk density estimation were taken by making use of a core sampler and core rings of known volume. The core rings were driven into the soil using the core sampler ensuring that the soil remains undisturbed. Once the core ring was completely submerged in the ground, a spade was used to dig up the soil around it and carefully remove the ring. The soil beyond the capacity of the ring was carefully removed by using a field knife (appendix 8). Caps on both sides of the soil rings were placed and the sampling ring appropriately labelled. The same samples collected for determining soil bulk density were used for determining soil particle density and hydraulic conductivity. Soil samples were also collected for laboratory analysis (appendix 9).
Figure 4-3: Infiltration data collection in the field

Figure 4-4: Cross sectional and discharge measurement location
(b) Event Based Rainfall Data

Rainfall data was also collected when discharge measurements were made. A bucket of known diameter was placed in an open area close to where the discharge measurements were made. During a period of 30min, the amount of rain falling was collected in the bucket. The volume of the water collected was then measured by making use of a graded measuring cylinder. Since the area of the bucket was known, that is the area through which the falling rain was collected, and the volume of the collected water was known, the height of the rain was calculated by employing equation 4-20:

\[ h = \frac{V}{\pi r^2} \]  

(4-20)

where \( r \) is the radius of the bucket, \( h \) is the height of the rain and \( V \) is the volume of the rain water that was collected. Figure 6-13 shows a reproduction of the rainfall data that was collected during the two rainfall events.

(c) Discharge Data

Discharge measurements were taken during a rainfall event from a sub-catchment. Simple methods were employed using a bucket of known volume and a stopwatch to make the measurements. At the outlet of the sub-catchment selected was an accessible drainage pipe as shown in Figure 4-4. The bucket of known volume was placed under the pipe so that all the water flowing out of the pipe falls into the bucket. The moment the bucket was in place, the stopwatch was started to record the amount of time it takes the bucket to fill up. This was done every 30 min.

An initial cross sectional measurement of the river Huai Nam Chun was done (as shown in figure 4-4), daily river height measurements were taken and the river velocity was also measured. Figure 6-35 shows the cross sectional area of the river.

(d) Land Use and Land Cover data

A land use/cover map produced by the Land Development Department (LDD) was used for this study. The map was produced through the interpretation of aerial photographs having a scale of 1:25000 and supported by field verifications. The information on the main land use/cover types was used to estimate interception storage, Manning’s coefficient and hydraulic conductivity from literature values required by the interception, kinematic wave and infiltration equations of the
semi empirical model. The land use/cover map was also used for the estimation of the CN values used in the SCS curve number method.

In order to assess the accuracy of the land use/cover map, randomly selected, ground truthing samples were collected during the fieldwork. In each case the main land use type of an area was recorded and its GPS coordinates entered. The accuracy assessment of the map is presented in chapter 5.

The ground cover data required by the interception model was used to estimate the proportion of the ground surface obscured by vegetation when viewed vertically from above. This value changes seasonally as it is dependant on the growth stage of a particular plant. For plants that do not grow beyond a height of 1m, a quadrant can be used to estimate this value. However, in cases where the vegetation growth exceeds 1m then the best way to determine this value is to make estimations based on observations (Morgan et al., 1998). As such, since much of the vegetation type in the study area at the time of the field work had a height greater than 1m (including the grass cover), ground cover data was collected through visual observations.

4.4.2.2. Secondary Data Collection

In addition to the data collected in the field, existing data on soil particle distribution in the study area was also gathered for those parts of the catchment where no samples were taken. This information was used in the production of the soil map (Chapter 5).
5. DATA PROCESSING AND ANALYSIS

5.1. Data Input

Primary data collected in the field was directly entered into the database constructed for this purpose, by means of a hand held computer (see appendix 4). The first task prior to data processing was to transfer this data into a GIS environment. This was done by importing the database as a table into ILWIS. Once transferred the database was linked to the geo-pedological and land use/cover maps. The database was then used in the generation of attribute maps required by the runoff models. Data collected for assessing the relationship between selected soil properties on different land use/cover types was organised in an excel spread sheet for further processing.

5.2. Selection of Spatial and Temporal Resolution

For the raster data used in the model, a spatial resolution of 30m by 30m was used. This resolution was selected because, the scale at which the input maps (land-use/cover, soil map and DEM) produced do not provide detail, thus increasing the spatial resolution would not have given more accurate results, only caused computational problems. The time step used for the empirical modelling approaches was 30 minutes because the rainfall data was collected in the field every 30 minutes. The time step used for the semi-physical model was however 60 seconds. This temporal resolution was selected in order to meet the “courant condition” for the kinematic wave equation employed in the model to route excess water. Satisfying the courant condition ensures that the time step of the model is less than the time for a wave to travel the distance of a pixel as per the following equation (Chow et al., 1988).

\[ \Delta t \leq \frac{\Delta x_i}{C_k} \]  

(5-1)

Where,

\( \Delta t \) = timestep

\( \Delta x_i \) = travel distance of wave

\( C_k \) = kinematic wave celerity, the flow rate at a point in time and space
If a large value is used for $\Delta t$, the courant condition will not be satisfied resulting in the accumulation of water in one pixel (Chow et al., 1988). The time for rainfall collection of 30 min would obviously not have satisfied this condition. Since representative hydrographs of the runoff response of the area were not available, a time step of 1 min was used for the kinematic wave equation assuming that the flow rate in the area does not exceed 0.5 m/s.

5.3. Generation of Attribute Maps

5.3.1. Location Attributes

PCRaster requires an initial clone map that defines the location attributes of the study area (spatial reference) and was produced as indicated in the figure below. This map is used in the production of all other maps for the study. It ensured that all maps used in all the models had the same size, geographical location and grid resolution. As mentioned earlier, a spatial resolution of 30 m was selected for this study implying that all the maps when rasterized for use in PCRaster, were rasterised with a pixel size of 30 m. This ensured that all input and output maps had the same resolution.

![Figure 5-1: Location attributes of the study area used to create clone map](image)

5.3.2. Processing Rainfall Data

For two events, rainfall data that was collected in the field at 30 minute intervals (as discussed in chapter 3). These were used as input data for the modelling. Since the rainfall data was collected at a single location at different times for each event, only the temporal variation of rainfall was considered and not the spatial variation. A station map was created in PCRaster having a unique identifying value. Using the spreadzone operator of PCRaster, a rainzone map was produced. The
operator assigns to each cell of the study area the unique cell value of the station map. The rainzone map was then linked to the raintimeseries data via the unique cell values. The raintimeseries data is an ASCII formatted time series file into which the collected information on the amount of rain for each time step was entered to account for the temporal variability of the rainfall data. The timeinput operation was then used in the iterative section of the dynamic model script (see appendix 1, 2 and 3) to generate the stack of rainfall maps showing the rainfall pattern for each time step using the raintimeseries data and the rainzone map. Appendix 6 shows the rainfall maps used for the semi physical modelling approach. The rainfall data collected over a period of 30 minutes was divided into rainfall amount per minute.

5.3.3. Geopedological Map

Following observations made on the soil-landscape relationship of the study area, and the preliminary interpretations made during the pre-field work of the study, the geo-pedological map was finalised. This map provided the basis for introducing the soil parameters into all the models.

5.3.4. Land Use/ Land Cover Map

A digital land use/cover map produced by the LDD was used for this study (figure 5-2). The accuracy of the map was assessed by making use of ground truth samples that were collected during the fieldwork. Using the location information of these samples, a point map was created in ILWIS. This map was rasterised and then crossed with the land use/cover map. This gave rise to a confusion matrix (table giving information on the overall accuracy of the land use/cover map. The overall accuracy of the map was 66% which was considered to be satisfactory for the purpose of this study (table 5-1). The map was imported into PCRaster in raster format and each class on the map was assigned a unique identifying number. These numbers were used to link the map with the database on the parameters required for the model.
Figure 5-2: Land use/cover map of the Nam Chun Watershed

Table 5-1 Confusion Matrix showing the overall accuracy of the land use/cover map

<table>
<thead>
<tr>
<th></th>
<th>CornField</th>
<th>DegradedForest</th>
<th>ForestArea</th>
<th>Grassland</th>
<th>MixedCrops</th>
<th>Orchard</th>
<th>Road</th>
<th>Stream</th>
<th>Urban</th>
<th>WaterBody</th>
<th>UNCLASS</th>
<th>ACCURACY</th>
</tr>
</thead>
<tbody>
<tr>
<td>CornField</td>
<td>16</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.54</td>
</tr>
<tr>
<td>DegradedForest</td>
<td>2</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.57</td>
</tr>
<tr>
<td>ForestArea</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.93</td>
</tr>
<tr>
<td>Grassland</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.59</td>
</tr>
<tr>
<td>MixedCrops</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.55</td>
</tr>
<tr>
<td>Orchard</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.67</td>
</tr>
<tr>
<td>Road</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Stream</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Urban</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WaterBody</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RELIABILITY</td>
<td>0.73</td>
<td>0.77</td>
<td>0.75</td>
<td>0.36</td>
<td>0.96</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
5.4. Model Implementation

5.4.1. Index Method

The soil map and the infiltration data collected in the field were used for this purpose. Infiltration values were assigned to each soil textural class based on the land use/cover type occurring in each class. The values were then divided by a certain arbitrary factor until the modelled runoff values coincided with the measured ones at the two locations where discharge measurements were taken in the watershed. The results are presented in section 6.3.1.

5.4.2. SCS Runoff Curve Number Method

In this case, the land use/cover and soil maps were used to determine the curve number parameter required by the model. Depending on textural information, soil groups A-D were assigned to the corresponding polygons of the soil map as shown in appendix 6. This map was then crossed with the land use/cover map. The cross map gave all possible combinations between land use/cover and the different soil groups. Based on this CN values were assigned to each combination. The values that were assigned are also given in appendix 6. The results of this method are presented in section 6.3.2.

5.4.3. Semi Physical Approach

5.4.3.1. Interception Parameter Generation

The parameters required for modelling interception (section 4.2.2.1) are the percentage canopy cover, Cov (dimensionless) and the maximum interception storage, ICStM (mm). The land use/cover map was used for this purpose. Each class was assigned the representative ICStM and Cov values as indicated in table 5-2 below. This information was entered into a PCRaster table format. It was linked to the land use/cover map via the unique identifying numbers and used to produce ICStM and Cov parameter maps. This was done in the initial section of the modelling script using the PCRaster operator lookupscalar (see appendix 3). Based on the unique numbers of each class on the map the operator assigns the corresponding ICStM or Cov value indicated on the table.

