1D2D Modelling of Sediment Transport and Deposition from Flash Floods

A Case Study in the Nam Chun Watershed, Thailand

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by

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Disclaimer

to Kerith & Yvonne Masters

for their unyielding support

Abstract

The rapid population growth in Thailand within the last decade has significantly intensified soil degradation, causing farmers to infringe on forests for the expansion of agricultural fields predominantly in upland areas. This has led to intense flooding events, accelerated soil removal, transport and deposition in the low lands. The aim of this study was to test and broaden the use of an existing tool for modelling two dimensional sediment transport and deposition during flash flood events over complex topography. To model the sedimentation processes, in the lowland flood plain of the Nam Chun Watershed, in Thailand, this study applied a physically based hydrological model (LISEM) to estimate the sediment yield from the upland catchment and a coupled one-dimensional/two-dimensional (1D2D) hydraulic model (SOBEK) to model the propagation of flash floods and sediment transport and deposition in the lowland floodplain. In the upstream catchment, model parameters were extracted from previous studies and integrated with a new fieldwork campaign. To improve outputs from previous years, a base flow was added to the total discharge exiting the catchment. The calibration of the LISEM model was carried out by comparing the simulated results versus measured hydrographs. The calibrated hydrographs from LISEM were used as the upstream boundary condition in the SOBEK schematisation. The innovative aspect of the study is the application, of a two-dimensional Water Quality (2DWAQ) module in SOBEK, which was originally used to model sediment transport and deposition for riverine floods. The hydrodynamics are computed for 1D and 2D in one integrated calculation. For the Water Quality, the calculation procedure is different; the 1D and 2D domains are calculated separately. The Water Quality model and the Flow model exchange information about the 1D-2D connections during every time step. For the purpose of validation, probable deposition zones were delineated based on four group interviews carried out in villages that have been most affected by flash floods in the study area. The results proved the applicability of the tool to flash flood events. However, a more detailed method of validation is recommended. To realistically model such hydrological processes a good knowledge of the historic events, soil properties and topography in the study area along with a meticulous validation strategy is crucial.

***Keyword**: LISEM, SOBEK, 2DWAQ, Erosion, Flash Floods, Two-Dimensional*

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List of Abbreviations

1D	One Dimensional
2D	Two Dimensional
WAQ	Water Quality
AMSL	Above Mean Sea Level
C	Celsius
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
GIS	Geographic Information System
GLASOD	Global Assessment of Soil Degradation
IM	Inorganic Matter
LDD	Land Development Department
LU	Land Use
LISEM	Limburg Soil Erosion Model
SWAT	Soil and Water Assessment Tool
USLE	Universal Soil Loss Equation
USDA	United States Department of Agriculture
WEPP	The Watershed Erosion Prediction Project

1. Introduction

1.1. Background

In recent years, relevant literature has increasingly paid attention on the issues of land degradation. The main reason behind this is the acknowledgement that much of the earth's surface is either degraded, being degraded or is at risk of degradation. The process can be defined as the loss of utility or potential utility or the reduction, loss or change of features or organisms which cannot be replaced. However, defining precisely the event is almost impossible, given the many factors which may be responsible (Barrow 1994). It has also been noted that the terms 'soil degradation' and 'land degradation' have been used loosely as synonyms even though they are not one and the same, despite the fact that soil degradation is undoubtedly the largest part of land degradation (Shrestha 2005).

A wide range of human activities can trigger and exacerbate soil degradation. On global basis, soil degradation is caused primarily by overgrazing (35%), agricultural activities (28%), deforestation (30%), overexploitation of land to produce fuel from wood (7%), and industrialization (4%) (GLASOD 1990). Soil erosion caused by water, on the other hand, is one of the most significant soil degradation problems worldwide (Eswaran 2001). According to the Global Assessment of Soil Degradation (GLASOD) report, the total land area subjected to human-induced soil degradation is estimated at 2 billion hectares. Of this amount the land area affected by soil degradation due to erosion is estimated at 11 billion hectares caused by water and 0.55 billion hectares by wind (GLASOD 1990).

Soil erosion is a three-stage process. It involves soil particle detachment, transport, and deposition. It is significant to note that soil erosion and deposition are complementary processes since soil material removed from steeper slopes is deposited to a variable extent on foot slopes and flood plains. This process is influenced mainly by climatic conditions, topography, soil properties, vegetation type and land management. Detachment of soil material is instigated by raindrop impact and drag force of running water. Detached particles are transported by overland flow (sheet erosion), concentrated flow (rill erosion) and deposited when flow velocity decreases as a result of slope and/or surface roughness (Lal 2001).

Soil erosion by water has both on-site and off-site effects. The effects of on-site water erosion are characterized by a number a factors including depletion of soil nutrients, reduction in soil depth, decline of infiltration capacity, surface sealing and crusting. Off-site effects, on the other hand, involve the movement of sediments and agricultural pollutants into watercourses. This can result in sedimentation in watercourses and dams, contamination of drinking water and increase runoff which may lead to downstream flooding and damage to property.

Thailand is one of many countries in South East Asia where soil erosion is the main cause of land degradation. According to the FAO/AGL, about 38% of the total land area of the country is prone to experience severe to very severe soil degradation (FAO/AGL 2005).

The rapid population growth in Thailand within the last decade has significantly intensified soil degradation (Shrestha 2005). The vast increase in population has lead to the need for high food production, which has resulted in infringement on forests and therefore deforestation and use of marginal lands. Another main reason for the encroachment on forest lands is for logging purposes, for fuel wood and for construction of roads and dams without the implementation of proper conservation measures (Solomon 2005). The outcome has been soil degradation manifested by low agronomic production capacity and reduction in water quality. In Thailand, the main soil degradation issues are soil erosion, land sliding, flooding, depletion of fertility, salinity and acidity. These problems affect the economy of the country as well as the lives of many (Shrestha 2005).

Several studies have been conducted to improve the understanding of the effects of water erosion and flooding events in Thailand. These investigations used a selected watershed to assess the problems of water erosion through GIS based modeling techniques. Some focused on soil and land cover parameters ((Solomon 2005); ((Prachansri 2007)), others considered terrain characteristics (Lerra 2006). This study aims to model two dimensional sediment transport and deposition as a result of flash floods, in an effort to improve hydrological modelling and flood risk[1] assessment.

1.2. Statement of the problem

Land degradation is among the major problems being faced by many developing countries. Problems of land degradation have notably intensified over the last decade in Thailand as a consequence of population pressures (Shrestha 2005). The rapid population increase has outweighed the resources of the country, causing farmers to infringe on forests for the expansion of agricultural fields. Forests are also at the mercy of the country’s need for fuel wood and the construction of roads and dams without

[1] The term risk refers to the expected losses (economic losses or number of lives lost) from a given hazard to a given element at risk, over a specified future time period.

the execution of appropriate conservation schemes. This has led to accelerated soil removal, transport and deposition in the low lands.

The main soil degradation problem in Thailand which will be the focus of this study, is soil erosion by water, and more specifically flash flooding. Soil erosion, decrease in soil fertility and flooding are mainly associated with rainfall (Shrestha 2005). In the region, flash flooding is common from July to October which is the Monsoon season. This phenomenon is usually caused by intense single or multiple thunderstorms.

In many lowland areas, flooding takes place almost every year. The flooding events cause destruction to properties and disrupt livelihoods. Part of the damage and disruption is not only caused by the flood water itself, but by the sediments that are left behind. Large quantities of sediments carried from upstream which blocked drains, caused damage to infrastructure and made riverbeds shallow and prone to future flooding.

1.3. Purpose

Water erosion and sedimentation processes are influenced by several biophysical factors such as soil erodibility, climate, and terrain among others. Human factors include economic, social and political. A combination of these factors causes soil erosion to take place at various intensities across the landscape. However, the spatial and temporal scales of the processes are still difficult to model, which makes monitoring and assessment of erosion and deposition processes a complex and cumbersome task, with a significant level of uncertainty (Saavedra, Schultz, and Mannaerts 2005). The purpose of this study is to add some clarity and comprehension on the spatial and temporal behaviour of sediment transport and deposition keeping in consideration the contributing bio-physical factors of soil erosion (See Chapter 2.1 for more detail).

1.4. Significance

A model is a simplification of reality. It can be defined as a pattern, plan, representation or description designed to show the structure or workings of an object, system or concept (Jetten 2008). Scientists model the world to understand how it works, envisage characteristics of unreachable or unseen areas and to predict future events and analyze what has happened in the past. To model the sedimentation processes, this study intends to use a physically based erosion model (LISEM) and a 1D2D hydrodynamic flood model (SOBEK). The significance of this research is to contribute scientifically to the development and improvement of hydrological modelling and flood risk assessment.

1.5. Objectives

The main objective of this research is to estimate sediment deposition from flash flood waters in the downstream area of the Nam Chun watershed, taking into account the soil erosion occurring within the upstream catchment. The specific objectives of the research are as follows:

1. Estimate the discharge and sediment concentration from the upland catchment for designed flood events using LISEM

2. Characterize the propagation of flood waters over a downstream flood plain by using a 1D2D model for designed flood events

3. Test the application of the 2D Water Quality model in SOBEK to characterize the transport and deposition of sediments in a downstream flood plain from flash floods

1.6. Research hypothesis

1. Large scale erosion modelling can be achieve by using LISEM in the upland catchment of the Nam Chun watershed

2. Flood propagation over a complex topography can be modelled using a 1D2D hydraulic model i.e. SOBEK

3. The 2D Water Quality module in SOBEK can model sediments transported and deposited by flash flood events

1.7. Research questions

The general question of this research is: Can a 1D2D hydrodynamic model be used to assess sediment deposition in a terrain with a complex topography? The specific questions are as follows:

1. What is the sediment concentration exiting the catchment outlet of the Nam Chun watershed for specific flash flood events?

2. What are the factors in the downstream area which will affect flood propagation?

3. What are the spatial/temporal characteristics of the sediment deposition in the downstream area of the catchment when modelled with the 2D-Water Quality model?

    a. What are the data requirements and the generated outputs?
    b. How can the sensitivity of the model be tested?
    c. How can the generated output be validated?

1.8. Innovative Aspect

SOBEK is a 1D2D model for flood forecasting, drainage systems, irrigation systems, sewer overflow, ground-water level control, river morphology, salt intrusion and in recent times water quality. The 1D2D Water Quality module of SOBEK was designed to model sediments and pollutant transport and deposition by riverine floods. The innovative aspect of this research is to test the applicability of the 1D2D Water Quality Module in SOBEK to model sediment transport and deposition from a high velocity flood wave.

2. Literature review

In this chapter the concepts related to hydrodynamic modelling and sediment transport are reviewed by chronological processes, from detachment to transport and in the end deposition. 2.1 highlights the bio-physical factors that contribute to soil erosion and detachment, 2.2 introduces the medium of transport (overland flow) in a watershed and 2.3 examines how sediment yield can be quantified from a watershed experiencing rainfall-runoff erosion. In continuation of the transport process 2.4 outlines how 1D2D hydrodynamic models can be used to characterize flood waters and finally 2.5 describes how sediment transport has been studied previously and the new developments in sediment transport and deposition modelling.

2.1. Factors influencing soil erosion

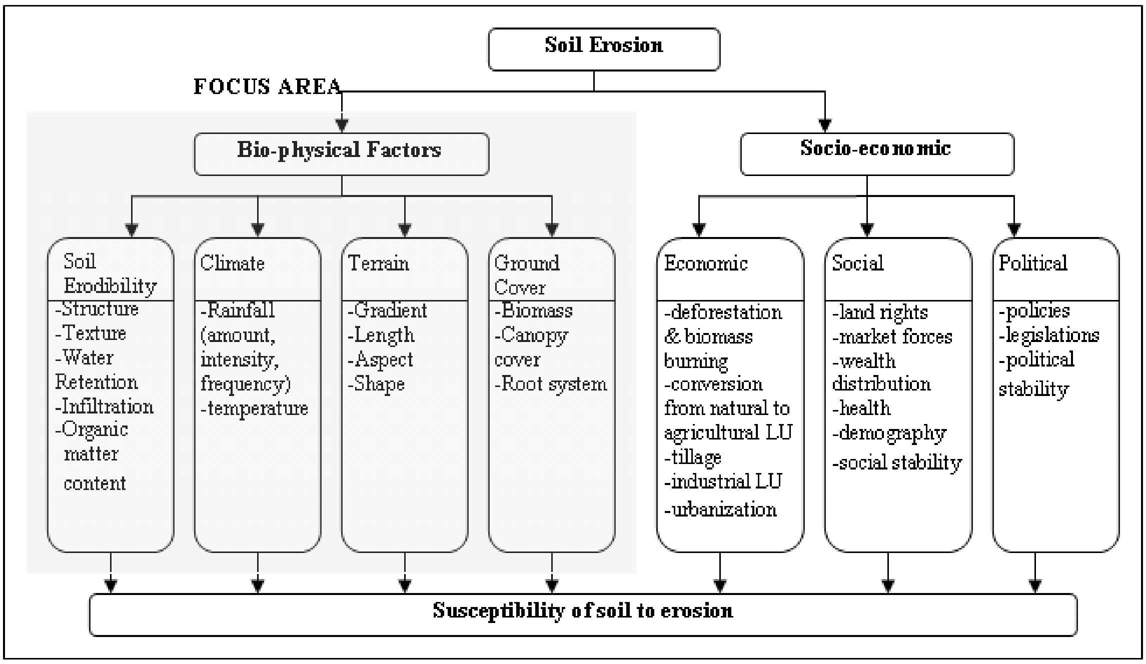


Figure 2-1: Modified diagrammatic representation of contributing factors of erosion (Lal 2001)

Detachment of sediment from the soil surface was originally considered to be exclusively the result of raindrop impact, although importance of overland flow as an erosive agent has now been recognized (Merritt, Letcher, and Jakeman 2003). Dethatched particles and micro aggregates are transported by flowing water (overland flow and interflow) and deposited when the velocity of water decreases by the effect of slope or ground cover. Before sediments are transported they must be dethatched from the soil mass or be in a dethatched state. The distance of physical displacement may range from a few millimetres to thousands of kilometres, and the time lapse from detachment to eventual deposition may range from a few seconds to thousands of years (Lal 2001). There are many factors contributing to soil erosion, both bio-physical and socio-economic. However, when evaluating where and when eroded sediments are transported and deposited, the bio-physical factors are directly related and will be considered (See Figure 2-1).