Values for Cov were estimated in the field. Values for ICStM were derived from the Eurosem documentation and User Guide (Morgan et al., 1998) based on the land use/cover.
### Table 5-2 Cov and ICStm values used in the model

<table>
<thead>
<tr>
<th>Land Use / Cover</th>
<th>COV (Estimated)</th>
<th>ICStM Values (Derived (mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Field</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>0.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Forest Area</td>
<td>0.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Grass Land</td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Orchard</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Road</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Stream</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Urban</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Water Body</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

#### 5.4.3.2. Infiltration Parameter Generation

The parameters required for running the infiltration model (see section 4.2.2.2) were the hydraulic conductivity \( (K_s) \), suction head \( (\psi) \) and moisture deficit \( (\theta) \) of the soil. Guide values obtained from literature were used for the parameterisation of the three parameters. The measured values of hydraulic conductivity showed a certain trend on different land use/cover classes of the watershed. The highest values were observed in soil samples collected from forested areas and the lowest from those collected in areas under cultivation (chapter 6). The average saturated hydraulic conductivity of soils from forest areas, were found to be \( 5 \times \) greater than the average hydraulic conductivity of those from corn fields. To account for this difference brought on due to different land use/cover practices, the low hydraulic conductivity values from the EROSEM Documentation and Users Guide (Morgan et al., 1998) were assigned to soils under agricultural practices and the high to forested areas based on the soil textural classes in which these land use/cover classes occur. The land use/cover map was crossed with the soil map in ILWIS to get a map with all the possible combinations between texture type and land use/cover class in the watershed. The table in appendix 7 shows the combinations that resulted and the values for hydraulic conductivity assigned to each combination. Suction head \( (\psi) \) and moisture deficit \( (\theta) \) parameterisation was done using guide values for the different soil textural classes occurring in the area based on the soil textural classes. The values used are shown in table 5-3:
Table 5-3: $\psi$ and $\theta$ values used in the model (Gerlach et al., 2003; Maidment, 1993)

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Wetting front suction $\psi$ (m)</th>
<th>Volumetric moisture deficit $\theta$ (dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Loam</td>
<td>0.208</td>
<td>0.15</td>
</tr>
<tr>
<td>Loam</td>
<td>0.089</td>
<td>0.25</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>0.11</td>
<td>0.25</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0.292</td>
<td>0.1</td>
</tr>
<tr>
<td>Silty Clay Loam</td>
<td>0.274</td>
<td>0.15</td>
</tr>
</tbody>
</table>

5.4.3.3. Surface storage parameter Generation

The maximum surface storage capacity of the soil depends on the surface roughness parameter ($RFR$). The values of roughness were derived from the EROSEM Documentation and Users Guide (Morgan et al., 1998) based on the type of tillage practices implemented in agricultural areas. For the remaining classes (non-agricultural), an arbitrary value of 2 was assigned. Very little micro-relief was observed in these areas. The values used for different land use/cover classes are shown in table 5-4 below.

Table 5-4: Calibrated $RFR$ values for each land use/cover types

<table>
<thead>
<tr>
<th>Land Use/cover</th>
<th>RFR (cm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Field</td>
<td>26</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>2</td>
</tr>
<tr>
<td>Forest Area</td>
<td>2</td>
</tr>
<tr>
<td>Grass Land</td>
<td>2</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>26</td>
</tr>
<tr>
<td>Orchard</td>
<td>26</td>
</tr>
<tr>
<td>Road</td>
<td>0</td>
</tr>
<tr>
<td>Stream</td>
<td>0</td>
</tr>
<tr>
<td>Urban</td>
<td>0</td>
</tr>
<tr>
<td>Water Body</td>
<td>0</td>
</tr>
</tbody>
</table>

5.4.3.4. Surface Water Routing Parameter Generation

As discussed in section 4.2.2.5, the kinematic wave model was used to route the excess water. Parameters required for using the model in PCRaster include:
• alpha and beta coefficients
• the local drain direction and
• the distance to down stream cell.

Alpha was computed using equation 4-17. The variables required for computing alpha include

• Manning’s roughness coefficient,
• the slope for each cell, and
• the bottom width of all channels

1) Manning’s $n$ was retrieved from literature based on the land use/cover type found in the area. Table 5-5 below shows the values used for each class.

2) The slope was computed using the DEM and the \textit{slope} operator in PCRaster. Only one value was used for the bottom width of all channels for the whole catchment and it was assigned the cell length of 30 meters.

3) The distance to downstream variable was computed by using the local drain direction map, cell length and the PCRaster operator \textit{downstreamdist}. The local drain direction map was produced using the DEM and the \textit{lddcreate} operator in Pcraster. It was then repaired to ensure it did not contain local pits using the PCRaster operator \textit{lddrepair}.

\textbf{Table 5-5: Guide values used for Manning's N for different land use/cover types (Morgan, 1995)}

<table>
<thead>
<tr>
<th>Land Use/ cover</th>
<th>Manning’s N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Field</td>
<td>0.08</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>0.3</td>
</tr>
<tr>
<td>Forest Area</td>
<td>0.3</td>
</tr>
<tr>
<td>Grass Land</td>
<td>0.3</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>0.08</td>
</tr>
<tr>
<td>Orchard</td>
<td>0.08</td>
</tr>
<tr>
<td>Road</td>
<td>0.011</td>
</tr>
<tr>
<td>Stream</td>
<td>0.011</td>
</tr>
<tr>
<td>Urban</td>
<td>0.011</td>
</tr>
<tr>
<td>Water Body</td>
<td>0.011</td>
</tr>
</tbody>
</table>
5.5. Developing the Model Scripts for Running the Model

The dynamic modelling language of PCRaster involves the use of a script. The script consists of different sections; the binding, area map, timer, initial and dynamic sections that are required to build an iterative dynamic model. Each section has a particular function in the model. Detailed explanation on each section of the script is provided on the PCRaster version 2 manual (Burrough et al., 2005). Examples of the scripts used for modelling runoff in this study are provided in appendix (1, 2 and 3). The area map section of the script was used to enter the location attribute information of the study area in the form of the clone map as previously discussed (section 5.3.1). It ensured that all the output maps had the same location attributes. The time step of the model given by the timer section of the script was defined for a period 180 minutes with a time slice of 30 minutes in the case of the empirical models and 1 minute in the case of the semi physical modelling approach. The initial section was used to generate the initial input variables for running the dynamic section at time step 1. Some of the variables in the initial section were defined directly and other values were generated from the database (as explained in previous sections) with the use of PCRaster operations. When a PCRaster script is run, the initial section is only used once at the start of the model and the values that result are used as input in the dynamic section of the script (Burrough et al., 2005).

The dynamic section of the script consists of PCRaster operations that are performed at each time step of the model run. This section is the iterative section and it is responsible for providing stacks of output maps that vary spatially and temporally depending on the parameters that are entered. When the model is run, in the first time step, the operations in the dynamic section are performed from top to bottom, line by line making use of the input data provided by the initial section. At the second time step, values obtained in the previous time step are used as input and the iteration continues in the same manner until the last time step. In the case of the semi physical approach for example, in this iterative approach, water that does not become runoff is stored and it accumulates. Thus in the next time step the amount of water that can be lost depends on the amount of water already accumulated in the preceding time step (Burrough et al., 2005).

Once all the data required by all three models had been organised in a manner suitable for use in PCRaster (as discussed above), the model was run. Further model calibration was conducted using measured discharge data from two different locations for the semi physical modelling approach.
6. RESULTS AND DISCUSSION

6.1. Soil Mapping

The geopedological map was generated based on the interpretation of aerial photographs at a scale of 1:25,000 following the geo-pedological approach proposed by (Zinck, 1988). Four main landscapes were identified in the area. These include 1) a narrow valley cutting across the watershed, 2) a high mountain area that includes very high steep ridges and lower dissected slope complexes, 3) a low mountain area 4) and finally bordering the north-western part of the watershed a high plateau. The scale of the aerial photos used for interpretation and the soil-landscape relationship established during the field work period allowed for a subdivision of the landscape units based on relief type and further division based on the slope. Figure 6-2 shows the geo-pedological map and table 6-1 shows its legend. Description of the landscapes follows:

The plateau Landscape

The plateau landscape (figure 6-1) accounts for about 16% of the total area of the watershed. It forms the north western border of the study area and includes the highest point in the watershed with an elevation of 1509 m asl. The main underlying lithology in the area is sandstone. Only two main relief types were identified which includes: cuesta/mesa complex and escarpment. The cuesta could not be further differentiated because of the scale of the aerial photographs. The escarpment however had three main landform units including a steep scarp, talus and an undulating slope complex area. The main soils in the area were Typic Haplustals. The soils in this landscape were found to be heavy clay soils and were classified in the silty clay or silty clay loam soil textural class. The soil structure following the FAO (1990) guidelines for soil description mainly belonged to the sub-angular blocky group and generally ranged in size from fine to medium. The pH in this area was found to be slightly acidic. Much of the area was forested but some of the scarp area was also found to be covered by grass.

The Mountain Landscapes

The high and low mountain landscape were found to be dominating in the area and accounted for about 80% of the total area of the watershed. The underlying lithology of these landscapes was mainly andesitic tuff, and andesitic and rhiolitic tuff. Two main relief types were observed in the high mountain landscape including ridges and erosional glacis. The low mountains consisted of
ridges of different elevations. The scale of the aerial photos allowed the identification of the following landform units in most of the relief types; a distinct narrow summit area, a mid-slope area that included the back slope and a foot slope area. Because of their slope position, the summit landforms generally had shallow soils (with an average depth of about 22 cm). This effect was found to be more pronounced in summit areas used for the cultivation of corn. In the other landform units the soils ranged from deep to very deep. The main soils were Ultic Haplustalfs, Lithic Haplustolls, Lithic Haplustalfs, Typic Paleustalfs, Ultic Haplustalts and Typic Dystrustepts. Laboratory analysis revealed that the soils in the area are characterised by high clay content and were mainly classified in the clay loam textural class. The soil structure was largely found to be sub-angular blocky with size varying from very fine to medium as per the guidelines for soil description (FAO, 1990). The soils were found to be slightly acidic like in the plateau landscape with a pH of about 5. Figure 6-1 shows a part of the landscape of the area.

Figure 6-1: Landscape of the study area

The Valley Landscape

The area delineated as the valley landscape was very narrow and accounted for only 2% of the total area. It mainly consisted of the Huai Nam Chun River and a narrow flood plain that could not be differentiated as a separate unit from the aerial photos. As a result, it was not possible to distinguish any landform units in this landscape.
The landform units delineated were used to account for the soil landscape relationship study (Farshad, 2003). The data collected at each point location in the landform units was considered to be representative for the entire mapping unit. Data on soils collected in the field were linked to this map via the legend of the map giving rise to an attribute table from which input maps required by the model were developed.

Figure 6-2: Geopedological map of Nam Chun Watershed
<table>
<thead>
<tr>
<th>Landscape</th>
<th>Relief</th>
<th>Lithology</th>
<th>Landform</th>
<th>Soils</th>
<th>Map unit</th>
<th>Area (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plateau (P)</strong></td>
<td>Cuesta (P1)</td>
<td>Sand Stone (P11)</td>
<td>Undifferentiated</td>
<td>(P111)</td>
<td></td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Escarpment (P2)</td>
<td>Sand Stone (P21)</td>
<td>Scarp</td>
<td>Typic Haplustalts</td>
<td>(P211)</td>
<td>730</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Talus</td>
<td></td>
<td>(P212)</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Undulating Slope Complex</td>
<td></td>
<td>(P213)</td>
<td>100</td>
</tr>
<tr>
<td><strong>High Mountain (HM)</strong></td>
<td>Ridge (HM1)</td>
<td>Andesite (HM11)</td>
<td>Summit</td>
<td></td>
<td>(HM111)</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slope Complex</td>
<td>Ul tic Haplustalfs</td>
<td>(HM112)</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>Ridge (HM2)</td>
<td>Andesitic Tuff (HM21)</td>
<td>Summit</td>
<td>Lithic Haplustolls</td>
<td>(HM211)</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Slope</td>
<td>Ultic Haplustalfs</td>
<td>(HM212)</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Foot Slope</td>
<td>Ultic Haplustalfs</td>
<td>(HM213)</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>Erosional Glacis (HM3)</td>
<td>Andesitic and Rhiolitic Tuff (HM31)</td>
<td>Summit</td>
<td>Lithic Haplustalfs</td>
<td>(HM311)</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Slope</td>
<td>Typic Paleustalfs</td>
<td>(HM312)</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Foot Slope</td>
<td>Lithic Haplustalfs</td>
<td>(HM313)</td>
<td>68</td>
</tr>
<tr>
<td><strong>Low Mountain (LM)</strong></td>
<td>High Ridges (LM2)</td>
<td>Andesitic Tuff (LM21)</td>
<td>Summit</td>
<td>Ul tic Haplustalts</td>
<td>(LM211)</td>
<td>271</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Slope</td>
<td>Ul tic Haplustalts</td>
<td>(LM212)</td>
<td>1,968</td>
</tr>
<tr>
<td></td>
<td>Moderately High Ridges (LM1)</td>
<td>Andesitic and Rhiolitic Tuff (LM11)</td>
<td>Summit</td>
<td>Typic Haplustalts</td>
<td>(LM111)</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Slope</td>
<td>Ul tic Haplustalts</td>
<td>(LM112)</td>
<td>286</td>
</tr>
<tr>
<td></td>
<td>Low Ridges (LM3)</td>
<td>Andesitic and Rhiolitic Tuff (LM31)</td>
<td>Summit</td>
<td>Typic Dystrustepts</td>
<td>(LM311)</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle Slope</td>
<td>Ul tic Haplustalts</td>
<td>(LM312)</td>
<td>308</td>
</tr>
<tr>
<td><strong>Valley (V)</strong></td>
<td>Alluvial Colluvial</td>
<td>Side slope/bottom complex</td>
<td>Fluvents and Haplumbrepts</td>
<td>(V111)</td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>
6.2. Relationship of soil properties with different land use/cover types

Infiltration has a reducing effect on the volume of runoff that is generated in a catchment (Schwab et al., 1981). Certain soil properties play an important role in determining the amount of water that can infiltrate into the soil for a given rainfall event. These properties can serve as indicators on the effects of different land use/cover types on the soils capability to take in water in the long run influencing the amount of water that will be available for runoff. Selected soil properties were therefore assessed in relation to major land use/cover types in the watershed and in relation to one another. The soil properties considered for the land use/cover-soil relationship study include; soil organic matter content, porosity, bulk density and saturated hydraulic conductivity. In addition to these, on site infiltration tests were also conducted to assess if any relationship with the different soil properties could be observed (Section 4.4.2.1). Laboratory analysis results of soils are presented in appendix 10.

6.2.1. Variability of soil properties on different land use/cover types.

The box plots in figure 6-3 show the variation of soil properties on different land use/cover types. Hydraulic conductivity and infiltration rate appear to be high in forested areas and much lower in cornfields. Soil porosity appears to exhibit the same trend as well. On the other hand, bulk density showed highest values in cornfields and lowest in forest areas. The cultivation of maize in the area is done mainly by means of mechanised ploughing (Shrestha, 2003). This brings about compaction which increases soil bulk density (Hillel, 1980). Thus the high bulk density in areas of corn cultivation could be attributed to land use/cover practices. Moreover, high variation of bulk density was observed on grassland areas. This could be attributed to the fact that some grassland areas in the watershed were in the past used for maize cultivation. Organic matter content seems to show the most variation on cornfields and this could be due to the influence of management practices.
Figure 6-3: Variation of soil properties in different land use/cover types.
Average infiltration rate measured in the field was found to be highest in the measurements taken from forest areas and lowest in areas of corn cultivation. Hydraulic conductivity values showed considerable variation on the different land use/cover types as well. The highest average hydraulic conductivity (61.93 cm/hr) was measured in soils from forest areas and the lowest (11.66 cm/hr) in corn fields. Average hydraulic conductivity of soils under grassland was 27.52 cm/hr. The figure below shows the variation of these properties on different land use/cover types and how they relate to one another.

![Figure 6-4: Average Infiltration rate and hydraulic conductivity in different land use/cover types](image)

The low infiltration rate and hydraulic conductivity on corn fields could be an indication that the soils in these areas are degraded as a result of human interventions. The use of heavy machinery for ploughing the land could be responsible for making the soil compact and negatively influencing hydraulic conductivity leading to reduced infiltration rates. Grassland areas also showed relatively lower values probably because most of these areas were previously used for agricultural purposes. The observations that were made in these areas were not entirely unforeseen and coincide with the findings of (Kunda, 2004). Forest soils showed higher values of hydraulic conductivity and infiltration rate. The reason for this could be that the soils in these areas are undisturbed and this has allowed them to maintain good soil structure and high porosity.

Analysis of soil porosity on different land use/cover types also showed a similar trend (figure 6-5) with the highest average porosity (56%) in forested areas and the lowest (50%) in corn fields. Bulk density, which is inversely related to soil porosity (figure 6-9), showed the highest values in corn fields with an average of 1.21 gm/cm$^3$ and the lowest in forested areas with an average value of 1.04 gm/cm$^3$ (figure 6-6). The increase in bulk density and reduction in porosity on corn fields
could be an indication that the soils in these areas are more compacted than the soil in forest or grassland areas due to the use of heavy machinery. Since porosity and infiltration rate are positively related soil properties (refer to section 6.2.2), a reduction in soil porosity results in a reduction in infiltration rate. Reduced infiltration rates, bring about a reduction in the amount of rainwater that can infiltrate into the soil. This implies that more water will be available at the surface after a rainstorm resulting in increased rates of runoff. An increase in the rate of runoff increases the capability of running water to detach and carry soil particles bringing about further soil degradation problems.

![Figure 6-5: Average soil porosity in different land use / cover types](image)

![Figure 6-6: Average soil bulk density in different land use / cover types](image)

The results of the organic matter content in relation to land use/cover, was observed to be similar to the pattern shown by bulk density (figure 6-7). It was highest on corn fields (2.1%) and gave a similar, lower value in the grassland and forest areas (1.6%). This was not unexpected and can be explained by management implementations such as the use of organic fertilisers in these areas.
Figure 6-7: Average soil organic matter content in different land use/cover types

A student’s t-test was conducted for all the soil properties for each possible land use/cover combination. This revealed a statistically significant difference (P<0.05), of soil properties on the different land use/cover types with the exception of organic matter content, bulk density and porosity on grasslands and cornfields.

6.2.2. Relationship between soil properties

The relationship between the different soil properties was assessed using a regression analysis. The level of the relationship between all cases assessed, was found to be statistically significant (P<0.05). Figure 6-8 shows the relationship between hydraulic conductivity and infiltration rate. The statistical significance of the relationship revealed a positive linear correlation with \( r=0.798 \) and \( R^2=0.638 \). 64% of the variation in infiltration rate is therefore explained by hydraulic conductivity in line with the physical nature of soil and its properties (Hillel, 1980). Land use/cover changes that bring about a reduction in soil hydraulic conductivity therefore also result in reduced infiltration rates. This observation further confirms the findings in section 6.2.1.
The relationship between hydraulic conductivity and infiltration rate

Soil bulk density and porosity showed a strong negative correlation with 
\[ r = -0.933 \] and \[ R^2 = 0.869 \] as indicated in figure 6-9. The two soil properties were found to be inversely associated. As bulk density of the soil increases as a result of management practices in the watershed, the porosity of the soil reduces. A reduction in soil porosity subsequently brings about a decline in hydraulic conductivity and infiltration rate of the soil as indicated in figures 6-10 and 6-11 respectively.

The relationship between soil porosity and hydraulic conductivity was significant (P<0.05). However, the results show a weak positive relationship (\( r = 0.56 \) and \( R^2 = 0.314 \)) between the two properties. The results obtained could have shown a stronger correlation with more number of observations. Figure 6-11 shows a positive correlation between infiltration and porosity (\( r = 0.653 \) and \( R^2 = 0.426 \)) as well. High porosity therefore promotes the passage of water into the soil inline with soil hydraulic properties. Porous soils accordingly facilitate infiltration of rain water into the soil reducing the amount of water that could be available for surface runoff in the long run.
The student t-test analysis was conducted to find out whether the soil properties showed significant difference with respect to slope position. Except for organic matter content and hydraulic conductivity of samples taken from corn fields, the remaining did not exhibit significant differences (P>0.05). The average saturated hydraulic conductivity of soils under maize cultivation analysed from samples taken in middle slope areas, had higher values with an average of 17 cm/hr. Samples taken from the summit areas on the other hand showed very low values with an average of 6.7 cm/hr. This could be attributed to higher water erosion taking place in these areas owing to their slope position. The cultivation of maize in these areas further promotes the degradation process of the already susceptible soils through the use of heavy machinery. This leads to a significant decline in the hydraulic conductivity of the soils in these areas. Moreover, average infiltration rate was also seen to be lowest in measurements taken from cornfields in summit areas which further support the findings. Areas of corn cultivation could therefore be resulting in increased surface runoff generation due to management practices which have reduced the infiltration capacity of the soils in these areas. As such, these areas could be target locations.
for further investigations in order to implement measures to improve the quality of the soils in these areas.