2.1.1. Soil Erodibility

Soil erodibility defines the resistance of the soil to both detachment and transport, based on the physical characteristics of the soil (Morgan 1995). The resistance of soil to erosion is linked to the degree of aggregation into soil particles and the stability of the particles. The corresponding soil characteristics that describe the ease with which soil particles may be eroded are soil detachability and soil transportability (Schwab 1993). Generally, soil detachability increases as the size of the soil particles or aggregates increase, inversely soil transportability increases with a decrease in the particle or aggregate size. The properties that influence erosion includes soil structure, texture, organic matter, water content, clay mineralogy and density and compactness, as well as chemical and biological characteristics of the soil (Shelton 1987). Schwab emphasizes that no single soil characteristic or index has been identified as a satisfactory means of predicting erodibility.

2.1.2. Climate

The primary climatic factors that influence soil erosion are rainfall amount, intensity and frequency. Soil detachment and transport by rainfall (raindrop splash) is greatest and most evident during short duration, high intensity thunderstorms. During an intense rain storm, most of the rainfall will become overland flow depending on the soil characteristics. This is due to either the high level of soil saturation or the high initial soil moisture content. Although the erosion caused by long lasting and less intense storms is not as spectacular or noticeable as that produced during thunderstorms, the amount of soil loss can be significant, especially when compounded over time (Shelton 1987).

Temperature is a climatic factor that also influencing erosion. It determines the amount of organic matter that accumulates on the surface and incorporates with the topsoil layer. Organic matter acts as a protective shield from the impact of precipitation and soaks up rainfall that would otherwise become runoff.

2.1.3. Slope

The likelihood of soil erosion is directly related to the slope steepness. Expressed in the simplest terms, steep land is more susceptible to water erosion than flat land for the obvious reason that the erosive forces, splash, scour, and transport, all have a greater effect on steep slopes (Hudson 1996). In flat or gently sloping areas, water infiltrates before it is able to runoff at the surface. The velocity of overland flow is considerably slower on gentle slopes, in this case water has less ability to erode and transport soil particles. On steeper slopes, overland flow occurs before the soil is fully saturated. The velocity of runoff is much greater on a steeper slope and therefore has a greater ability to remove and transport soil.

2.1.4. Vegetation

Vegetation provides a protective cover on the land which sheilds the soil from rain splash erosion and prevents soil erosion by slowing down runoff allowing more time for infiltration to occur. Plant roots act as a cohesion mechanism to prevent soil from being washed away (Morgan 1995). The loss of protective vegetation through deforestation, over-grazing, ploughing, and fire makes soil susceptible to being removed by water. Additionally, over-cultivation and compaction cause the soil to lose its structure and cohesion which makes it more likely to be eroded. Erosion removes the top-soil first. Once this nutrient rich layer of soil is gone, few plants grow in the soil again.

2.2. Streamflow and surface runoff in a watershed

Streamflow is the flow rate, or discharge, of water in cubic feet per second (ft^3/s) or cubic meters per second (m^3/s), along a defined natural channel which may vary in size from the one containing the smallest trickle to the ones containing the largest rivers. It is the component of the hydrologic cycle which transfers water, originally falling as rain onto a watershed, from the land surface to the oceans. Hence, streamflow at a particular point on a channel system is contributed by runoff from the watershed (also known as the *catchment* or *drainage basin*) upstream of that point, and return flow from the ground water aquifer [(Maidment 1993),(Ward and Robinson 1990)].

Streamflow is generated by precipitation during rainstorm events and by groundwater entering surface channels. During dry periods, streamflows are sustained by groundwater discharges (Viessman, Lewis, and Knapp 1989).

When precipitation occurs, it may initially distribute to fill depression storage, infiltrate to fill soil moisture and ground water, or travel as interflow to a receiving stream. Subsurface lateral flow or interflow occurs through soils on slopes, or when vertical flow into the subsoil is impeded. Lateral flow of ground water is much slower than surface runoff and interflow and provides the bulk of the stream's baseflow. The difference between what infiltrates and that running off constitutes surface runoff or overland flow which generates a rapid response in streamflow in a catchment ((White 1997); (Bedient and Huber 1988))

Overland flow occurs on hillsides during a rainstorm when surface depression storage and either, in the case of prolonged rain, soil moisture storage or, with intense rain, the infiltration capacity of the soil are exceeded (*hortonian overland flow*) (Morgan 1995). The rate of runoff flow depends on the ratio of rain intensity to the infiltration rate. If the infiltration rate is relatively low, such as when a soil is crusted or compacted, and the intensity is high, then the runoff rate will also be high (USDA-ARS-MWA 2008). Overland flow is generally described in literature as a uniform sheet of water. However, in reality this is rarely the case. More commonly overland flow is a mass of braided water courses with no defined channels. The flow is separated by large stones, cobbles and vegetation cover.

A flood event as a result of runoff is caused from short duration highly intense rainfall and long duration low intensity rainfall. Flood runoff has often been considered to consist of surface runoff produced at the ground surface when hortonian overland flow occurs. Saturated overland flow and throughflow are now recognized as two other processes which may contribute to flood runoff as a result of observations on natural watersheds during storm periods and many detailed studies of instrumented plots and small areas (Maidment 1993).

2.3. Estimating sediment yeild

Erosion modelling is based on an understanding of the physical laws and landscape processes such as runoff and soil formation occurring in the natural environment. Modeling translates these components into mathematical relationships, describing the fundamental water erosion processes of detachment, transport and deposition (Jetten 2003). The construction and application of watershed models describing precipitation to streamflow processes has been the prime focus of hydrological research and investigations for many decades (Jakeman 1993).

Soil erosion prediction has been a challenge to scientists since the 1930s and several models have been developed, with every model having limitations in terms of its representation of erosion processes. Erosion and runoff models can be divided into three main categories depending on the physical processes simulated. These three categories are empirical, physically based and conceptual [(Lal 2001), (Morgan 1995), (Jetten, de Roo, and Favis-Mortlock 1999), (Jetten 2003)]. A selection of erosion models were examined in this study in order to understand the various processes they represent, data requirements and limitations (See Table 2-1).

Table 2-1: Selection of erosion and sediment transport models

Model	Type	Spatial scale	Temporal scale	Input requirements	Output
LISEM	Physical	Small catchment	Event	High	Runoff, sediment
WEPP	Pysical	Hillslope/catchment	Continuous	High	Runoff, sediment, soil loss
SWAT	Conceptual	Catchment/basin	Continuous	High	Runoff, erosion, sediment
USLE	Empirical	Hillslope	Annual	High	Erosion

Empirical models are generally the simplest of all three model types. They are by strict definition based on observation and experiment, not on theory. These models usually have a high spatial and temporal aggregation and are based on the analysis of the erosion processes using statistical techniques. They are particularly useful as a first step in identifying the sources of sediments. However, empirical models are often criticised for employing unrealistic assumptions about the physics of the catchment system, for ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and soil types, and for ignoring inherent nonlinearities in a catchment system ((Merritt, Letcher, and Jakeman 2003); (De Roo 1993)).

In contrast to empirical models physically based models are based on an understanding of the physics of the erosion and sediment transport processes and describes the system using equations governing the transfer of mass, momentum and energy (Kandel 2004). Physically based, spatially distributed models simulating hydrologic and soils erosion processes at a catchment scale should be able to predict spatial patterns of erosion and deposition in a catchment. A well-known problem with the application of those physically based models is the requirement of large number of input parameters and variables, which are spatially and temporally variable and not always easy to measure or estimate (Takken et al. 1999).

Conceptual models are characterized based on the representation of a catchment as a series of internal storages. They typically integrate the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in the catchment as a series of storages, each involving some characterization of its dynamic behaviour. Conceptual models have a propensity to include a broad description of catchment processes, without including details regarding the process interactions, which would require specific catchment information (Merritt, Letcher, and Jakeman 2003).

In this study, the upper catchment determines the sediment yield which exits the watersheds outlet. A physically based model was used to simulate rainfall-runoff for designed flood events. A physically based model is preferred because models which are physically based provide a platform for quantitative modelling of both discharge and sediment yield at an outlet.

2.3.1. Limburg Soil Erosion Model (LISEM)

The Limburg Soil Erosion Model (LISEM) (See Chapter 4 for more detail) is a physically based hydrologic and soil erosion model, developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division at the Winanrd Staring Centre in Wageningen, the Netherlands, for planning and conservation purposes. LISEM has been designed to simulate runoff and erosion for event based rainstorms in agricultural catchments ((Merritt, Letcher, and Jakeman 2003); (De Roo and Jetten 1999)).

The LISEM model generates totals for such variables as runoff, sediment yield, infiltration and storage depression. Output maps showing the spatial distribution of soil erosion and deposition, and maps of overland flow at user defined time intervals during simulation are also produced by LISEM. In addition, the model is capable of producing hydrographs and sediment graphs for a rainfall event simulation which can be compared to measured discharge data.

2.3.2. The Watershed Erosion Prediction Project (WEPP)

The Watershed Erosion Prediction Project (WEPP) is a physics based model developed in the United States. The purpose of this model is to estimate sediment yield of a watershed (a non-point source) and to assess the cost effectiveness of possible land use treatments within the watershed. The model has been applied to hill slopes widely in the United States and worldwide with a daily timestep simulation. For everyday, plant and soil parameters relevant to the erosion process are updated ((Hudson 1996); (Merritt, Letcher, and Jakeman 2003); (Laflen 1991)).

When rainfall occurs, the characteristics of the plants and soils are considered in determining if a runoff event occurs. If runoff is predicted to happen the model calculates soil detachment, transport and deposition at frequently spaced points along the profile. However, the model does not consider erosion, transport and deposition processes in permanent channels, such as classical gullies and perennial streams ((Merritt, Letcher, and Jakeman 2003); (Laflen 1991)). An illustration of how the WEPP model can be applied to a watershed is shown in Figure 2-2.

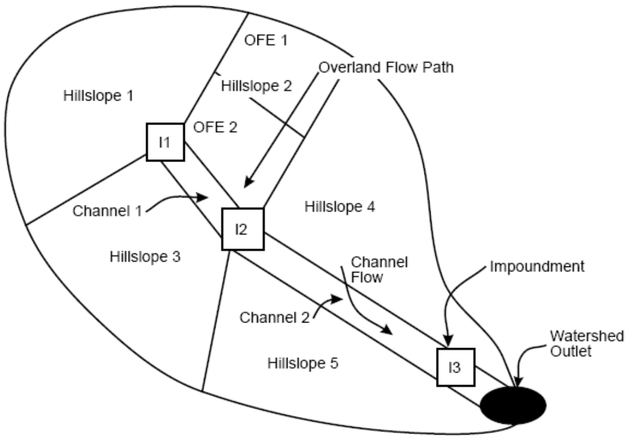


Figure 2-2: schematic of a small watershed which the WEPP model could be applied to. Individual hillslopes (1-5), or the entire watershed composed of 5 hillslopes, 2 channel segments and 3 impoundments (Flanagan 1995).

2.3.3. Soil and Water Assessment Tool (SWAT)

The soil and water assessment tool is a watershed scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). This model was designed to forecast the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying characteristics. For modelling purposes the SWAT model considers the watershed as a number of sub-watersheds.

The data requirements for the SWAT model are specific information about weather, soil properties, topography, land cover and management practices within the watershed. From these input the processes associated with water and sediment movement, crop growth, nutrient cycle etc. are modelled by SWAT. This model is a continuous time model, which indicates the lack of simulating detailed, single flood events (Neitsch 2005).

2.3.4. Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) was created by the USDA-Agricultural Research Service for use as a conservation planning and assessment tool. The equation utilized by USLE to estimate erosion is, $A=R \cdot K \cdot L \cdot S \cdot C \cdot P$ where A is the computed spatial average soil loss and temporal average soil loss per unit area. The factors within the equation are rainfall-runoff erosivity (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), cover management factor (C) and support practice factor (Renard 1997) (Nearing and Jetten 2005).

USLE was designed to predict average annual soil loss over a long period which is carried by runoff from specific field slopes in specific cropping and management systems. The model does not have the capability of routing sediments through channels, for this reason its application is limited to small areas (Renard 1997). The data requirements for USLE are low in comparison to other models. These include annual rainfall, land cover information, topographic information and a estimate of soil erodibility is required (Merritt, Letcher, and Jakeman 2003).

2.4. 1D2D Hydrodynamic modeling

Wave phenomena are ubiquitous in nature according to Singh. Treatment of these phenomena is vital to dealing with a range of problems in hydraulics, hydrology and soil science among other related fields. Water waves can occur in all conditions where the surface of water is free to move. When a steady open channel flow is distributed, waves are created and the flow becomes unsteady. Therefore, a water wave may be defined as a temporal disturbance in flow velocity which propagates through the water medium. The velocity of propagation of such a disturbance relative to the water medium is known as the wave celerity. The wave celerity can be distinguished from the local changes in water velocity that it produces and is generally of much greater magnitude (Singh 1996).

Different types of waves may develop in open channels. Table 2-2 summarizes the waves and the forces dominating them. The wave type of interest for this study is the dynamic wave. The 1D-2D hydrodynamic simulation package SOBEK solves water flow by using the full De Saint Venant equations and is specially suited to simulate the dynamic behaviour of overland flow over initially dry land, as well as flooding and drying processes on every kind of geometry, including lowlands and mountain areas ((Stelling 1998); (Werner 1999)).

Table 2-2: Shallow water waves and the forces dominating them (Singh 1996)

Wave Type	Forces Included				
	Local Inertial	Convective Inertial	Pressure	Gravity	Friction
Small gravity (or inertial waves)	X	X	X		
Diffusion (diffusive kinematic waves)			X	X	X
Diffussive (or nondiffusive kinematic waves)				X	X
Steady dynamic waves		X	X	X	X
Dynamic waves	X	X	X	X	X

Lowland flooding occurs swiftly as a result of intense rainfall in mountainous areas. Flood propagation is a very complex occurrence involving the dynamics of a fluid free boundary in intense turbulent motion under the acceleration of gravity. The floodwater is characterized by shallow waves that have water depths several orders of magnitude smaller than their wavelengths. Hence, sheet flow or shallow overland flow, resulting from the sudden outburst of an intense rainstorm, can be viewed as a kinematic wave and its movement can be described as kinematic wave propagation ((Alcrudo 1994); (Singh 1996)). This type of wave defines runoff characteristics in the Limburg Soil Erosion Model.

Numerical models of shallow water flow have proved to be useful tools in predicting in-bank and overbank fluvial hydraulics for scientific and engineering research. However, to characterize flood propagation as a function of topography, physically based hydrodynamic or hydraulic models are needed. Such models are based on the principle of conservation of mass, momentum and energy ((Alkema, Nieuwenhuis, and de Jong 2007); (Horritt 2006)).

Flood simulation can be accomplished using one of many approaches that differ in representation and numerical implementation. Hydraulic models can be classified according to the number of dimensions in which they represent the spatial domain and flow processes, and for particular problems a one, two or even three dimensional model may be appropriate. Limiting factors include computational feasibility and the problems of accurately representing turbulence (Hunter et al. 2007). Therefore, due to the complexities involved in three dimensional modelling, dynamically varying flows in compound channels have to date, been treated predominantly with 1D and 2D models.

Flood levels and discharges in river systems have been widely studied with the aid of one dimensional hydrodynamic models. These models allow for fast evaluation of distributed water levels and discharges in both dendritic and networked river systems. One dimensional models of river hydraulics are on average parameterised through a series of cross-sections of channels perpendicular to the flow direction and flood plain topography which can be derived from ground surveys at a reasonable cost. Such models have been shown to give good predictions of bulk flow properties and water surface elevations despite topography being limited to a minimal number of widely spaced cross-sections (Horritt 2006). A number of one dimensional model are being used recently, among the popular 1D flood models are HEC-RAS, which is designed by the United States Army Corps of Engineers, MIKE 11 produced by the Danish Hydraulic Institute. However, as with many other 1D models, these have severe problems in simulating water depth and velocity when overbank discharge occurs.

Although 1D flow modelling is computationally very efficient it suffers from a number of drawbacks when applied to floodplain flows. Some of these include the inability to simulate lateral diffusion of the flood wave, the discretization of topography as cross-sections rather than as a surface and subjectivity of cross-section location and orientation. All of these fundamental constraints can be overcome with the aid of two dimensional modelling [(Hunter et al. 2007), (Sanders 2008)]. 2D models are capable of providing information on the inundation depth of overbank flow and its spatial distribution but also the variation of flood extent and flow velocities over a user-defined time frame. Thus, 2D models are becoming more and more popular among the modelling community nowadays. Among the popular 2D flood models are LISFLOOD FP, Telmac 2D, TELEMAC-2D, SMS, Delf FLS and SOBEK.

The combination of one dimensional and two dimensional modelling in one model (eg. MIKE_FLOOD, SOBEK) solves the problem of balancing the requirements for a high resolution representation of main channel flow and overbank inundation. SOBEK-Rural, developed by WL | Delft Hydraulics is a fully dynamic 1D2D hydraulic model, specifically designed for floodplain inundation modelling. This model is suited to simulate the dynamic behaviour of overland flow over an initially dry area, as well as flooding and drying processes on every kind of geometry (Dhondia 2002). In this study the SOBEK hydrodynamic model is used to characterize the propagation of flood waters in a lowland flood plain. Chapter 5 includes details on the application of this model.

In SOBEK both the 1D and the 2D computational layers have finite difference formulations for volume and momentum equations, based on staggered grid approach (See Figure 2-3). In the schematization, the 1D domain is modelled with the de Saint Venant equations applied over the full water depth. Above this level, the flow description in the 2D cell takes control. SOBEK allows for very efficient and also realistic flooding of dry beds when the 1D rivers are flooding their 2D surroundings
((Verwey 2006); (Dhondia 2002)).

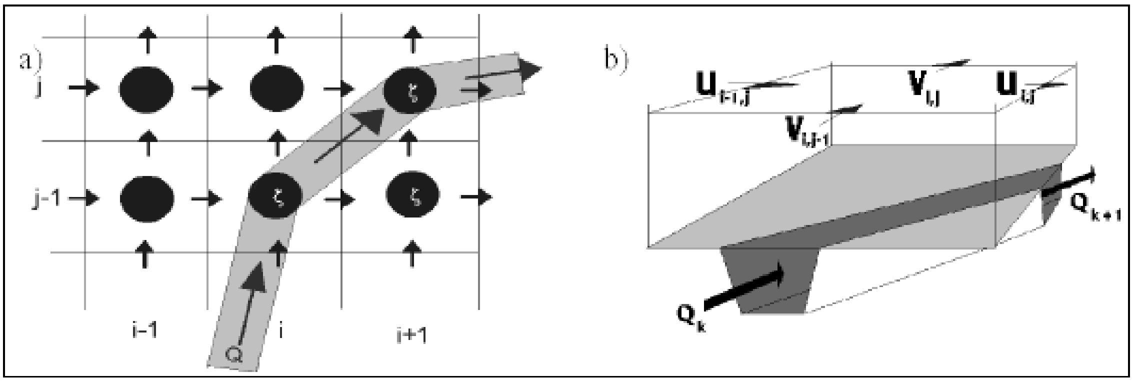


Figure 2-3: Schematisation of the hydraulic model: (a) combined 1D2D staggered grid and (b) combined finite mass volume for 1D2D computations (Dhondia 2002)

2.5. Modelling sediment transport

When the entire motion of a solid particle is such that it is surrounded by fluid, it is said to be in suspension. Sediment transport is determined by the size, shape, concentration, fall velocity and bulk density of particles. Depending on the weight of the particles, there is an inclination for settling, which however is counterbalanced by the irregular motion of the fluid particles. Consequently, the hydraulic conditions of a stream determine if and when a given size fraction will be in suspension. Sediment particles which are a part of suspended load at one time may, at another time, be part of the bed load. There is an active substitution between the suspended load and bed load, but also between the bed load and the bed itself ((Maidment 1993); (Graf 1984)).

Suspended sediment dynamics are still imperfectly understood according to Rovira. Over the last several years, interest in overbank processes has become greater than before, due to the need for an improved understanding of the suspended sediment dynamics of lowland river systems. Also, an increased concern for environmental issues such as the transport of sediment associated contaminants, reservoir sedimentation, channel and harbour silting, soil erosion and loss[2] as well as the ecological and recreational impacts of sediment management suggests the need to understand the mechanics of suspended sediment transport (Rovira and Batalla 2006).

Lowland river floodplains are significant components of the drainage basin system, acting both as transportation channels and storage zones during the passage of floodwaves, and as sinks for suspended sediment deposited during such periods of overbank flow. The amounts and patterns of sedimentation on floodplains for the duration of overbank flooding depends on various factors, including frequency and duration of inundation, suspended sediment concentration in the main channel, and the flow patterns and stream velocities in the floodplain ((Nicholas 1997); (Middelkoop 1998)).

In the past decade, several authors have developed one and two dimensional models to replicate patterns of sediment deposition on floodplains. Some of these models structure is the finite element approach eg. (Hardy 2000), other models on finite difference approach. Finite element models are advantageous because they employ a mesh that can be optimised for local situations to reduce numerical errors. However, these models have the disadvantage that their output cannot be imported

[2] Soil loss refers to the transport of soil away from the site of origin.

directly into a raster GIS for further processing (Thonon 2007). This limitation is solved with the use of dynamic models.

A primary prerequisite for dynamic models of floodplain hydraulics and sediment transport is the need to be able to represent a continuously deforming flow field boundary. The need to incorporate areas which are not inundated within the model, in an attempt to represent a dynamically moving flow boundary, highlights several difficulties that fixed grid finite element solvers for fluvial sediment transport have, so far, failed to overcome. Previous numerical approaches to river sediment transport modelling have thus either been confined to fully inundated domains or have applied exclusively to steady state flows (Hardy 2000).

Delft Hydraulics has developed a one dimensional and two dimensional Water Quality model in SOBEK-Rural that can be used simultaneously with the 1D2D flow component. The Water Quality simulations in SOBEK are described by the full de Saint Venant equations which characterize unsteady flow in channels and pipes coupled with the complete shallow water equations for overland flow. The 1D2D flow domain is computed jointly while the Water Quality calculations separate the 1D domain from the 2D. The exchange of sediments between channels and inundated areas can be simulated with the combination of these models over an initially dry area (Delft Hydraulics 2007).

Several boundary conditions are available including tides, floods, hydraulic structures, rainfall, evapotranspiration and the effect of wind. The simulated flow from the SOBEK-flow model provides the foundation for the simulation of transport, dispersion and interaction of a user defined set of water quality parameters, such as nutrients, heavy metals, organic micro pollutants, temperature, algae, oxygen, suspended sediments, etc These processes are defined in the Water Quality processes library, which is an extensive collection (Delft Hydraulics 2008).

Delft Hydraulics has carried out various studies since the development of the Water Quality model in 1997. These studies are predominantly for riverine floods and to a lesser extent dam breach scenarios. Due to the successful application of this model in other researches, the applicability to flash floods was tested in this study (See Section 5.3 for more detail).

3. Case study area and research procedure

This chapter is divided into four sections which firstly introduce the case study area (3.1), and then the overall methodology is presented (3.2), after which the specific research procedures carried out in order to achieve the objectives of this study (3.3) which is further divided into pre-fieldwork procedure, fieldwork procedure and post-fieldwork processing. Finally the materials and software implemented to accomplish the final results (3.4).

3.1. Study Area

The case study area is located in the Nam Chun sub-watershed and consists of an upper catchment and a low land flood plain, situated in Petchabun province, north central Thailand. It lies between latitudes $16^{0}40'$ to $16^{0}50'$ North and longitude $101^{0}02'$ to $101^{0}15'$ East (See Figure 3-1)

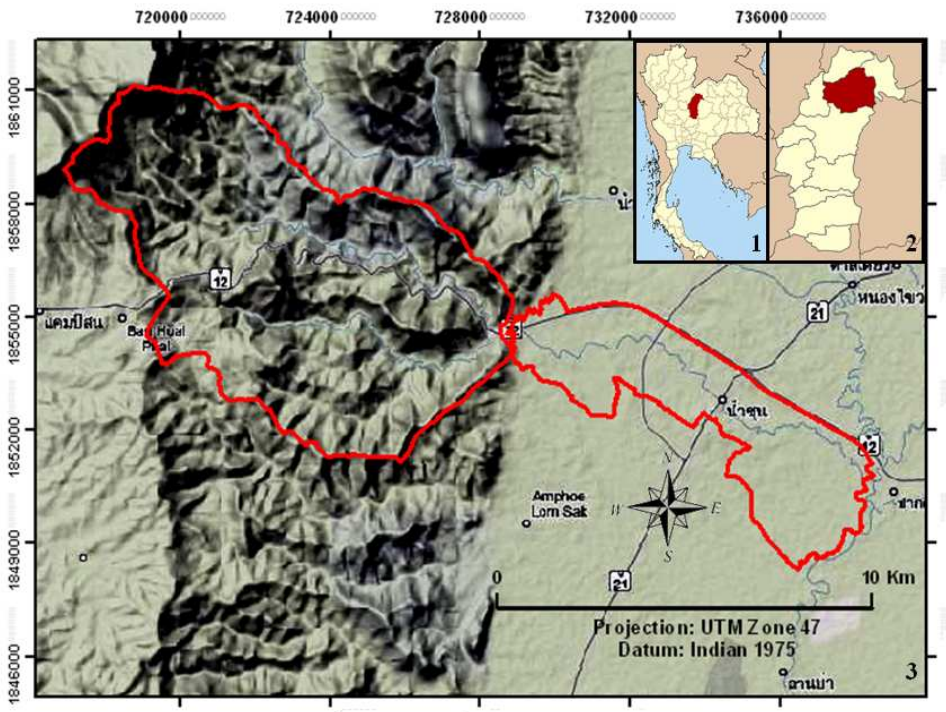


Figure 3-1: Location map showing (1) Thailand highlighting Phetchabun province, (2) Lom Sak District in Phetchabun Province and (3) Upland and lowland study extent

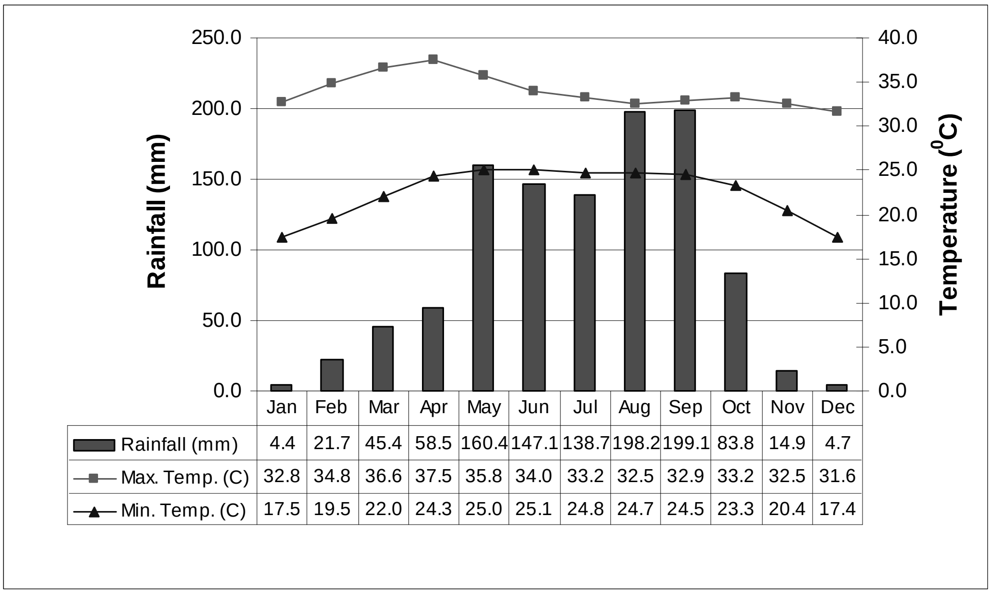
The watershed which spans across an area of approximately 92km^2 and is a part of a larger river basin of the Pa Sak River which flows North to South and with elevations ranging from 240 to 1,509 m AMSL in the upland area. The low land flood plain of the Nam Chun catchment has a slope gradient of 0-2%, making the area susceptible to flooding during the rainy season which begins in July and ends in October. In August 2001 a typhoon Usagi devastated the area, causing landslides in highland areas, and flooding in the lowlands (See Figure 3-2).