6.3. Modelling Runoff Using Empirical Approach

6.3.1. Estimation using the Index method

A simple script with very few PCRaster operators was employed to simulate runoff in this case (appendix 1). The infiltration values introduced via the soil map as described in section 5.4.1 had no scientific basis making the approach entirely empirical based. This approach has some advantages because of its simplicity, its minimal data requirements and its capability of providing reasonable estimates of runoff rates at different locations in a catchment. Some output maps showing the results of this modelling approach are presented in figure 6-12. The rainfall data used for this method is presented in figure 6-13.

Figure 6-12: Results of the Index Method, time steps showing a period of 30min
6.3.2. Estimation with the Curve Number Method

The second approach involved the use of the curve number method of estimating excess precipitation in PCRaster. As described in section 4.2.1, it considers an initial abstraction that incorporates all losses before surface runoff occurs. This initial abstraction was determined based on the soil and land use/cover characteristics of the watershed as discussed in section 5.4.2, through the use of tabulated curve number values (USDA, 1986) which were corrected using equation 4-5 to account for antecedent soil moisture conditions (appendix 6). In addition to this, the approach also considers the retention of water in the watershed over a period of a rainfall event. This accounts for an increase in the amount of water available for runoff due to the accumulation of water that is initially abstracted. These attributes allowed for the simulation of the runoff process in the watershed as it could occur on the ground for each time step. The resulting maps with information on the amount of water available for surface runoff in each cell for each time step of 30 minutes are presented in figure 6-14.
The rainfall data used for the simulation are shown in figure 6-13. When comparing the maps that were obtained to the land use/cover map (figure 5-2), it can be seen that the areas used for agricultural purposes, to the west of the study area, show the highest levels of available surface water. In the most part, the areas classified as forest show lower values except for those found in the north-western part of the study area. The reason for this could be that the soils in these areas were found to be heavy clay soils and were placed in group D of the hydrologic soil groups as defined by the U.S Soil Conservation Service (USDA, 1986). Group D soils are considered as having relatively low infiltration rates and water conductivity and were assigned high CN values in accordance to this. The degraded forest and grass land areas showed moderate levels of excess precipitation.
6.4. **Modelling runoff using the Semi-physical approach**

The third and final approach involved the use of several equations to model the different components of surface runoff generation and route the excess water as described in section 4.2.2. Unlike the previous two approaches, this approach was mainly based on the physical nature of the components involved. The spatial and temporal distribution of surface runoff as predicted by the model (base simulation) is presented in figure 6-15. Figures 6-16 to 6-18 show the simulation of the loss factors (figure 4-1): total cumulative interception, total cumulative infiltration and average surface storage respectively.

The rainfall data presented in figure 6-13 shows the highest rainfall was observed in the first 30 minutes of the rainfall event. However, no runoff was estimated in the first few time steps (1-10min) as shown in time step 1 in figure 6-15. This was because much of the rain water contributed to loss factors in the model for the first few minutes into the rainfall event. Therefore, no runoff occurred until the initial losses were satisfied. Half an hour into the event, surface runoff was observed throughout the catchment occurring, at different magnitudes in different areas. At this time, the losses had been satisfied and the excess precipitation was routed over the catchment as surface runoff. In time step 60, the volume of surface runoff had gradually declined because the rainfall had significantly reduced (figure 6-15). Although the amount of rainfall between time steps 60 and 90 was very small (0.008mm/min), runoff continued to occur because the model takes into account the accumulation of rainwater from preceding time steps in the watershed and also because of the delay factor introduced by the kinematic wave equation. The effect of the latter continued particularly along the main drainage lines from time steps 90 to 180 although rainfall had already stopped.
Figure 6-15: Spatial and temporal distribution of surface runoff (time step =1min)
Figure 6-16: Spatial distribution of cumulative interception loss

Figure 6-17: Spatial distribution of cumulative infiltration loss

Figure 6-18: Spatial distribution of average surface storage
Notable surface runoff took place between time steps 30 to 90. As such, the model results were evaluated with respect to different land use/cover classes in the watershed during this period. The average surface runoff rate predicted by the model during this period ranged from a minimum of 0.00 to a maximum of 0.41 m³/s. The average surface runoff rate estimated for the whole area was $1.98 \times 10^{-4}$ m³/s. The weighted average surface runoff rates estimated per pixel for different land use/cover types are given in Table 6-2. The highest volume of surface runoff was predicted for orchard plantations with an average value of $6.88 \times 10^{-4}$ m³/s and the lowest was predicted for forest areas with an average of $0.61 \times 10^{-4}$ m³/s. On the whole, agricultural areas showed approximately $2 \times$ higher values of surface runoff rates with an average of $4.78 \times 10^{-4}$ m³/s than the non-agricultural areas having an average surface runoff value of $2.04 \times 10^{-4}$ m³/s.

Table 6-2: Predicted surface runoff for different land use/cover types

<table>
<thead>
<tr>
<th>Land use/ cover</th>
<th>Average surface runoff (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Field</td>
<td>$3.32 \times 10^{-4}$</td>
</tr>
<tr>
<td>Orchard</td>
<td>$6.88 \times 10^{-4}$</td>
</tr>
<tr>
<td>Mixed Crop</td>
<td>$4.16 \times 10^{-4}$</td>
</tr>
<tr>
<td>Grassland</td>
<td>$3.18 \times 10^{-4}$</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>$2.34 \times 10^{-4}$</td>
</tr>
<tr>
<td>Forest</td>
<td>$0.61 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The relatively lower runoff level observed in areas of corn fields can be attributed to the combination of high surface cover and surface roughness values that were assigned to the interception and surface storage components of the model respectively. This implies that very little water becomes available for runoff by the time both interception and surface storage have been satisfied irrespective of the low infiltration rates in these areas. However, this occurs only when the corn is mature and the effects of tillage on surface storage have not been worn down by rain drops which was the case during the field work period of this study. The situation would be completely different when the corn is harvested. Interception store becomes minimal and surface storage diminishes as a result of direct impact of rainfall on the bare soil. The average surface runoff for the same rainfall event in corn field areas, with these values altered increases by up to $25 \times$ more than the previous value. This raises the average surface runoff value for agricultural areas to $3.088 \times 10^{-3}$ m³/s making it $15 \times$ larger than the average surface runoff rate from non-agricultural areas. This significant difference in surface runoff rates emphasizes the need for the
development of conservation strategies to protect the soils in agricultural areas in the Nam Chun watershed from further degradation.

As per the (FAO, 1990) slope categorisation, the area was divided into four slope classes to assess the effects of slope gradient on the predicted surface runoff rates. The classes include gentle slopes (0-5%), moderate slopes (5-15%), steep slopes (15-30%) and very steep slope (>30%). The results are presented in figure 6-19.

![Figure 6-19: Figure showing the predicted runoff rates on different slope classes](image)

The figure shows that the gentle slopes have higher discharge than the steeper slopes. The reason for this could be that a large portion of the area classified as very steep slope belongs to the forest, degraded forest or grassland land use/cover classes. These areas compared to the areas of agriculture practice have lower runoff rates. The use of gentler slopes for agriculture practices is therefore a good management strategy being employed in the catchment which has lower impacts on the rate of runoff.

### 6.4.1. Model calibration and Water balance

The results of the model were compared with measured discharge data measured from a sub-catchment in the field (section 4.4.2.1). The simulated and measured hydrographs are presented in figure 6-20.
Figure 6-20: Simulated and observed hydrographs

As can be seen from the figure, the model slightly over predicted the volume of peak surface runoff generated at the discharge measurement location. It did not also manage to simulate the time to peak runoff accurately. The difference between the observed and the modelled hydrographs can be attributed to a number of factors.

1. The observed discharge measurements were probably erroneous because the measurements were done using crude procedures (section 4.4.2.1).
2. The values used for most of the parameters required by the model could also have been another source of error as it was done using literature values based on soil and land use/cover characteristics of the catchment and were not measured onsite in the field.

Nevertheless, the model was successful in predicting the shape of the observed hydrograph. It did also manage to simulate the gradual decline of discharge even though rainfall had stopped after time step 90.

A water balance was also computed for each time step as shown in figure 6-21. It was done to ensure that no errors occurred during the simulation. All the rainwater falling into the catchment was either lost to interception, infiltration, surface storage or contributed to surface runoff. The water balance simulation was computed for each time step by subtracting the sum of all the losses and surface runoff from the total rainfall.
Figure 6-21: Water Balance

The figure shows that the water balance does not come to zero. But the values obtained were very close to zero in most of the area. This implies that the model needs to be further assessed in order to determine where the extra water is coming from or going to.

6.5. Sensitivity Assessment

The need for a sensitivity assessment when modelling complex environmental process such as runoff is apparent. The importance becomes even more pronounced in the present study since values for most of the parameters used were retrieved from literature. A sensitivity analysis helps in identifying which parameters have the most effect on the models prediction when altered by a certain magnitude. This will provide crucial information for future studies in the area as to which of the parameters should be given more emphasis and measured as accurately as possible in the filed to improve the quality of the model output. The sensitivity assessment was conducted for the following parameters; saturated hydraulic conductivity ($K_s$), roughness measure ($RFR$) and interception storage. The initial values of these parameters were increased by percentages of 5, 25 and 50. The model was re-run using the altered values one at a time while values of the other parameters remained unchanged. These values were selected to see how the model responds to
slight, moderate and major changes on the values of the selected parameters. (N.B. Base simulation refers to the first simulation that was conducted and calibrated)

6.5.1. Sensitivity of Model to Saturated Hydraulic Conductivity

The importance of saturated hydraulic conductivity in modelling surface runoff, with respect to the specific objectives at hand has already been discussed. Saturated hydraulic conductivity is an important parameter because of its integral role in the infiltration component of the model. As such it was considered necessary to assess the sensitivity of the model to increase of different magnitudes on the values used for this parameter. The changes observed on the runoff rate from different land use/cover classes is indicated in the figure 6-22.