Figure 3-2: (1) Oblique aerial photograph perceivably illustrating the large volumes of deposited sediments and (2) Photographs showing sediment rich water and structural damage

3.1.1. Climate

Thailand's climate is tropical, both high humidity and temperatures are experienced throughout the year. The temperatures are highest between March and May, while a part of the year is dominated by the northeast and southwest monsoons with an average rainfall of 1,000 mm. Thailand experiences three seasons; a cool and dry winter (November to February) with temperatures ranging from 30^0-35^0 C and humidity between 50% - 60%, a sweltering summer (March to June) where temperatures can soar to 40^0 C and a rainy season (July to October). By late September and October, the major rivers are high and there is sometimes permanent flooding along these areas. Most of the country suffers from flooding, particularly in the north, north eastern and central regions.

The Nam Chun area experiences an average annual rainfall of 1076.9mm with maximum rainfall in one month reaching as high as 199.1mm. The mean annual temperature of the area is 34^0 C with the highest temperature recorded in April as 37^0 C (See Figure 3-3).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	4.4	21.7	45.4	58.5	160.4	147.1	138.7	198.2	199.1	83.8	14.9	4.7
Max. Temp. (C)	32.8	34.8	36.6	37.5	35.8	34.0	33.2	32.5	32.9	33.2	32.5	31.6
Min. Temp. (C)	17.5	19.5	22.0	24.3	25.0	25.1	24.8	24.7	24.5	23.3	20.4	17.4

Figure 3-3: Average annual rainfall and temperature of the study area (1970-2007)

3.1.2. Geology

The Nam Chun watershed is a part of the central highlands in Thailand. The upper part of the watershed is predominantly created by uplifted sedimentary rocks from the gently westerly dipping Khorat Group. The oldest rocks are of the Huai Hin Lat formation which consists of conglomerate, sandstone and shale, partly intercalated with andesitic tuff and agglomerate. Following the Huai Hin Lat formation is the Nam Phong which consists of reddish-brown cross-bedded sandstone and conglomerate. Both formations were created during the upper Triassic period. The next formation is the Phu Kradung formation which consists of shale, siltstone and sandstone, this is present in the scarp of the study area and was formed in the Jurassic period. The youngest formation of the Khorat Group within the study extent is Pha Wihan which consists of white and pink, cross-bedded sandstone with some intercalations of the reddish-brown and grey shale. The lower part is characterized by quaternary colluvial and alluvial terrace deposits ((Solomon 2005; Kunda 2004; Yumuang 2006; Sapkota 2008; Prachansri 2007)).

3.1.3. Soils

Soils in the upland area are mostly derived from sedimentary rocks and are mainly categorized into silty loam and silty clay loam (Sapkota 2008). The soils in the area are very shallow to moderately deep and well drained in the upper catchment. The soil temperature regime is classified as isohyperthermic, which is described by the Soil Survey Staff of 1996 as the condition where the difference between the hottest and coolest temperatures of the soil is less than 5^0C and the average annual temperature is greater than 220C (Kunda 2004). The soil temperature regime dictates the soil moisture regime, in this area it would be classed as Ustic. This means moisture that is restricted but is present at a time when conditions are suitable for plant growth.

3.1.4. Landuse/land cover and farming practices

The steep mountain slopes in the study area are mainly forested, although in some areas there is evidence of degraded forests and the lowlands are traditionally used for growing rice in the wet season. Where irrigation water is available, crops such as mungbeans, soybean and tobacco are grown after the rice is harvested. Most of the lands in the upland area have been deforested in the last 25 years and are now used mainly for maize cultivation, and locally groundnuts, as a single cash crop, sometimes followed by mungbeans as a second crop. At present land use is mainly grassland, agricultural land and patches of forest (Patanakanog et al. 2004).

3.2. Overall Methodology

The overall methodology is simplified in diagrammatical flow chart in Figure 3-4. The first step in the process was data collection in the case study area, followed by analysis of the collected and available datasets. The main step in the simulation of rainfall-runoff in the upland catchment was done using the LISEM model with the designed rainstorms being the main input parameters. The results from LISEM were the input boundary conditions in the 1D2D Hydrodynamic model (SOBEK-flow) and the 1D-2D Water Quality model (SOBEK-2DWAQ). The final step of "Assessment of upland erosion processes on lowland flood risk" is a further step that is desired for continued study.

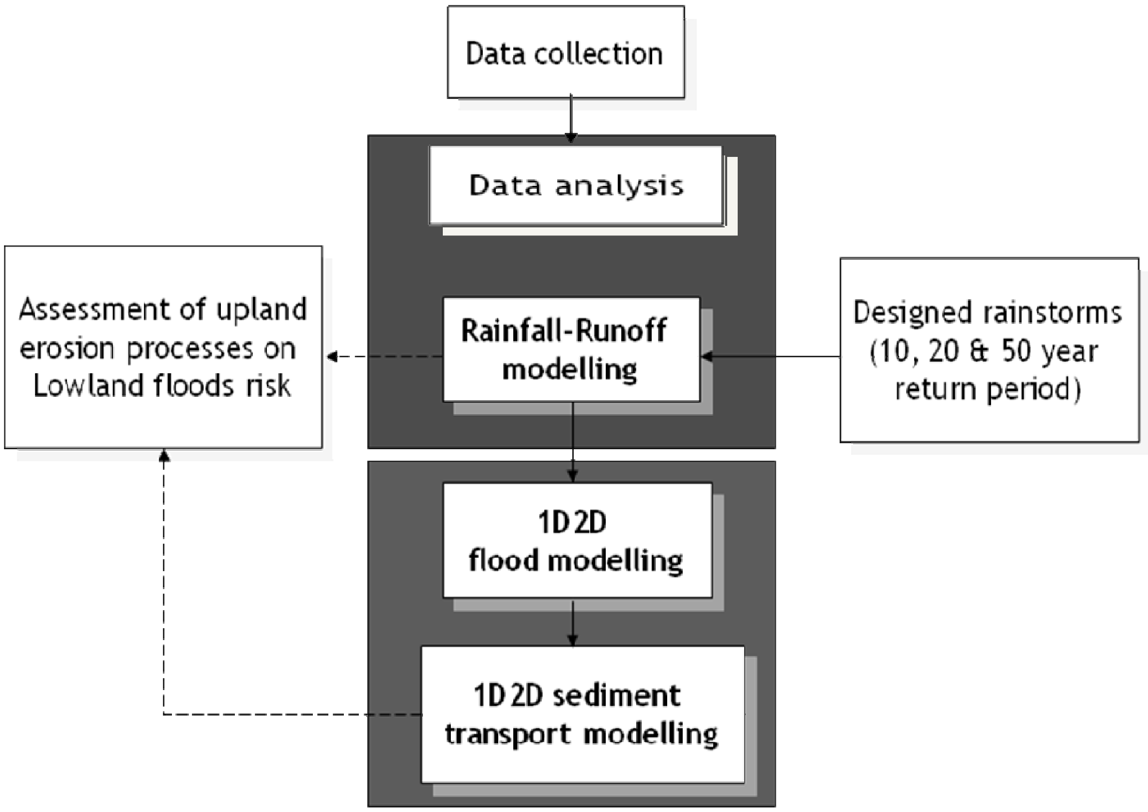


Figure 3-4: Methodology Overview

3.3. Research Procedure

The research procedure is divided into three parts; the pre-fieldwork procedure (3.3.1), the fieldwork procedure (3.3.2) and the post field work processing (3.3.4).

3.3.1. Pre-fieldwork procedure

The pre-fieldwork phase of the research was used to gather information from previous researches done on related fields, identifying areas that were not studied in detail in an attempt to fill scientific gaps and provide an avenue for continued research for the improvement in hydrological modelling and further understanding of sediment transport. The following activities were also carried out during this phase:

- Collection of relevant data in relation to the study area
- Preparation of interview sheet and identification of group interview locations
  (See Appendix 1)
- LISEM and SOBEK tutorials
- Design methods and acquire materials for data collection
- Aerial photo image interpretation

3.3.2. Field work procedure

The field work procedure involved collection of primary and secondary data for a period of 3 weeks in the month of September 2008. The field work started with reconnaissance and planning to locate suitable investigation sites, identify accessibility to various areas of interest and design an efficient transport plan based on the study area locations of accompanying colleagues.

3.3.3. Primary data collection

Primary data collection included validation of an existing land cover map, bridge and culvert profiles, Nam Chun catchment outlet velocity measurements and group interviews.

3.3.3.1. Land cover map validation

A land cover map of the lowland study area was created by using an existing land cover map created by the LDD, (1999) in a mobile GIS, IPAQ. This land cover map was used as a starting point to navigate around the study area and identify the changes that have occurred over time.

3.3.3.2. Bridge and culvert profiles

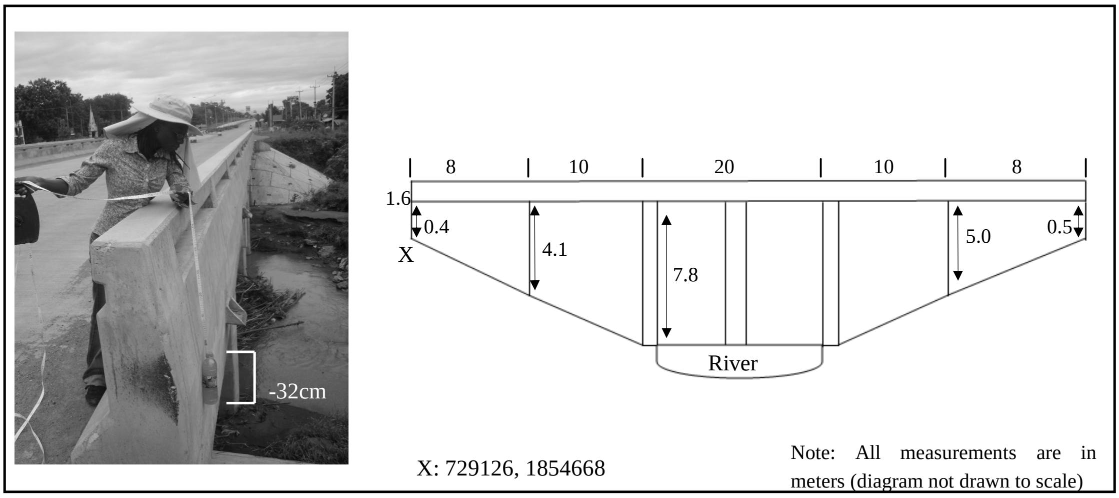


Figure 3-5: Bridge profile measurement procedure and example of profile obtained

The importance of engineering features such as bridges and culverts were considered for the reason that the inclusion of such features may have an impact on flood propagation and sediment routing and deposition. Therefore, 13 bridge and 15 culvert profiles were measured as input features for the SOBEK hydraulic model. A weight was attached to a 30m tape and lowered to measure the vertical distances. The length of the weighted object used was subtracted from all measurements to obtain the "true" distance (See Figure 3-5). A note was also made about the type (round/square) and approximate width of the support columns of each bridge.

3.3.3.3. Outlet velocity measurements

The velocity measurements were carried out by taking the total width of the channel and measuring the velocity with a current meter at four intervals along a measuring tape (See Figure 3-6). The final results of the average velocity exiting the catchment outlet were calculated with the consideration of the current meter's constants. (See calculations below)

Figure 3-6: Velocity measurement procedure

Calculations:

- 10 counts are equal to 1 rotor revolution
- Time of observation = 30 seconds
- Standard speed rotor constant = 26, 873

A. Distance in meters = $\frac{\text{Difference in Counts * Rotor Constant}}{999999}$

B. Speed cm/sec = $\frac{\text{Distance in meters * 100}}{\text{Time in seconds}}$

C. Volume m3 = $\frac{\text{3.14*(Net diameter)2}}{4}$ * Distance

Table 3-1: Discharge calculations

Discharge Calculations							
Av. Depth	Av. Revolutions	Difference in Counts	Dist. (m)	Speed (cm/sec)	Speed (m/sec)	Area (m2)	Q (m3/s)
0.37	114.75	1147.50	58.55	195.15	1.95	6.62	12.91
0.43	109.75	1097.50	29.49	98.31	0.98	7.70	7.56
0.43	109.75	1097.50	55.99	186.65	1.87	7.79	14.53
0.33	79.75	797.50	40.69	135.63	1.36	5.85	7.93
				Average Discharge (Base flow)			**10.73**

3.3.3.4. Interviews

Four group interviews were carried out in villages within the lowland study extent (See Figure 3-7). These interviews allowed the experiences of the people in the area to be incorporated in the GIS results. The questions were in reference to the 2001 event which occurred in the area. This is event was recorded as a 20 year return flood by the LDD. For each interview session a “village head” was contacted to organize and mediate the meeting. Also the aid of the “soil doctor” for the region was requested. This person is an expert on the farming practices and soil properties in the Lom Sak district. Based on the interviews, a fuzzy outline of the probable deposition zones was delineated (See Chapter 6). This served as a validation platform for model outputs.

Figure 3-7: Group interview session

Table 3-2: Interview Locations

Village	Coordinates	
Namchun Hin Ngong	735403	1852098
Namchun Yai	728881	1854723
Ban Mai Patana	735403	1852098
Ban Non Tong	736183	1851023

3.3.3.5. Secondary data collection

Secondary data collection involved visits to various offices including the Land Development Department (LDD) in Phetchabun for information on farming practices in Nam Chun and Lom Sak and organizing group interviews. The metrological station in Lom Sak was visited to acquire climatic data.

3.3.4. Post field work processing

The post field work phase of the study involved the simulation of surface runoff and erosion in the upland area and modelling flood propagation and two dimensional sediment transport in the low land area. Various return period scenarios were generated from historical rainfall events to assess the spatial distribution of sediment deposition in low land as a result of the erosion occurring in the upland area.

3.4. Materials and software

The materials and software used in this study is outlined in Table 3-3 and Table 3-4 below.

Table 3-3: Materials used

Materials	Type	Scale	Source
Contour map	Digital	10m	LDD
Land cover map	Digital	1:25, 00	Prachansri, 2007
K’sat map	Digital		Prachansri, 2007
DSM	Digital		Prachansri, 2007
Soil map	Digital		Solomon, 2004
Climatic data	Sheets	N/A	Royal Irrigation Dept.
Topographic maps	Sheets	1:50,000	ITC
Soil particle size results	Lab experiments	N/A	Watsusi, 2009

Table 3-4: Software used

Software	Purpose
Microsoft Office Word	Writing text
Microsoft Office Excel	Calculations and creation of graphs
Endnote	Reference aid
Rankplot	Analysis of historical rainfall data
PCRaster	Construction of LISEM input data
ILWIS	Image processing
ARCGIS 9.0	Map outputs and image processing
LISEM	Surface runoff modelling
SOBEK	1D2D Flood modelling and 1D2D sediment transport

4. Surface runoff modeling

4.1. Introduction

In this study The Limburg Soil Erosion Model (LISEM) was used to estimate runoff and sediment yield from an upland catchment. LISEM is a physically based hydrologic and soil erosion model constructed with the PCRaster dynamic modelling language to describe interception, infiltration and soil water transport, storage in surface depressions, splash and flow detachment, transport capacity and overland and channel flow. When there is limited data available, the user can choose Green and Ampt or the Hotan equation to calculate infiltration. The model is fully incorporated in a raster GIS for ease of use and was designed to simulate event based rainstorms in agricultural catchments ranging from 1 ha to 100 km^2 ((De Roo and Jetten 1999); (De Roo 1995)).

4.2. The LISEM model structure

The structure of the LISEM model can be divided into hydrological and erosion processes (See Figure 4-1). In the model, interception is subtracted from rainfall and the residual is either infiltrated or stored on the surface. However, when the soils maximum capacity is exceeded surface runoff will occur. The main parameters that determines the infiltration and as a result, the amount of runoff and erosion are the hydraulic conductivity and initial moisture content (Hessel et al. 2003; Hessel 2002).

Vertical and lateral movement of water in the soil is simulated using the Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right)\right]$$

Equation 4-1: Richard's equation

Where:

K is the hydraulic conductivity,

ψ is the pressure head,

z is the elevation above a vertical datum,

θ is the water content, and

t is time

The erosion processes of LISEM are simulated by rainfall splash, overland flow and channel flow. The kinematic energy of the rainfall and the depth of an existing surface water layer are used to calculate the splash erosion. Overland flow and channel flow are the erosion forces that transport sediments.

An important characteristic of the LISEM model is that it is grid based. Therefore, flows are determined locally in each grid cell. Due to this feature, when the slope angle changes abruptly, LISEM may simulate sudden deposition because it assumes that the transport capacity decreases radically (Hessel et al. 2003). However, in this study runoff processes and sediment yield are the major factors considered.

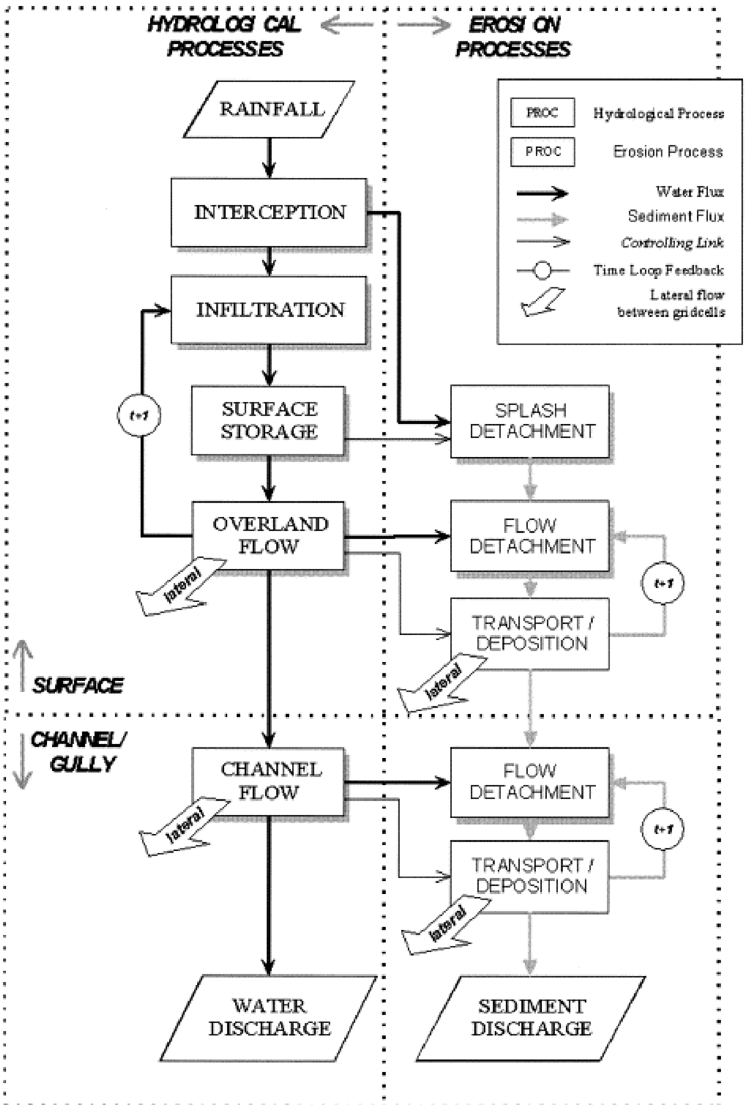


Figure 4-1: Flowchart of the LISEM model structure (De Roo and Jetten 1999)

4.2.1. LISEM input maps

The LISEM model is process based and requires large amounts of input data. Once field data is available most of the required maps can be obtained from 3 basic maps: DEM, soil map and land cover map (Hessel 2002). This study is a continuation of the research done by Prachansri (2007); therefore, fieldwork data collection was primarily concentrated in the lowland area. The basic input maps used were the DEM, soil map, and land cover map, which were a compilation of those created by Prachansri (2007), Solomon (2005), and the Land Development Department of Thailand (2004) respectively (See Appendix 2-Appendix 4). The improvement made to the runoff model generated by Prachansri (2007) was the addition of a base flow parameter.

Table 4-1: Input data for LISEM version 2.56, with the use of the Green and Amt infiltration sub model.

Parameter	Name	Method	Unit
Basin characteristic			
Local drain direction	Ldd.map	derived from DEM	-
Catchment area	Area.map	derived from DEM	-
Rain gauge locations	Id.map	Mapping	-
Slope gradient	Grad.map	derived from DEM	-
Location of outlet	outlet.map	derived from DEM	-
Rainfall data	*.tbl	Prachansri, 2007	mm/hr
Soil and land use			
Leaf area index	Lai.map	derived from PER.map	-
Plant cover	Per.map	field observation	-
Plant height	Ch.map	field observation	m
Manning's n scalar	n.map	derived from literature	-
Random roughness	rr.map	derived from literature	cm
Road width	roadwidt.map	mapping	m
Green and Ampt Layer 1			
Saturated hydraulic conductivity	Ksat1.map	Prachansri, 2007	mm/hr
Saturated volumetric soil moisture content	Thetas1.map	Prachansri, 2007	-
Initial volumetric soil moisture content	Thetai1.map	Prachansri, 2007	-
Soil water tension at the wetting front	Psi1.map	derived from literature	cm
Soil depth	Soildepth1.map	Solomon, 2005	mm
Channels			
Drainage direction	Lddchan.map	derived from ldd.map	-
Channel gradient	Changrad.map	derived from grad.map	-
Manning's n for the channel	Chanman.map	derived from literature	-
Width of channel scalar	Chanwidt.map	derived from ldd.map	m
Channel cross section shape	Chanside.map	field observation	-
Channel base flux	Chanbaseflux.map	derived from channel mask	m^3/s
Initial channel volume	Chanvini.map	derived from channel mask	m^3
Increase in base flux	Chanincrease.map	derived from channel mask	-

4.2.2. Model parameterization

The allotted time for field data collection is not sufficient to fulfil the data requirements of LISEM. Given this limitation, some of the parameters used in the model were taken from previous studies in the Nam Chun Catchment or derived from literature in conjunction with knowledge of the area. In the following section the main hydrological parameter of interest will be explained.

4.2.2.1. Baseflow parameter

The baseflow parameter is constructed with 3 maps: the flux entering the channel (chanbaseflux.map) in m^3/s, the initial channel volume (chanvini.map) in m^3 and the increase in baseflux (chanincrease.map) which is a factor 0-1 of increase in chanbaseflux.map from the beginning to the end of the event. Due to the combined effect of other contributing factors such as manning's n, gradient and network length, it cannot be predicted what the baseflow in m^3/s will be at the outlet from a given base flux map (chanbaseflux.map).

Subsequent to this simulation, the output channel volume is used as the initial volume for the model run. A rainfall event is then added to the baseflow generated. These results illustrate an increase in baseflow. See Figure 4-3 and Figure 4-4 for an illustration of a rainfall event without and with baseflow, in that order.

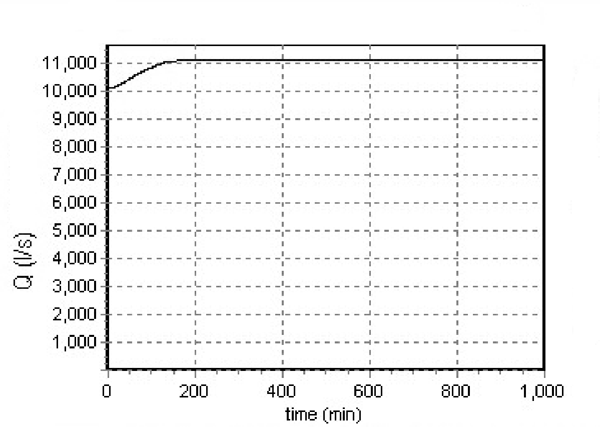


Figure 4-2: Baseflow simulation

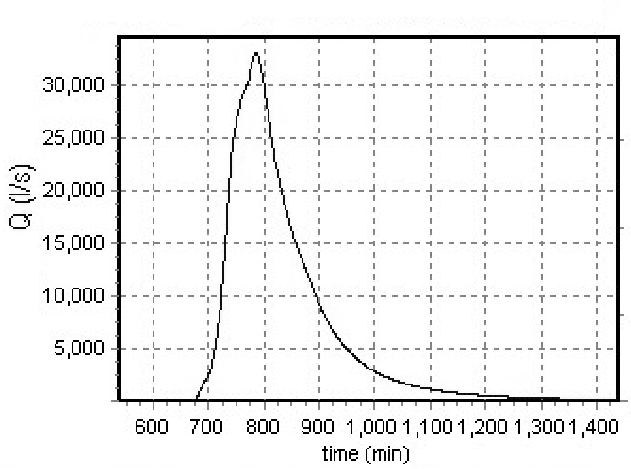


Figure 4-3: Rainstorm event 260905 without baseflow

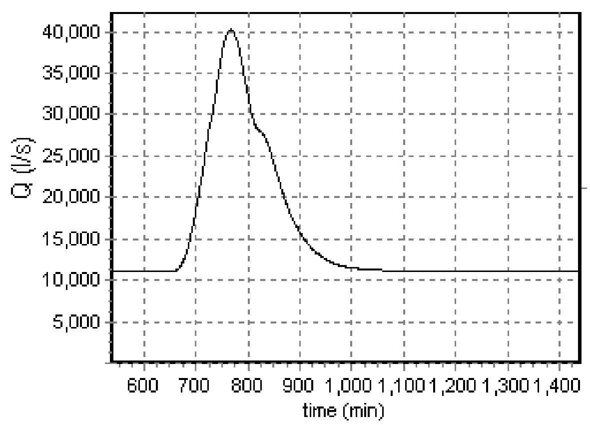


Figure 4-4: Rainfall event 260905 with baseflow

4.3. Model Calibration

In this study, the LISEM model was evaluated using 2 previously calibrated rainstorm events (Prachansri 2007). Due to the addition of the baseflow parameter to these events, it was necessary to re-calibrate to ensure acceptable results. The criteria for calibration were based on peak discharge including time to peak and hydrograph shape. The simulated hydrograph was visually compared to the measured data, subsequently changes were made to selected input parameters. These parameters were altered in an attempt to improve simulated results:

- Saturated hydraulic conductivity (K_{sat})
- Manning's n coefficient for the channel

The parameters were altered within reasonable boundaries assuming that the initial soil moisture content was almost completely saturated. This assumption was made from historical rainfall analysis which showed that prior to a maximum rainfall event for a given year, there were significant rainstorms which contributed to the saturation of the catchment (See 4.5.1. for more detail).