![Figure 6-22: Runoff rate with increase of different magnitudes on hydraulic conductivity](image)

The results show that the model predictions are much more sensitive to shifts in low hydraulic conductivity values than to shifts in higher hydraulic conductivity values. The average percentage change in runoff prediction in agricultural areas for a 5%, 25% and 50% increase in hydraulic conductivity was found to be 17%, 63% and 83% respectively. Whereas in areas of non-agriculture practice, an average percentage change on the predicted runoff of 8%, 47% and 64% respectively was observed for the same shift (table 6-3). The overall trend observed however, indicates that the prediction of the model changes when values of hydraulic conductivity are slightly altered. The model is therefore sensitive to hydraulic conductivity and it is a parameter that should be measured as accurately as possible in the field to improve on the model predictions.
Table 6-3: Models sensitivity to Hydraulic conductivity

<table>
<thead>
<tr>
<th>Land use / cover</th>
<th>5% Change in ( K_s )</th>
<th>25% change in ( K_s )</th>
<th>50% change in ( K_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>13</td>
<td>42</td>
<td>59</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>2</td>
<td>54</td>
<td>67</td>
</tr>
<tr>
<td>Grassland</td>
<td>11</td>
<td>47</td>
<td>68</td>
</tr>
<tr>
<td>Corn Field</td>
<td>19</td>
<td>67</td>
<td>88</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>13</td>
<td>54</td>
<td>74</td>
</tr>
<tr>
<td>Orchard</td>
<td>20</td>
<td>69</td>
<td>87</td>
</tr>
</tbody>
</table>

The observations made on areas of agriculture practice apart from indicating the sensitivity of the model, could also implicate that slight changes to increase hydraulic conductivity of the soil could significantly reduce the runoff rates in these areas. The hydrographs in figure 6-23 show the discharge pattern in the river Huai Nam Chun at the outlet of the catchment of the base simulation results and the results of the sensitivity assessments.

![Figure 6-23: Hydrographs of base simulation and sensitivity assessment of hydraulic conductivity](image)

It can be seen from the hydrograph that a raise in hydraulic conductivity does not bring about a significant reduction on the peak runoff because of the very high rainfall at the start of the simulation (figure 6-13). But, it does reduce the river discharge after the peak. The average percentage change from the base simulation was found to be 6%, 20% and 30% with 5, 25 and 50% increments respectively in the saturated hydraulic conductivity values used. This could be an indication that increased hydraulic conductivity values increase the amount of rainwater that infiltrates into the soil. With increased infiltration rates throughout the catchment, the portion of rainwater that contributes to surface runoff during a rainstorm is reduced which influences the
amount of water reaching the outlet. Higher infiltration rate thus has a reducing effect on the amount of surface runoff that is generated. Land use/cover types that negatively influence soil properties related to the infiltration of rain water into the soil therefore also affect the amount of surface runoff that is generated. This shows that areas of agricultural practice could be a cause of concern in the watershed that require the implementation of strategies to protect the physical quality of the soils in order to reduce the overall surface runoff taking place in the catchment.

6.5.2. Sensitivity of Model to Roughness Measure

Roughness measure was the only parameter required by the surface storage component of the model. It accounts for surface storage losses in the model and drastically changes in areas of agriculture depending on the season due to the combined effects of tillage practices and rainfall. The effects of increasing roughness measure on the prediction of the model are shown in figure 6-24.

Figure 6-24: Changes in runoff rate with an increase of different magnitudes to roughness measure

Slight increase in roughness values result in greater percentage change in areas of agriculture with a 5% shift ensuing a 71% change and the same shift resulting in an 8% change in areas of non-agriculture. This indicates that the prediction of surface runoff is largely controlled by higher surface roughness values. Smaller roughness measure values observed in non-agricultural land use/cover types do not cause a significant change when slightly increased. Table 6-4 shows the percentage change in average surface runoff observed on different land use/cover classes.
Table 6-4: Models Sensitivity to Roughness Measure

<table>
<thead>
<tr>
<th>Land use / cover</th>
<th>Change in runoff rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5% Change in RFR</td>
</tr>
<tr>
<td>Forest</td>
<td>18</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>2</td>
</tr>
<tr>
<td>Grassland</td>
<td>6</td>
</tr>
<tr>
<td>Corn Field</td>
<td>75</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>61</td>
</tr>
<tr>
<td>Orchard</td>
<td>77</td>
</tr>
</tbody>
</table>

The roughness measure is an important parameter in that it instigates significant changes on the runoff rate in the catchment with slight changes and should therefore be measured accurately to enhance the model predictions. Its accurate estimation becomes particularly important in areas of agriculture practice where higher roughness measures are used to account for the influence of tillage practices. The hydrographs in figure 6-25 show the discharge pattern of the river Huai Nam Chun as predicted by the base simulation and the sensitivity assessments done on surface runoff. The average percentage changes were found to be 30, 45 and 60% with 5, 25 and 50% changes respectively on roughness measure. It shows that an increase in roughness reduces the peak as well as the overall discharge pattern of the river. In this modelling approach, the water that goes to surface storage does not accumulate. If in the first time step rain water contributes to a certain maximum surface storage, then in the next time step, surface storage is empty and ready to fill up again. This could be a reason why it has a significant reducing effect on the rate of runoff when slightly altered.

Figure 6-25: Hydrographs of base simulation and roughness measure sensitivity assessment
6.5.3. Sensitivity of Model to Maximum interception storage

The interception storage parameter is an important parameter in that together with the vegetation cover parameter of the interception equation, determines how much of the rain water actually makes it to the ground. As such it was considered important to assess the sensitivity of the model predictions to this parameter. The changes in model predictions that resulted with a 5%, 25%, and 50% increase in the initial derived maximum interception storage values are shown in figure 6-26.

![Figure 6-26: Changes in runoff rate with different magnitudes of maximum interception store](image)

In general, relative to the previous sensitivity assessments, the shifts in this parameter did not result in significant changes on the model predictions. Table 6-5 shows the percentage changes that were observed. An increase in 5% resulted in very small changes with an average of 2.25% for all the land use/cover types. Increase in 25% and 50% resulted in changes of 16% and 30% respectively. The model is therefore less sensitive to this parameter which coincides with the findings of (Dijck, 2000). Implying that the use of literature values (Morgan et al., 1998) for this parameter can serve the purposes of attaining reasonably accurate surface runoff predictions provided good land use/cover information is available.
Table 6-5: Models Sensitivity to Interception Store

<table>
<thead>
<tr>
<th>Land use / cover</th>
<th>Change in runoff rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>Forest</td>
<td>1.64</td>
</tr>
<tr>
<td>Degraded Forest</td>
<td>1.71</td>
</tr>
<tr>
<td>Grassland</td>
<td>2.52</td>
</tr>
<tr>
<td>Corn Field</td>
<td>3.61</td>
</tr>
<tr>
<td>Mixed Crops</td>
<td>1.44</td>
</tr>
<tr>
<td>Orchard</td>
<td>2.62</td>
</tr>
</tbody>
</table>

The hydrographs in figure 6-27 show the discharge pattern in the river Huai Nam Chun of the base simulation predictions and the predictions of the interception storage sensitivity assessment. It can be seen that very little change was observed in the overall discharge pattern of the river with increase of various magnitude on interception storage values used. The percentage changes that were observed were 4, 7 and 11% changes by increases of 5, 25 and 50% respectively in interception store values. This indicates that, interception storage plays a less crucial role in determining the rate of runoff by the model employed.

6.6. Generation of Scenarios

Scenarios were generated to assess the effects of major changes in catchment management practices or cases of increasing rainfall amounts on the rate of the predicted surface runoff. If the model accurately estimates the runoff pattern, these scenarios will be very useful in decision making processes on catchment management. These assessments could aid in answering questions such as
• What are the effects of implementing agricultural practices throughout the watershed?
• What pattern will be observed in surface runoff if the land use/cover of the entire catchment is converted to forest?
• How does the catchment, with present land use/cover, respond to rainfall events of different magnitudes?

Such information can be used to implement changes in an effort at reducing the rate of surface runoff in the long run diminishing problems of land degradation in the catchment and controlling flooding hazard in the lowlands. Scenario studies help to answer what if questions that may be impractical to realize on the ground but that can easily be simulated in a model. Three different scenario studies were done in response to the questions above and the results are discussed in the following sections.

6.6.1. Effects of Changing Land Use/Cover to Corn Cultivation in the Watershed

The values of all the parameters used were converted to those used for representing cornfields (before harvest) in the watershed (section 5.4.3) in order to make this scenario. Additionally to assess the effects when the corn is harvested and the soil is bare, another scenario was also carried out by minimising the interception store and surface storage values used (section 6.4). The hydrographs in figure 6-28 show the discharge pattern of the river Huai Nam Chun, at the outlet of the catchment, as predicted by the base simulation and the two scenarios.

Figure 6-28: Hydrograph showing the base simulation at the river Huai Nam Chun and the changes incurred by the scenarios
The hydrographs show significant increase in the predictions of the scenarios from the predictions of the base simulation in both cases. This indicates that the integrated effect of converting all parameter values to those used to account for cornfield land use/cover types, ultimately brings about an increase in the amount of surface runoff generated ensuing in large volumes of water flowing out of the catchment. The effects of the corn field scenario after harvest are even more magnified. The extent of the overall increase in both cases shows that expanding areas of agricultural practices in the watershed could result in degradation of soil physical characteristics that reduce the infiltration capacity of the watershed and reduce interception by vegetation cover which both lead to extensive increase in surface runoff. Higher runoff rates could lead to increased water erosion which could continue to intensify problems of soil degradation. The hydrographs also indicate a sharp increase in peak runoff. At peak runoff the predictions of the scenario before harvest were found to be $10\times$ greater than that of the base simulation and in the case of the after harvest scenario, the peak runoff was found to be about $100\times$ greater than that of the base simulation. Although this was a hypothetical situation, it shows that a decline in the catchments storage capacity brought about due to changes in land use/cover could lead to disastrous outcomes.

### 6.6.2 Effects of changing the land use/cover to Forest in the Watershed

Like in the previous case, the values of all the parameters were converted to those used to account for forest areas (section 5.4.3) in the base simulation and the model was re-run. As would be expected the results show to be the opposite of the previous scenario. Converting the whole catchment into forest results in an overall decline in the amount of surface runoff from the watershed. This consequently reduces the amount of erosion that takes place in the catchment. It also reduces the amount of water leaving the catchment. The hydrographs in figure 6-29 shows the discharge pattern in the river Huai Nam Chun as predicted by the base simulation and the scenario.
Figure 6-29: Base simulation results compared with forest scenario

It can be seen from the hydrographs that foresting the catchment reduces the peak runoff as well as the overall discharge pattern of the river. The implication of this is that by increasing the water storage capacity of the catchment through land use/cover practices, the amount of surface runoff generated is also reduced. This accordingly reduces the amount of water at the catchment outlet in the Huai Nam Chun River. In cases of high rainfall events therefore, the reducing effect of the catchment on the amount of runoff brought on by foresting the entire catchment could perhaps prevent the occurrence of disastrous floods downstream.

6.6.3. Effects of different rainfall amounts

In order to see the response of the catchment to different rainfall amounts, scenario studies were done by changing the rainfall amount used in this study (figure 6-13) by 5%, 25% and 50% and keeping all other parameters unchanged. The results attained are depicted in figure 6-30.
Figure 6-30: Figure showing the effects on predicted runoff rates with different rainfall events

The results show that slight increase in rainfall amount (5% increase) results in higher runoff responses from cultivated areas, with an average percent change of 120%. In non-cultivated areas average percent change of 58% for a 5% increase in rainfall results. It seems that areas under agricultural practice generate high surface runoff and would eventually be the places of concern for land degradation problems. The hydrographs in figure 6-31 shows the discharge pattern of the river Huai Nam Chun at the catchment outlet as predicted by the base simulation and different rainfall amounts.

Figure 6-31: Hydrographs of base simulation and predictions of different rainfall amounts

6.6.4. Discharge pattern of River Huai Nam Chun

Figure 6-32 shows the cross section of the Huai Nam Chun River at the outlet of the catchment. Table 6-6 shows the maximum, minimum and average daily measurements that were made on the river during the field work period of the study.
Figure 6-32: Cross section of the river Huai Nam Chun

Table 6-6: Daily Measurements done on the river Huai Nam Chun

<table>
<thead>
<tr>
<th>Value</th>
<th>Cross Section (m²)</th>
<th>Velocity (m/s)</th>
<th>Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1.5</td>
<td>0.48</td>
<td>0.72</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.1</td>
<td>1.3</td>
<td>5.33</td>
</tr>
<tr>
<td>Average</td>
<td>2.5</td>
<td>0.87</td>
<td>2.2</td>
</tr>
</tbody>
</table>

When comparing the discharge measurements done on the river with predicted values obtained at the same location from the scenario studies (section 6.6.1 and 6.6.2) the following observations were made:

1. The cornfield scenario before harvest resulted in an average discharge of 2.1 m³/s contributed only by surface runoff from the catchment, which is almost the same as the measured average discharge of the river which also includes base flow.

2. The cornfield scenario after harvest resulted in an average discharge of 20 m³/s which exceeded the maximum onsite discharge measurement by about 4×.

3. Finally in the case of the forest scenario (section 6.6.2), the average predicted runoff rate at the same location was found to be 0.175 m³/s which was about 4× less than the minimum discharge measured in the river when it had not been raining for two weeks.
The very high discharge that resulted in the cornfield scenarios suggests that increasing agricultural practices in the watershed could be a major cause of concern. It reflects the consequences of management practices, which have an impact on the reducing effect of the catchment, on the amount of rain water that is converted to surface runoff. Land use/cover practices therefore play a crucial role in determining the amount of water that contributes to the generation of surface runoff and ultimately adds to the discharge of the river. Additional to the land use/cover practices, the influence of the soil textural type in the area could also be another reason that intensifies the problems caused by land use/cover changes. The soils in the area have high clay contents which significantly reduces their ability to take up water. Implementing agricultural practices that influence the soils properties such as hydraulic conductivity, porosity, bulk density further reduce its infiltration capacity. This leads to high rates of runoff that not only bring about an increase in water erosion but also increases the discharge of the river which ultimately could result in severe problems of land degradation and flooding.

6.6.5. Comparison of runoff rates with soil loss map

The results of this study were correlated with the soil loss rates estimated by (Saengthongpinit, 2004), using the RMMF model (Morgan, 1995). The base simulation surface runoff predictions obtained in section 6.4 was used for this purpose. The estimated runoff rates were classified into 4 severity classes including; low runoff (0-1 cm$^3$/s), moderate runoff (1-100 cm$^3$/s), high runoff (100-200 cm$^3$/s) and very high runoff (>200 cm$^3$/s). The map in figure 6-33 shows the result of the classification. The runoff class map was crossed with the soil erosion class map and it was found that 65% of the area classified as having the lowest erosion rate (up to 10 ton/ha/yr accounting for 75% of the total catchment) was found to belong to the area classified as low and moderate runoff. On the other hand, about 60% of the area classified as having the highest rates of erosion (41-60 ton/ha/yr) was found to belong to the very high and high runoff rate classes. The remaining classes did not exhibit much relation with increasing rates of runoff but only accounted for a small portion of the study area.
Figure 6-33: Surface runoff hazard map

Figure 6-34: Erosion hazard map (adopted from Saengthongpinit, 2004)
7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

Three models were applied to quantify the rate of runoff in the Nam Chun watershed and assess the effects of different land use/cover types on its generation. The index approach was simple, required very little data, and its application in a spatially distributed modelling environment allowed for estimates of runoff rates at different locations in the catchment. Though simple this approach, it was deemed unsuitable for this particular study. The reason for this was that, the approach made no considerations on the physical laws that govern the processes involved in the generation of surface runoff. It also did not consider accumulation of lost rainfall in the catchment which, under natural conditions would influence the amount of rain water lost in each time step. Since data for model validation was not available in this study, making conclusions based on results obtained from purely black box modelling approaches that are not validated with ground truths could be misleading. It could lead to decisions that do not coincide with the reality on the ground. With adequate data however, a good approximation of the impacts of different land use/cover types on the rate of runoff could be obtained easily using this approach which could be used as a start of runoff investigations in an area.

The second approach was the SCS curve number approach. Like in the previous case this method is not data demanding and also took into consideration the effects of different land use/cover types and soil characteristics of the catchment in predicting runoff. The results obtained were similar to those of the semi physical approach. It showed that areas of agriculture practice have higher excess precipitation values than non-agricultural areas. However the empirical basis of the equations used in this method and the lack of long term discharge data for validation made this approach also unsuitable for this study.

The final approach was a semi physical based approach. Most of the equations used in the model were based on the physical laws that govern the components of surface runoff. It was therefore deemed the most suitable approach for this study because it was assumed that its physical basis would allow it to make predictions of surface runoff as it would occur in nature. It was also considered the most appropriate approach for this study because it explicitly considers the effects of different land use/cover types on the generation of parameter values used in the model.
The results of the study revealed that areas of agricultural practice could be concerns of soil degradation problems that are resulting in increased rates of surface runoff in the watershed. It was observed that in areas of agriculture practice, soil properties related to the infiltration of water into the soil were being negatively influenced due to the land use/cover practices being implemented in these areas. The consequence of this was seen in the high rates of surface runoff being generated in areas of agriculture practice. The scenario studies further confirmed that changes in land use/cover to agricultural practices could lead to significantly altered outcomes in the discharge pattern of the river Huai Nam Chun which could lead to severe flooding problems in low lying areas.

The study showed that PCRaster was a valuable tool to quantify the rate of surface runoff and assess the impacts of different land use/cover types on runoff generation. Its flexibility in allowing the application of different runoff modelling approaches (one of which was based on the integration of equations from different sources) in the context of the Nam Chun Watershed made it an effective means to assess the impacts of different land use/cover types on environmental problems such as surface runoff. It enabled the integration and analysis of large data sets that vary both spatially and temporally which emphasised the practicality of employing GIS tools for assessing dynamic environmental problems. Therefore, it can be concluded that PCRaster was a suitable tool for making the assessments this study set out to achieve.

7.2. Limitations of the Study

The main limitation of this study was that the available data for model calibration and validation was not adequate. Studies on the discharge pattern of the watershed had not been done previously thus imposing limitations on the availability of long term discharge data from the catchment. Model calibration was done based on measured data from one rainfall event which is not representative enough. Thus the first two empirical approaches were abandoned as being unsuitable for this study. Furthermore, almost all the values used for the parameters implemented in the semi physical approach were obtained from literature. Gathering of this data from the field in future particularly those to which the model was found to be sensitive (6.5) could result in better model performance. The rainfall data that was used for the modelling procedures was obtained from only one location in the watershed. Thus the spatial variation of rainfall in the watershed was not taken into account despite the fact that the area exhibits extensive altitudinal variation. In addition, the methods used for collecting the data were very crude and more refined techniques that measure rainfall every minute could lead to better estimations. Finally owing to
various reasons, the number of samples used for making relational studies and assessing the effects of different land use/cover types on different soil properties related to the generation of runoff were too few. Better results could have been obtained with more observations.

7.3. Recommendations

The results of all the modelling approaches indicated that there is a trend in the surface runoff pattern of the watershed on different land use/cover types. Areas used for agriculture exhibited higher surface runoff rates than areas of non-agriculture. The soil analysis results also further substantiated this indicating that soil properties associated with the generation of runoff generally were being negatively influenced by agricultural practices. Since the study revealed that there is a cause of concern in areas of agricultural practice, further investigations should be conducted in the catchment. Perhaps through the collection of adequate model validation data and making field measurements of the parameters required by the model more accurate predictions can be made. Because of its physical nature, the model can then be implemented in other catchments in the area. With this information, suitable management strategies can be formulated and implemented in an effort at reducing the rate of surface runoff ultimately reducing soil erosion by water and the flooding hazard in the low lying areas.
References


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   and Earth Observation, Enschede, 92 pp.
Appendices

Appendix 1: Script used to model runoff using the index method (Burrough et al., 2005)

```plaintext
# Index method for simulation of runoff
# one time slice represents 30 min

binding
RainStation=rainst.map;           # map with location of rain station
RainTimeSeries=rain.tss;             # time series with rain at rain stations
rain=rainfall;              # reported maps with rain (m/30min)
SamplePlaces=samples.map;           # runoff at sampling location
RunoffTimeSeries=runoff.tss;          # reported time series with runoff at sampling location
Infiltrationtable=infilcap.tbl;   # table with infiltration capacity information
Dem=dem.map;                           # digital elevation map
RainZone=Rainzone.map;  # map with the rain area

area
close.map;                               # map providing information on the location attributes

timer
1 7 1;                                   # Model time step

initial
report Infilcap=lookupscalar(Infiltrationtable,infiltration.map);# Infiltration loss (m)
report Ldd=lddcreate(Dem,1e31,1e31,1e31,1e31);          #local drain direction map
CA=cellarea();               # cell area

dynamic
report rain=timeinputscalar(RainTimeSeries,RainZone);       # maps with rainfall for each
timestep
report Exprecip, Infiltration=
accuthresholdflux, accuthresholdstate(Ldd,rain,Infilcap);    # computation of both runoff (m)
# and actual infiltration (m)
report runoff= (Exprecip*CA)/1800;                          # runoff in m3/s
report RunoffTimeSeries=timeoutput(SamplePlaces,runoff);
```
Appendix 2: Script used to model runoff using the curve number method (Deursen, 1995)

```plaintext
# SCS curve number method for simulation of excess precipitation runoff
# 7 time steps of 30min => modelling time 3.30hrs

binding
RainStation=rainst.map;           # map with location of rain station
RainTimeSeries=rain.tss;              # time series with rain at rain stations
RainZone=rainzone.map;     # reported stack of maps with rain
rain=rainfall;             # reported maps with rain (inch/30min)
SamplePlaces=samples.map;           # map with runoff sampling locations
RunoffTimeSeries=runoff.tss;          # reported time series with runoff at sampling location

areamap  # map providing information on the location attributes
clone.map;

timer  # Model time step
1 7 1;

initial
RainZone=spreadzone(Rainarea.map,0,1);   # Area covered for rainfall
sump=0;         # cumulative rainfall (inch)
SumIa=0;         # cumulative initial abstraction
sumPe=0;         # Cumulative excess precipitation (inch)
cn=lookupscalar(cn.tbl,cncode.map);            # table with Curve numbers
s=1000/cn-10;         # definition of parameter s using the CN's
maxIa=0.2*s;         # maximum initial abstraction

dynamic
rain=timeinputscalar(RainTimeSeries,RainZone); # maps with rainfall at each time step (mm/30min)
sump=sump+rain;          # Cumulative rainfall
SumIa=if(sump>maxIa,maxIa,sump); # cumulative Initial abstraction
sumfa=s*(sump-SumIa)/(sump-SumIa+s);     # cumulative abstractions
report Pe=sump-sumfa-SumIa-sumPe;         # reported maps with excess precipitation
# at each time step
sumPe=sumPe+Pe;          # cumulative excess precipitation
report RunoffTimeSeries=timeoutput(SamplePlaces,Pe);   # reported maps with excess
# Precipitation for each time step
```