Table 4-2: Observed and simulated peak discharge in Nam Chun catchment

Events	Event characteristics			
	Total Rainfall (mm)	Max. rainfall intensity (mm/hr)	Peak discharge	
			Obs (m3/s)	Sim (m3/s)
180905	20.00	18.00	24.00	25.37
260905	32.00	30.50	41.45	40.21

The two events selected to calibrate the model were 180905 (18th September 2005) and 260905 (26th September 2005) (See Appendix 8). Table 4-2 gives a synopsis of the event characteristic and comparison to simulated peak discharge. The results of the model were compared with discharge measured from the outlet of the catchment in a previous study in combination with baseflow measured at the same location in September of 2008.

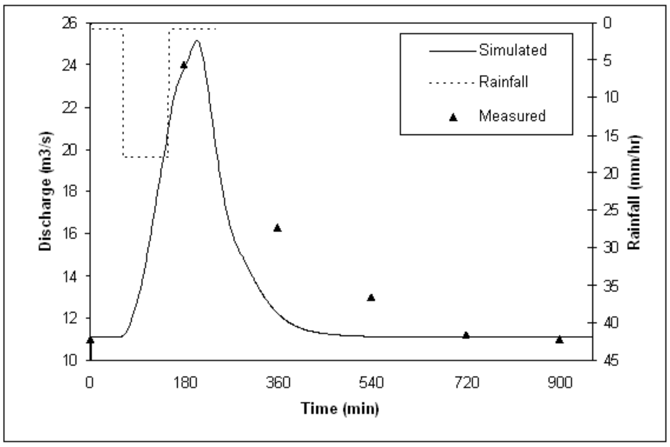


Figure 4-5: Measured and simulated discharge in the Nam Chun catchment on 180905

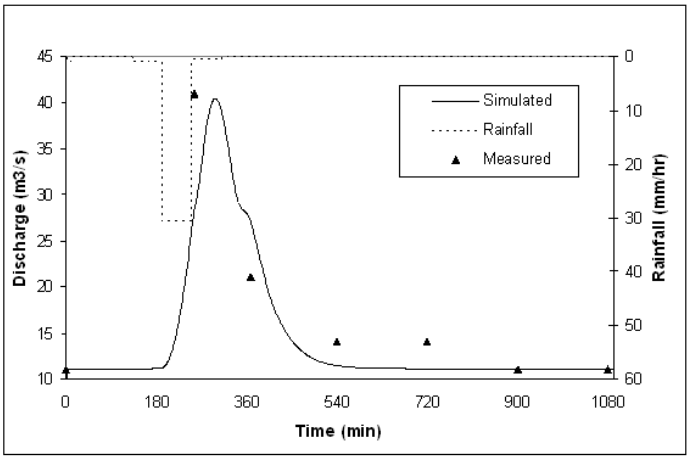


Figure 4-6: Measured and simulated discharge in the Nam Chun catchment on 260905

4.4. Model sensitivity analysis

Sensitivity analysis is an evaluation of how the model reacts to extreme changes in its parameters. A sensitivity analysis was used to investigate the parameters that have the most influence on the model results. For this study the two parameters considered are Saturated Hydraulic Conductivity (K_{sat}) and Manning's n values. The K_{sat} determines infiltration rate and runoff amount while the manning's n is the resistance of the bed of a channel to the flow of water in it. The coefficient is expressed as '*n'* in Manning's equation:

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

Equation 4-2: Manning's equation

Where:

V is the cross-sectional average velocity,

k is a conversion constant,

n is the Manning coefficient of roughness,

R_h is the hydraulic radius, and

S is the slope of the water surface

The calibrated values (K_{sat}=70 and Manning's n=0.062) for the events 180905 and 260905 were altered by +10% and -10% to examine which of the two parameters affects the model results more significantly. The model appears less sensitive to changes in the channel surface roughness compared to that of changes in the K_{sat} values. The effect of increasing the channel roughness results in a decrease of the peak discharge by 5.36% (event 180905) and 7.69% (event 260905). While, an increase in the K_{sat} values resulted in a 4.80% decrease (event 180905) and a 10.24% decrease (event 260905). The variation between the two illustrates that small changes in the K_{sat} values are more sensitive to the model results than surface roughness (See Table 4-3).

Table 4-3: Model sensitivity of calibrated parameters by +10% and -10%

Parameters	**Percentage change in peak runoff**			
	Event 180905		**Event 260905**	
	+10%	-10%	+10%	-10%
K_{sat}	-4.80	17.60	-10.24	22.45
Manning's n	-5.36	8.57	-7.69	9.22

4.5. Scenario generation

Designed rainstorms were generated in this study to replicate flash floods for 10, 20 and 50 year return period floods. A frequency analysis was done using rainfall data from 37 years to obtain the probable total amount of rainfall (mm) that would be generated by the desired flash floods. From rainfall analysis it was assumed for the scenario events that the watershed was completely saturated. After obtaining the total rainfall amount for a particular event, the temporal distribution of the rainfall was designed by using Intensity Duration Frequency (IDF) relationships.

4.5.1. Rainfall frequency analysis

"The magnitude of an extreme event is inversely related to its frequency of occurrence, very severe events occurring less frequently than more moderate events (Parodi 2006)." The main aim of frequency analysis of hydrologic data is to establish a relationship between the magnitude of an extreme event and the rate of recurrence. Parodi explains that hydrologic data are generally independent and identically distributed, while rainfall systems are considered to be stochastic, space-independent, and time-independent. The hydrologic data should be selected so that the assumptions of independence and identical distribution are fulfilled. This is often attained by identifying the annual maximum of the variable being analysed.

Historical rainfall events starting from the year 1970 to 2007 were analysed. This was done by observing the maximum rainfall for each year, the condition of the catchment (total rainfall for 5 days) before and after the event and the amount of rain which occurred the day immediately before and after the event. From this analysis a justified assumption was made that the catchment is saturated before a flash flood event (See Appendix 5)

4.5.2. Return period prediction

The return period predictions were obtained with the aid of the program RANKPLOT, which was designed to analyse frequency distributions. The input dataset (See Appendix 9) is a chronological list of yearly maximum rainfall event amounts (mm). These were distributed with a linear partition on the Y axis and Log Pearson III on the X. The result of this distribution is the total rainfall (mm) for a predicted recurrence interval with a corresponding probability (See Figure 4-7). For example, 98% of the historical rainfall data in the distribution is below the predicted amount of rainfall (139 mm) for the 50 year recurrence interval. This means there is a 2% probability of occurrence of such an event based on the available data. For the 2 year recurrence interval there is a 50% chance of occurrence since 50% of the historical data is above and below the possible amount of rainfall (73 mm) for this period.

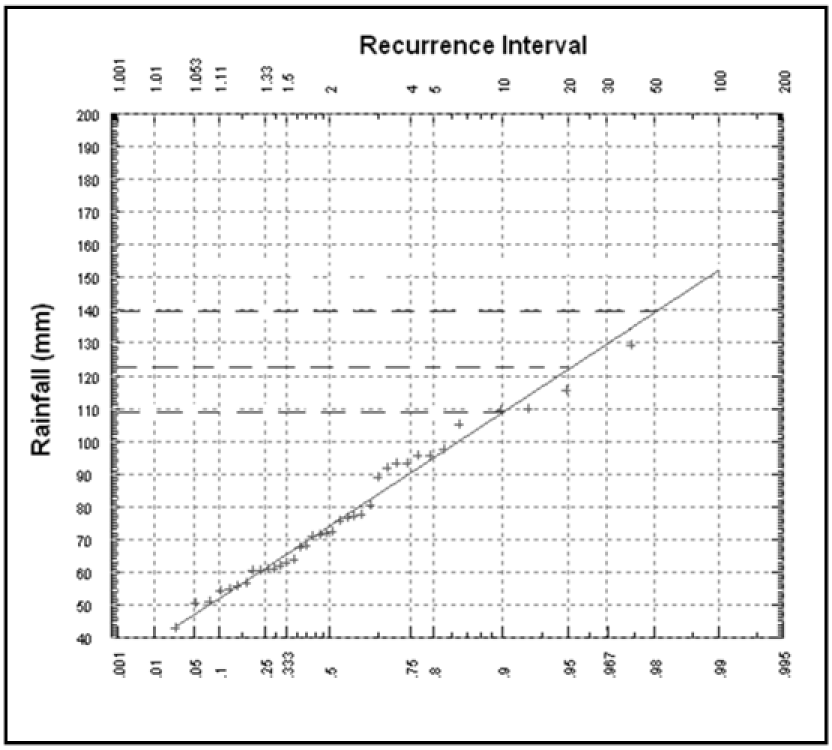


Figure 4-7: Return period prediction

4.5.3. Design Storms

A design storm is a precipitation prototype defined for use in the design of a hydrological system. Frequently the design storm is the system input, and the resulting rates of flow through the system are calculated using rainfall runoff procedures (Chow 1988). The LISEM model requires rainfall data in user defined time steps. Therefore, it is necessary to distribute the total amount of rainfall for a particular recurrence interval temporally. The criteria for the desired flash flood events are:

- 4 hour temporal resolution
- Peak intensity within the first hour
- Total rainfall equivalent to recurrence interval prediction (10, 20 and 50 year return flood)

The temporal resolution chosen was decided based on the type of flood event that is being replicated. A flash flood is characteristic of high intensity rainfall with short duration. The time of peak intensity was chosen based on observations in the field. The highest intensity was noticed during the first hour of a rainstorm. A triangular hyetograph method was selected to design the desired rainstorms because a triangle is a basic shape for a design hyetograph. Once the precipitation depth P and duration Td are known, the base and height of the triangle can be determined (Parodi 2006).

e.g. $P = 0.5.Td.h$

Therefore: $h = \frac{2P}{Td}$

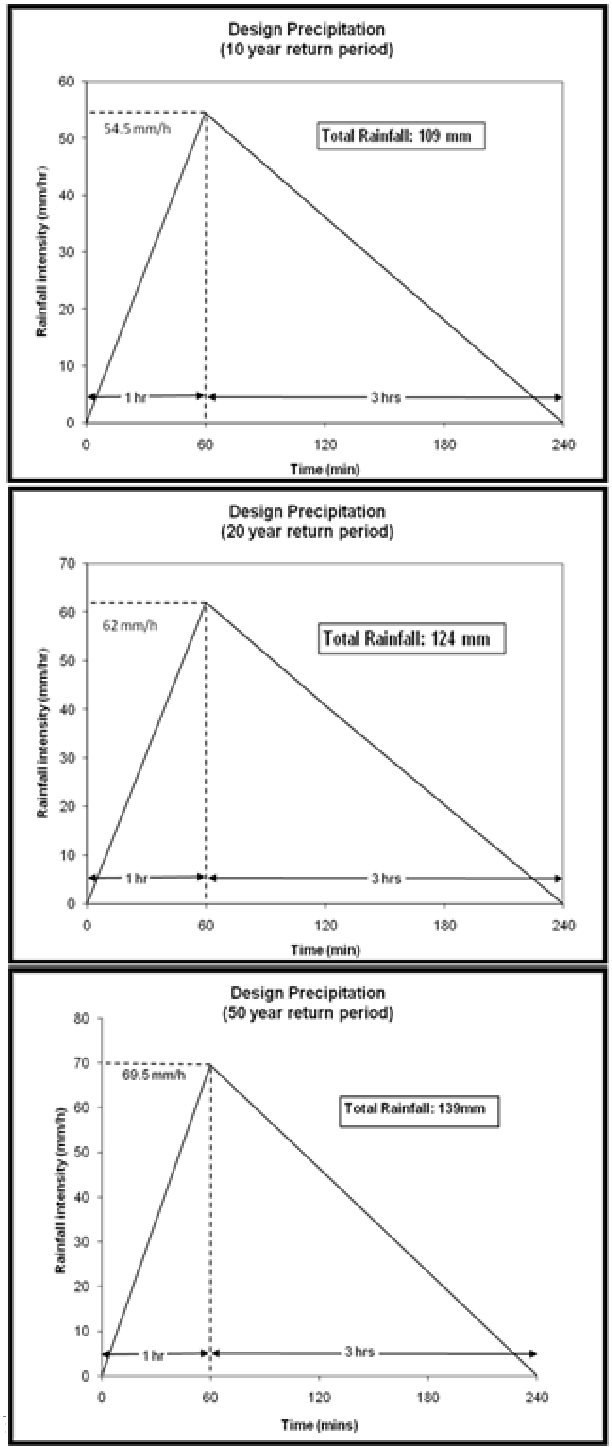
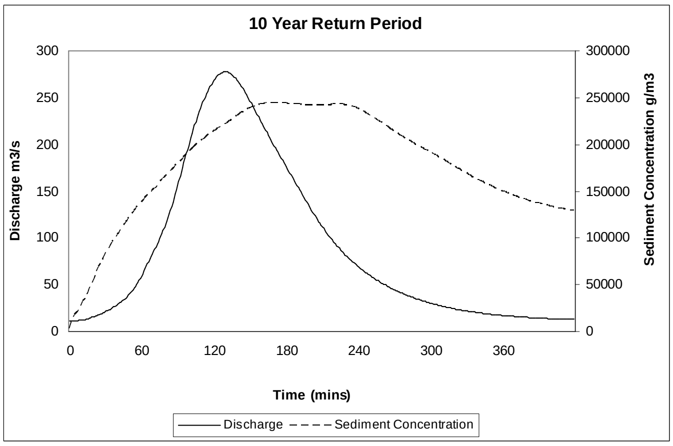
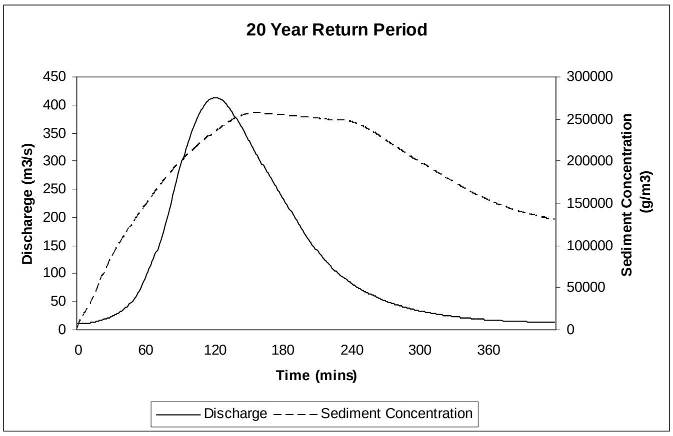