---

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Appendix 3: Script used to model runoff using the third approach (Burrough et al., 2005; Karssenberg, 2002)

```plaintext
# model for simulation of runoff
# One time slice represents 60 seconds

binding

## GENERAL
T=scalar(60); # time of one time step (s)
sampleplaces=samples.map; # map with location for reporting maps

## PRECIPITATION
Raintimeseries=rain1min.tss; # timeseries with rainfall data (m/min)
Precip=rain; # reported maps with precipitation
Rainzone=rainzone.map; # map with the rain area

## INTERCEPTION
Covtbl=cov.tbl; # fraction of surface covered by vegetation
ICStI=scalar(0); # initial content interception store
ICStMtbl=ICStM.tbl; # maximum content of interception store

## INFILTRATION
Kstbl=Ks.tbl; # saturated hydraulic conductivity (m/h)
Btbl=b.tbl; # suction head below wetting front (m)
MDtbl=MD.tbl; # Volumetric moisture deficit (dimensionless)

## SURFACE STORAGE
RFRTable=rfr.tbl; # surface roughness (cm/m)

## ROUTING
Dem=Dem.map; # elevation map (m)
NTable=n.tbl; # Manning’s N
Bw=scalar(30); # bottom width for channels (m)
Beta=scalar(0.6); # Beta
QIni=scalar(0.000000000001); # initial streamflow (m3/s)
HIni=scalar(0.000000001); # initial waterheight (m)

Areamap # map providing information on the location
clone.map; # attributes
timer
1 180 1; # Model time step
```
initial

## GENERAL

\[ CA = \text{cellarea}(); \]

#cellarea \( \text{(m}^2 \)\)

## PRECIPITATION

\[ PCum = 0; \]

cumulative rain \( \text{(m)} \)

## INTERCEPTION

\[ ICSt = \text{ICStI}; \]

#initial content of interception store \( \text{(m, for area covered)} \)

\[ ICStM = \max(\text{lookupscalar}(ICStMtbl, \text{landuse.map}), 0.0000001); \]

#maximum content of interception store (should be \( > 0 \))

\[ COV = \text{lookupscalar}(Covtbl, \text{landuse.map}); \]

#fraction of surface covered with vegetation (-)

\[ \text{IntCum} = \text{scalar}(0); \]

# initial intercepted water, cumulative \( \text{(m)} \)

## INFILTRATION

\[ Ks = \text{lookupscalar}(Kstbl, \text{soilcalib.map}); \]

#saturated Hydraulic conductivity \( \text{(m/h)} \)

\[ \text{SurW} = \text{scalar}(0); \]

# total amount of water on surface \( \text{(m)} \)

\[ KsSt = (Ks/3600)*T; \]

# saturated conductivity \( \text{(m/timestep)} \)

\[ \text{FcA} = \text{scalar}(0.00000001); \]

# actual initial infiltration per timestep ('rate', \( \text{m/timestep} \))

\[ \text{FCum} = \text{scalar}(0.0000000001); \]

# cumulative initial infiltration \( \text{(m/timestep)} \)

\[ B = \text{lookupscalar}(Btbl, \text{soil.map}); \]

# suction head at wetting front \( \text{(m)} \)

\[ \text{MD} = \text{lookupscalar}(MDtbl, \text{soil.map}); \]

# Volumetric moisture deficit

## SURFACE STORAGE

\[ \text{RFR} = \text{lookupscalar}(RFRTable, \text{Landuse.map}); \]

# Surface roughness in direction of flow \( \text{(cm/m)} \).

\[ D = \exp(-6.6+0.27*\text{RFR}); \]

# maximum surface storage \( \text{(m)} \)

\[ \text{DSt} = \text{scalar}(0); \]

# amount of water in surface storage \( \text{(m)} \)

\[ \text{Dstcum} = \text{scalar}(0); \]

## ROUTING

\[ \text{CL} = \text{celllength}(); \]

# cell size \( \text{(m)} \)

\[ \text{Ldd} = \text{lddcreate}(\text{Dem}, 1e31, 1e31, 1e31, 1e31); \]

# local drain direction map

\[ \text{DCL} = \max(\text{downstreamdist(Ldd)}, \text{CL}); \]

# distance to downstream cell \( \text{(m)} \)

\[ \text{Slope} = \max(0.001, \text{slope}(\text{Dem})); \]

# slope \( \text{(m/m)}, \text{must be larger than 0} \)

\[ Q = QIni; \]

# initial streamflow \( \text{(m}^3/\text{s)} \)

\[ QR = \text{scalar}(0); \]

# initial flow out of cell \( \text{(m/T)} \)

report \[ N = \text{lookupscalar}(NTable, \text{Landuse.map}); \]

# manning's \( \text{n} \)

\[ H = HIni; \]

# initial water height \( \text{(m)} \)

\[ \text{AlpTerm} = (N/(\sqrt(\text{Slope})))^{**Beta}; \]

# term for \( \text{Alpha} \)
AlpPow=(2/3)*Beta;          # power for Alpha  
P=Bw+2*H;                    # initial approximation for Alpha  
Alpha=AlpTerm*(P**AlpPow);   #cumulative runoff (m/timestep)  
Rcum=scalar(0);              #cumulative runoff (m3/s)  
Qcum=scalar(0);              

## PRECIPITATION  
report Precip=timeinputscalar(Raintimeseries,Rainzone); #precipitation (m/15s)  
PCum=Precip+PCum;            #cumulative rain (m/15s)  
report Precip.tss=timeoutput(sampleplaces,Precip);  
report PCum.tss=timeoutput(sampleplaces,PCum);  

##INTERCEPTION  
Int=Precip*COV;              # intercepted water (m/timestep,)  
report Int.tss=timeoutput(sampleplaces,Int);  
IntCum=IntCum+Int;           # intercepted water, cumulative (m)  
report IntCum.tss=timeoutput(sampleplaces,IntCum);  
ICStOld=ICSt;                # interception store, previous timestep (m)  
ICSt=ICStM*(1-exp(-PCum/ICStM)); # interception store (m, for area covered)  
ToICSt=ICSt-ICStOld;         # to interception store (m/timestep)  
ToICStC=COV*ToICSt;         # to interception store (m/timestep, spreaded over whole cell)  
report ToICStC.tss=timeoutput(sampleplaces,ToICStC);  
TF=Int-ToICStC;              # throughfall (m/timestep)  
report RainNet=TF+(Precip-Int); # total net rain per timestep (m/timestep,)  

## INFILTRATION  
QR=(Q*T)/CA;                 # flow out of the cell (m/timestep)  
SurW=RainNet+QR+DSt;         # total amount of water on surface, waterslice (m)  
FCum=FCum+Fca;              # cumulative infiltration (m)  
report Fcum.tss=timeoutput(sampleplaces,FCum);  
Fc = KsSt*((B*MD+FCum)/FCum); # potential infiltration per timestep ('rate', m/timestep)  
Fca=if(SurW gt Fc,Fc,SurW);  # actual infiltration per timestep (m/timestep)  
report Fca.tss=timeoutput(sampleplaces,Fca);  
report SurW=max(SurW-Fca,0);  # total amount of water on surface after infiltration (m)  
report SurW.tss=timeoutput(sampleplaces,SurW);
## SURFACE STORAGE

# amount of water in surface storage (m)

report DSt=if(SurW gt D,D,SurW);
report Dst.tss=timeoutput(sampleplaces,DSt); # flux to surface storage (m/timestep)
Dstcum=Dstcum+DSt;
report Dstcum.tss=timeoutput(sampleplaces,Dstcum);

## POST INTERCEPTION, INFILTRATION, AND SURFACE STORAGE

report SurWw=max(SurW-DSt,0);   # total amount of water on surface after infiltration and surface storage (m)
q=SurWw-QR;   # amount of water added to streamflow (m/timestep)

## ROUTING

QIn=(q*CA)/T;   # lateral inflow (m³/s)
# lateral inflow per distance along stream ((m³/s)/m))
report Q=kinematic(Ldd,Q,QIn/DCL,Alpha,Beta,T,DCL); # discharge (m³/s)
H=(Alpha*(Q**Beta))/Bw; # water depth (m)
P=Bw+2*H; # wetted perimeter (m)
Alpha=AlpTerm*(P**AlpPow); # Alpha
report Runoff.tss=timeoutput(sampleplaces,Q);
R=(Q*T)/CA; # runoff (m/timestep)
Rcum=Rcum+R; # cumulative runoff (m/timestep)
report Rcum.tss=timeoutput(sampleplaces,Rcum);
report Budget=PCum-(IntCum+FCum+DSt+Rcum);
report Budget.tss=timeoutput(sampleplaces,Budget);
report Qcum=Qcum+Q; # Cumulative runoff (m³/s)
report Qcum.tss=timeoutput(sampleplaces,Qcum);
Appendix 4: Example of the database created for entering field data

![Database](image1)

<table>
<thead>
<tr>
<th>Station /</th>
<th>Date</th>
<th>UTM X</th>
<th>UTM Y</th>
<th>Altitude</th>
<th>Geological Unit</th>
<th>Landuse</th>
<th>LandCover</th>
<th>Slope</th>
<th>Soil Composition</th>
<th>Horizon Description</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 01</td>
<td>08/17/2004</td>
<td>725247</td>
<td>1656001</td>
<td>410</td>
<td>Summit (Mo411)</td>
<td>Maize Cultivation</td>
<td>Maize Plantation (60%)</td>
<td>2%</td>
<td>1.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station 02</td>
<td>08/20/2004</td>
<td>725017</td>
<td>1656057</td>
<td>394</td>
<td>Middle Slope (Mo412)</td>
<td>Sweet Tamaneide Cultivation</td>
<td>Sweet Tamaneide (203%) and Grass (60%)</td>
<td>30%</td>
<td>2.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station 03</td>
<td>08/18/2004</td>
<td>721386</td>
<td>1855081</td>
<td>648</td>
<td>Summit (Mo511)</td>
<td>Planted Forest</td>
<td>Trees (60%)</td>
<td>12%</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station 04</td>
<td>08/20/2004</td>
<td>726114</td>
<td>1855645</td>
<td>252</td>
<td>Slope (Mo413)</td>
<td>Sweet Tamaneide Cultivation</td>
<td>Sweet Tamaneide (203%) and Grass (60%)</td>
<td>37%</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **A & B Horizons**: Indicates a layer of clay or silt in the soil profile. A clay layer is followed by a silt layer.
- **C Horizon**: Indicates a layer of organic material (e.g., peat) or a layer that is less dense than the underlying layer.

**Station Details**

- **Station 01**: Located on a summit with a slope of 2% and a soil composition of 1.40. The horizon description is not specified.
- **Station 02**: Located on a middle slope with a slope of 30% and a soil composition of 2.25. The horizon description is not specified.
- **Station 03**: Located on a summit with a slope of 12% and a soil composition of 1.45. The horizon description is not specified.
- **Station 04**: Located on a slope with a slope of 37% and a soil composition of 1.5. The horizon description is not specified.
Appendix 5: Maps showing the rainfall amount at different time steps

Time step 1-30 (0.41mm/min)  Time step 30-60 (0.04mm/min)

Time step 60-90 (0.01mm/min)  Time step 90-120 (0mm/min)

Time step 120-150 (0mm/min)  Time step 150-180 (0mm/min)
Appendix 6: Soil group assigned to each geopedological unit based on the textural class and the CN values assigned to each land use/cover types based on the soil groups and the land use/cover (USDA, 1986)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Texture</th>
<th>Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM111</td>
<td>loam</td>
<td>GroupB</td>
</tr>
<tr>
<td>HM112</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>HM211</td>
<td>loam</td>
<td>GroupB</td>
</tr>
<tr>
<td>HM212</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>HM213</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>HM311</td>
<td>Sandyloam</td>
<td>GroupB</td>
</tr>
<tr>
<td>HM312</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>HM313</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>LM111</td>
<td>clayloam</td>
<td>GroupD</td>
</tr>
<tr>
<td>LM112</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>LM211</td>
<td>loam</td>
<td>GroupB</td>
</tr>
<tr>
<td>LM212</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>LM311</td>
<td>siltyclay</td>
<td>GroupD</td>
</tr>
<tr>
<td>LM312</td>
<td>clayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>P111</td>
<td>siltyclayloam</td>
<td>GroupC</td>
</tr>
<tr>
<td>P211</td>
<td>siltyclay</td>
<td>GroupD</td>
</tr>
<tr>
<td>P212</td>
<td>clay loam</td>
<td>GroupD</td>
</tr>
<tr>
<td>P213</td>
<td>siltyclay</td>
<td>GroupC</td>
</tr>
<tr>
<td>V111</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>Land use</th>
<th>CN Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GroupB</td>
<td>CornField</td>
<td>90.75</td>
</tr>
<tr>
<td>GroupB</td>
<td>ForestArea</td>
<td>77.53</td>
</tr>
<tr>
<td>GroupB</td>
<td>DegradedForest</td>
<td>86.15</td>
</tr>
<tr>
<td>GroupB</td>
<td>Orchard</td>
<td>86.15</td>
</tr>
<tr>
<td>GroupB</td>
<td>Grassland</td>
<td>83.66</td>
</tr>
<tr>
<td>GroupB</td>
<td>MixedCrops</td>
<td>85.54</td>
</tr>
<tr>
<td>GroupC</td>
<td>CornField</td>
<td>94.4</td>
</tr>
<tr>
<td>GroupC</td>
<td>ForestArea</td>
<td>86.15</td>
</tr>
<tr>
<td>GroupC</td>
<td>DegradedForest</td>
<td>91.29</td>
</tr>
<tr>
<td>GroupC</td>
<td>Orchard</td>
<td>91.29</td>
</tr>
<tr>
<td>GroupC</td>
<td>Grassland</td>
<td>89.64</td>
</tr>
<tr>
<td>GroupC</td>
<td>MixedCrops</td>
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<td>GroupD</td>
<td>CornField</td>
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<td>GroupD</td>
<td>ForestArea</td>
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<td>GroupD</td>
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<tr>
<td>GroupD</td>
<td>Orchard</td>
<td>93.39</td>
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<td>Grassland</td>
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<td>GroupD</td>
<td>MixedCrops</td>
<td>92.87</td>
</tr>
<tr>
<td>-</td>
<td>Road, stream, waterbody, urban</td>
<td>98</td>
</tr>
</tbody>
</table>
Appendix 7: Values used for Hydraulic conductivity

<table>
<thead>
<tr>
<th>Land use/ Cover</th>
<th>Soil Texture</th>
<th>Hydraulic conductivity (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built up area +</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Stream</td>
<td>Siltyclay</td>
<td>0.5</td>
</tr>
<tr>
<td>CornField</td>
<td>loam</td>
<td>2</td>
</tr>
<tr>
<td>CornField</td>
<td>Clayloam</td>
<td>0.4</td>
</tr>
<tr>
<td>CornField</td>
<td>Siltyloam</td>
<td>3</td>
</tr>
<tr>
<td>ForestArea</td>
<td>Siltyclay</td>
<td>5</td>
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<tr>
<td>ForestArea</td>
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<td>65</td>
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<tr>
<td>ForestArea</td>
<td>Clayloam</td>
<td>38</td>
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<tr>
<td>ForestArea</td>
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<td>ForestArea</td>
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<td>DegradedForest</td>
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<tr>
<td>DegradedForest</td>
<td>loam</td>
<td>13</td>
</tr>
<tr>
<td>DegradedForest</td>
<td>Clayloam</td>
<td>2</td>
</tr>
<tr>
<td>DegradedForest</td>
<td>SiltyClayloam</td>
<td>1.5</td>
</tr>
<tr>
<td>DegradedForest</td>
<td>Siltyloam</td>
<td>7</td>
</tr>
<tr>
<td>Orchard</td>
<td>Siltyclay</td>
<td>0.5</td>
</tr>
<tr>
<td>Orchard</td>
<td>Clayloam</td>
<td>0.4</td>
</tr>
<tr>
<td>Orchard</td>
<td>Siltyloam</td>
<td>3</td>
</tr>
<tr>
<td>Grassland</td>
<td>Siltyclay</td>
<td>0.9</td>
</tr>
<tr>
<td>Grassland</td>
<td>loam</td>
<td>13</td>
</tr>
<tr>
<td>Grassland</td>
<td>Clayloam</td>
<td>2</td>
</tr>
<tr>
<td>Grassland</td>
<td>SiltyClayloam</td>
<td>1.5</td>
</tr>
<tr>
<td>MixedCrops</td>
<td>Siltyclay</td>
<td>0.5</td>
</tr>
<tr>
<td>MixedCrops</td>
<td>loam</td>
<td>2</td>
</tr>
<tr>
<td>MixedCrops</td>
<td>Clayloam</td>
<td>0.4</td>
</tr>
<tr>
<td>MixedCrops</td>
<td>SiltyClayloam</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Appendix 8: Photos showing the collection of soil samples in the field for laboratory analysis.
Appendix 9: Photos showing soil analysis laboratory at the LDD in Bangkok Thailand

Appendix 10: Laboratory Analysis Results on Soil Properties from samples collected in the field
<table>
<thead>
<tr>
<th>UTM-X</th>
<th>UTM-Y</th>
<th>Bulk Density (gcm⁻³)</th>
<th>Particle Density (gcm⁻³)</th>
<th>Organic Matter (%)</th>
<th>Porosity (%)</th>
<th>Hydraulic Conductivity (m/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>725661</td>
<td>1854946</td>
<td>0.97</td>
<td>2.28</td>
<td>1.82</td>
<td>57.5</td>
<td>0.756</td>
</tr>
<tr>
<td>725394</td>
<td>1855302</td>
<td>1.16</td>
<td>2.19</td>
<td>1.96</td>
<td>47</td>
<td>0.115</td>
</tr>
<tr>
<td>719847</td>
<td>1853471</td>
<td>1.04</td>
<td>2.49</td>
<td>1.73</td>
<td>58.2</td>
<td>0.583</td>
</tr>
<tr>
<td>719843</td>
<td>1853438</td>
<td>1.09</td>
<td>2.29</td>
<td>1.79</td>
<td>52.4</td>
<td>0.463</td>
</tr>
<tr>
<td>721921</td>
<td>1854024</td>
<td>1.04</td>
<td>2.4</td>
<td>1.08</td>
<td>56.7</td>
<td>0.118</td>
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<tr>
<td>720800</td>
<td>1853698</td>
<td>0.98</td>
<td>2.44</td>
<td>1.34</td>
<td>59.8</td>
<td>0.393</td>
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<tr>
<td>725641</td>
<td>1856097</td>
<td>0.96</td>
<td>2.26</td>
<td>1.04</td>
<td>57.5</td>
<td>1.463</td>
</tr>
<tr>
<td>725686</td>
<td>1856182</td>
<td>1.07</td>
<td>2.41</td>
<td>1.54</td>
<td>55.6</td>
<td>1.064</td>
</tr>
<tr>
<td>725636</td>
<td>1855038</td>
<td>1.09</td>
<td>2.38</td>
<td>2.63</td>
<td>54.2</td>
<td>0.469</td>
</tr>
<tr>
<td>725266</td>
<td>1855240</td>
<td>1.28</td>
<td>2.3</td>
<td>2.08</td>
<td>44.3</td>
<td>0.198</td>
</tr>
<tr>
<td>719898</td>
<td>1853576</td>
<td>0.97</td>
<td>2.44</td>
<td>1.11</td>
<td>60.2</td>
<td>0.649</td>
</tr>
<tr>
<td>719960</td>
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