Figure 4-8: Triangular design hyetographs for 10 (1), 20 (2), and 50 (3) year return periods.

4.6. LISEM results





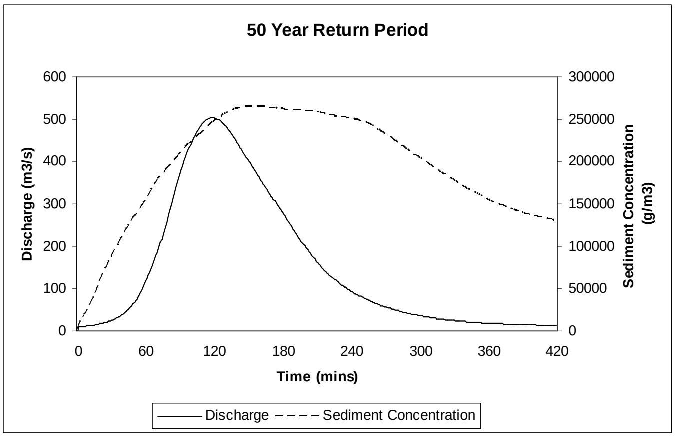


Figure 4-9: Discharge and sediment concentration for designed return period events

The discharge results are the main boundary condition for the SOEBK-flow model while the sediment concentrations derived from the LISEM output is the main input for the SOBEK-2DWAQ model.

The discharge and sediment concentration generated from the designed storms are illustrated in Figure 4-9. The peak of the discharge for all return periods occurs at approximately 120 minutes. The sediment concentration rises gradually as the discharge increases, however, even when the falling limb occurs and returns to the baseflow the concentration remains above 120,000 g/m3). Therefore, it is based on reason, to state that the concentration is extremely high approaching the end of the simulations based on the catchment discharge versus sediment load. However, the spatial temporal maps generated for sediment concentration do not reflect this rationale (See Appendix 6 and Appendix 7).

It could also mean that this high concentration is within the channel and not visible in the output maps. The 10 year return flood is used as an example to illustrate this discrepancy (See Figure 4-10).

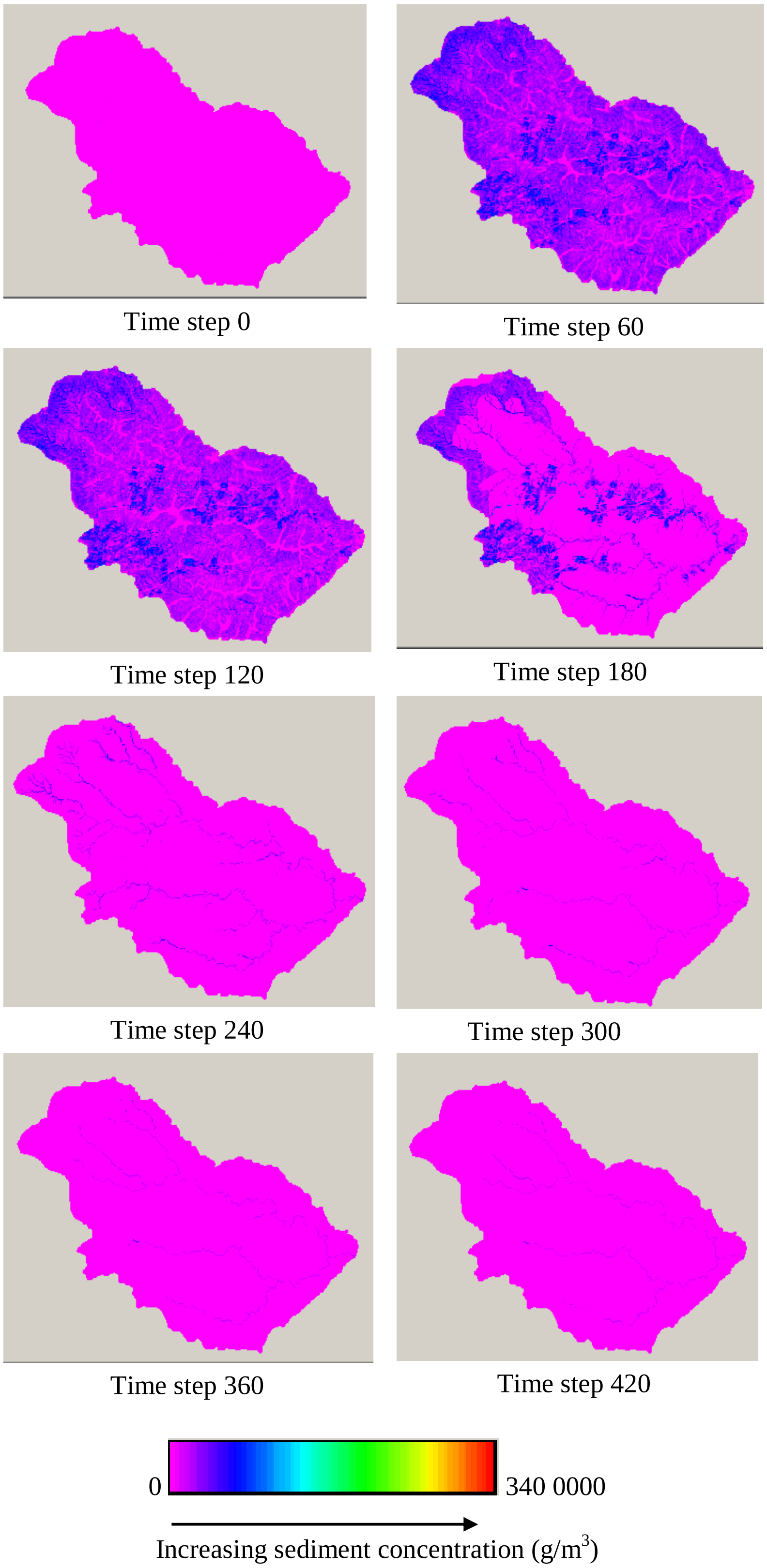


Figure 4-10: Spatial temporal distribution of sediment concentration for 10 year return flood (time step = 1 min)

5. Flood modeling and 2D sediment transport

5.1. Introduction

This chapter illustrates the procedures and results of flash flood and sediment transport and deposition simulations in the lowland flood plain of the Nam Chun watershed. During flood events, huge amounts of sediments are transported in the lowland area of the Nam Chun catchment. The highest reported level of sediment rich flood water was 190-200 cm above the ground level, which occurred in 2001as a result of the typhoon Usagi (Yumuang 2006). The Water Quality model framework is presented in this chapter. With this model the sediment transport during designed flood events of different return periods are studied. The model enhances the probable spatial distribution of sand, silt and clay. A better understanding of the sediment deposition during flood events is of great use for the evaluation of measures that should be employed to avoid the excess sedimentation of lowland areas.

SOBEK-Rural version 2.11.002b was the tool used to characterize flood propagation and sedimentation processes in the case study area. SOBEK is a combined 1D2D model package to simulate; rainfall-runoff modelling (lumped approach), 1D channel flow, sewer flow, real-time control (irrigation), water quality, emissions, 2D overland flow and ground water flow. The SOBEK model has a modular structure to allow a combination of the various models. The specific models used in this study to achieve the final results are the:

- combined channel and overland flow model
- one dimensional water quality model
- two dimensional water quality model

The main advantage of employing SOBEK 1D2D hydrodynamic model in this study is the relationship between the model behaviour and reality. Flow in open channels can be replicated with extensive detail by incorporating structures such as: bridges, embankments, culverts and buildings. The model simulates the 2D system with similar detail. It creates the possibility for the inclusion of obstructions, like roads and a detailed digital surface model which is the basis for overland flow routing.

The sensitivity of the model was tested by analysing the flow results with and without the influence of structures (i.e. bridges and culverts). These findings demonstrate the importance of engineering features in hydrological and sediment transport models.

5.2. Flow model input

The required data for flood simulation in SOBEK are: 1) a detailed digital surface model containing all major surface features, 2) surface roughness map which represents the resistance of the water flow on various land cover types, 3) boundary conditions which can be, discharge in user defined time steps, water level and sediment concentration and 4) initial conditions which represents the situation at the start of the simulation. These and other input variables are explained in more detail below.

5.2.1. DSM construction

A Digital Surface Model (DSM) illustrates the elevations of the top surfaces of buildings, vegetation and other features elevated above the bare terrain (Maune 2001). In this study, an existing DEM constructed with road, embankment and terrain elevations were enhanced with the addition of building elevations (See Figure 5-1). In ILWIS version 3.31 Academic, a rasterized map of the buildings in the lowland flood plain were used to generate a binary map (VILLAGE) with a mask map of the study area. The following formula was used to add a constant building height of 5 meters to the existing DEM (DEM_PRE):

DEM_FINAL=IFF(VILLAGE=0,DEM_PRE,DEM_PRE+5)

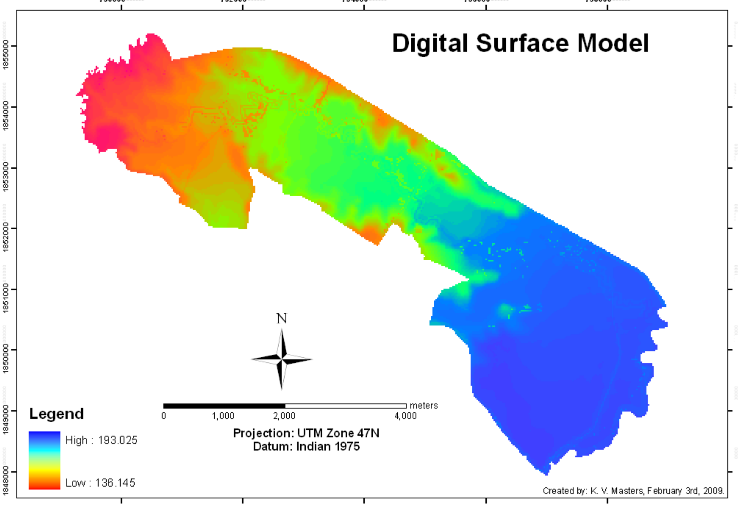


Figure 5-1: Digital surface model of the Nam Chun floodplain

5.2.2. Surface roughness

The land cover map was created from field validation of an existing land cover map which was produced by the Land Development Department (LDD) in 2002. This map was generated from image interpretation of an aerial ortho-photo at a scale of 1:25, 000. The existing map was imported into Arcpad for use in a mobile GIS which served as a form of reference for checking the current land cover types (See Figure 5-2).

Manning's roughness coefficient values were selected for each land cover type based on pictorial examples taken from the USGS guide for selecting manning's roughness coefficients (See Table 5-1).

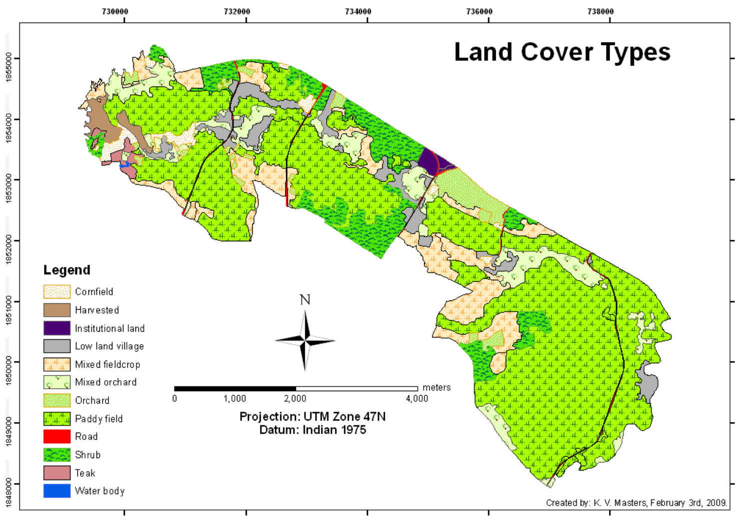


Figure 5-2: Land cover types of the lowland extent

Table 5-1: Manning's roughness coefficient used for flood plain surface roughness (Arcement 2008)

Land Cover Type	Manning's n coefficient
Shrub	0.0400
Mixed field crop	0.0350
Cornfield	0.0450
Road	0.0010
Mixed orchard	0.1500
Orchard	0.1000
Teak	0.0150
Water body	0.0330
Paddy Field	0.1000
Village	0.1500
Harvested land	0.0400
Institutional land	0.0010

5.2.3. Boundary conditions

Boundary conditions are defined by boundary nodes. These nodes mark the extent of a hydraulic schematization. Several options are available to define boundary conditions, such as water level, discharge or a Q-H relationship where the user imports a relationship between water level and discharge. In this study there are five boundary nodes which include:

- One 1D node at the catchment outlet of the Nam Chun catchment. The input data (discharge time series) for this boundary node was obtained from the output of the LISEM model for return period flood events of 10, 20 and 50 year.
- Two downstream nodes which are water level constant
- Two 1D2D internal boundary nodes for the downstream area are water level constant

5.3. Water quality model

The water quality model was configured in the 1D2D Water Quality Module of SOBEK. This modle uses the process library Delwaq as the central hub. The process library contains various process equations with a wide range of substances including water quality problems.

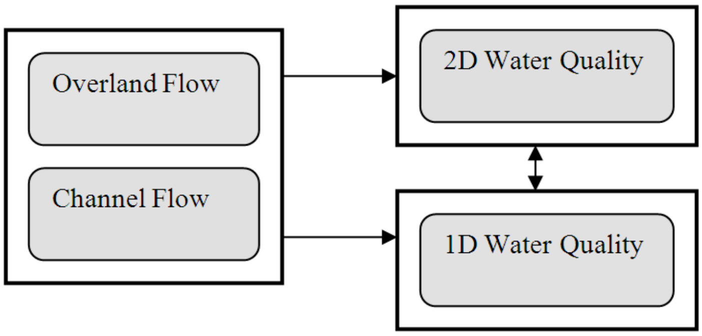


Figure 5-3: Configuration of the SOBEK modules that are used for the sediment transport calculations. Channel flow and overland flow and integrated while the 1D and 2D water quality calculations are running simultaneously (Delft Hydraulics 2007).

The 1D and 2D Water Quality modles can be used concurrently. This allows the exchange of sediments between channels and flooded areas to be simulated. 1D and 2D flow are computed jointly in one integrated calculation, however for the water quality, the 1D domain and the 2D domain are calculated separately. Both water quality module simulations exchange information about the 1D2D flow connections during every time step. This simulation process is shown in Figure 5-3.

Three sediment fractions are considered in the water quality module for this study: sand (IM1), silt (IM2) and clay (IM3). Each fraction has its own sedimentation characteristics. The fraction of sand (20%), silt (51%) and clay (20%) within the sediment layer being removed from the upland catchment was computed based on lab analysis (Watsusi 2009). An average of the sediment concentration results obtained from the LISEM model were used to obtain the sediment fractions within the sediment layer for each return period. For the purpose of this study only one sediment layer is consider (S1), which is deposited on a consolidated parent material in the flood plain of the Nam Chun watershed. Therefore, no erosion occurs in the lowland as a result of the flood events. The output variables of the water quality module are summarized in

Table **5-2**.

Table 5-2: The output variables of the sediment model

Variable	Description	Name	Units
IM1	sand in water	mineral fraction 1-sand	g/m^3
IM2	silt in water	mineral fraction 2-silt	g/m^3
IM3	clay in water	mineral fraction 3-silt	g/m^3
IM1S1	sand in sediment	mineral fraction 1 in sediment	g/cell
IM2S1	silt in sediment	mineral fraction 2 in sediment	g/cell
IM3S1	clay in sediment	mineral fraction 3 in sediment	g/cell
RHOIM1	density IM1	density of fraction 1-sand	g/m^3
RHOIM2	density IM2	density of fraction 2-silt	g/m^3
RHOIM3	density IM3	density of fraction 3-clay	g/m^3
IM1S1M2	deposited sand	amount of mineral fraction 1 in sediment	g/m^2
IM2S1M2	deposited silt	amount of mineral fraction 2 in sediment	g/m^2
IM3S1M2	deposited clay	amount of mineral fraction 3 in sediment	g/m^2

The sediment transport is modelled with the processes of re-suspension and sedimentation. The parameter that determines re-suspension and sedimentation is the bed shear stress. "The bed shear stress is a function of the flow velocity, the roughness of the river bed and the water depth". When the bed shear stress is low sedimentation occurs, at an intermediate threshold, particles are in a state of equilibrium and when the bed shear stress and flow velocity exceeds this threshold re-suspension prevails (See). The sedimentation velocity and critical shear stress for sedimentation vary for each sediment fraction. Contrarily, the re-suspension velocity and critical shear stress for re-suspension are the same for all sediment fractions (Delft Hydraulics 2007). The re-suspension process is modelled using the following formulation (Delft Hydraulics 2005):

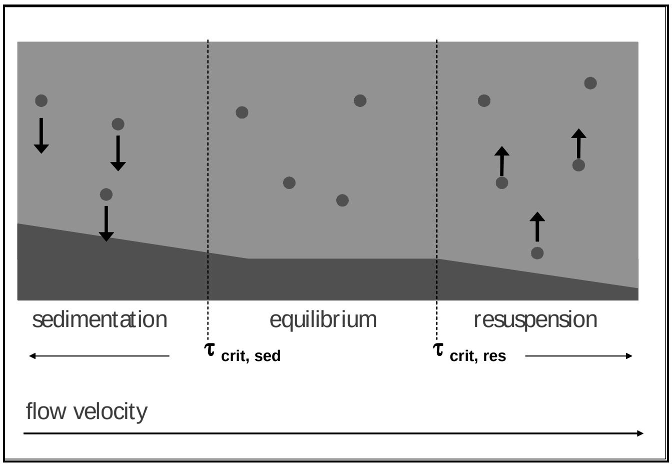


Figure 5-4: Re-suspension and sedimentation in the sediment model (Delft Hydraulics 2007).

Implementation:

The process is implemented for the following sediment fractions:

i = IM1, IM2 and IM3

and for one sediment layer:

j = S1

Formulation:

$$fRes_j\, i = fRes_j\, DM \times Fr_{ij}$$

$$dRes_j\, i = \frac{fRes_j\, i}{Depth}$$

$dRes_j i$	=	re-suspension flux of sediment component i from layer j
$fRes_j DM$	=	re-suspension flux of dry matter from layer j
$fRes_j i$	=	re-suspension flux of sediment component i from layer j
Fr_{ij}	=	fraction of substance i in sediment layer j
Depth	=	depth of a Water Qualiy segment

The simulation starts on September 8th 2007 at 2:00am and ends at 8:00pm. The sedimentation of silt and clay particles may take days to deposit in reality. However, it is assumed that the areas which are inundated at the end of the simulation are also the areas which those sediments will be deposited based on their sedimentation velocity.

In order to study the sedimentation and deposition of fresh suspended sediment material in the study area, the sediment layer contains no sediments at the start of the simulation. In other words, IM1S1 equal zero.

Table 5-3: Boundary and initial conditions for sediment concentration in the Water Quality model

Return Periods	IM1	IM2	IM3
	20%	**51%**	**29%**
	Sand (g/m^3)	**Silt (g/m^3)**	**Clay (g/m^3)**
10 year	35774.67	91225.41	51873.27
20 year	37616.74	95922.68	54544.27
50 year	38824.21	99001.73	56295.10

5.4. Model schematization

Schematization is the process where real world parameters are entered into SOBEK, such as DSM, river channel, bridges and cross-sections. Reality is reconstructed in the model so that simulations can be calculated to observe how water would behave in such an environment. The data input and editing interface in SOBEK is called the NETTER (See Figure 5-5). The schematization in this study consists of boundary nodes, bridge and culvert nodes, calculation points, cross-sections, history stations, connection nodes etc., whose attributes are defined in the attribute editing mode. A selection of schematization input features are briefly explained below:

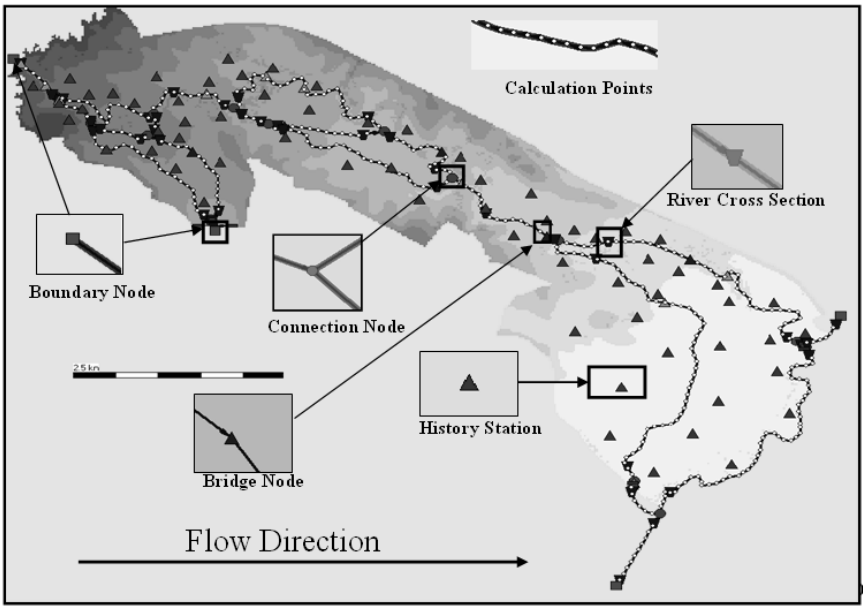


Figure 5-5: Model schematization of SOBEK

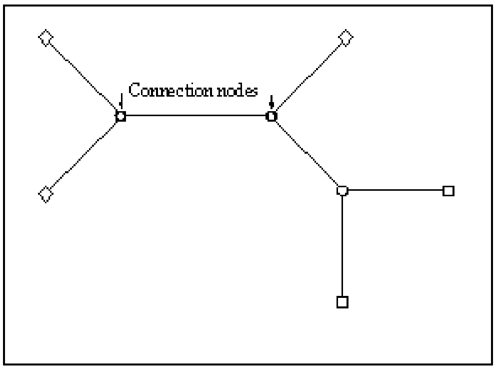


Figure 5-6: Connection nodes in SOBEK-flow schematization (Delft Hydraulics 2008)

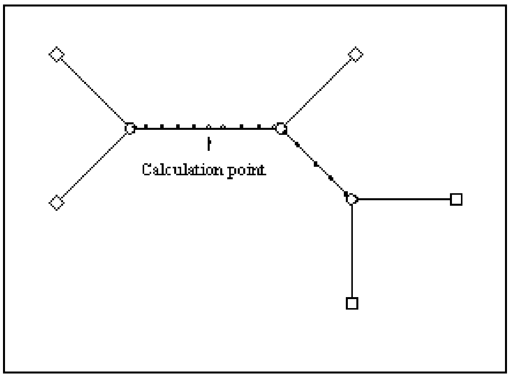


Figure 5-7: Calculation points in SOBEK-flow schematization (Delft Hydraulics 2008)

Connection node: The SOBEK-flow model consists of a network of reaches. A connection node is placed at a location where reaches can be attached to other reaches. Therefore, when the river channel is separated by multiple branches a connection node is used at the point of separation. This is illustrated in Figure 5-6.

Calculation points: In each reach several calculation points can be defined. Theses calculation points correspond to the spatial numerical grid to be used in the simulation which yields the resulting water levels at these points (See Figure 5-7).

History stations: History stations are user defined locations within the schematization where flood information such as depth, duration or velocity at that particular point can be obtained.

5.4.1. 1D network schematization

The ID flow network is the hydrological system within the river channel. The definition of the 1D network begins with the boundary nodes. These nodes are connected by reaches after which the river network shape is delineated. The channel characteristics are determined by cross sections which are characterized by the shape and size of the channel perpendicular to the direction of flow. The cross section type used in this study's schematization is trapezium (See Figure 5-8). Each reach has at least two cross sections. The bridges within the network reflect the cross section information which they are nearest to in conjunction with profiles measured in the field. The following types of bridges can be modelled in the 1D network schematization: pillar, abutment, fixed bed and soil bed bridge. The bridge types used in this study are pillar and abutment which are illustrated in below in Figure 5-9.

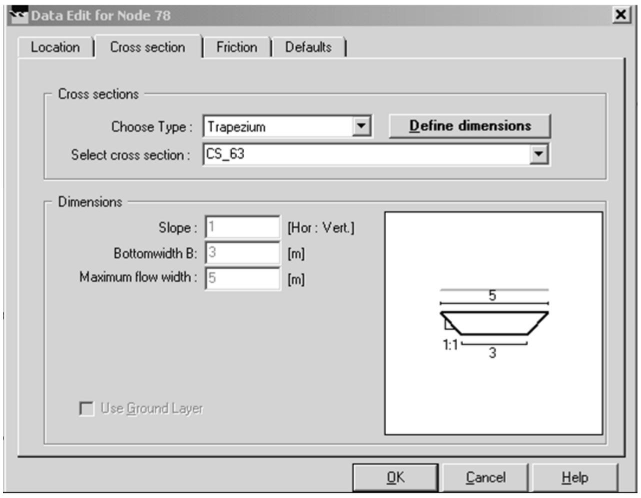


Figure 5-8: River cross section input window

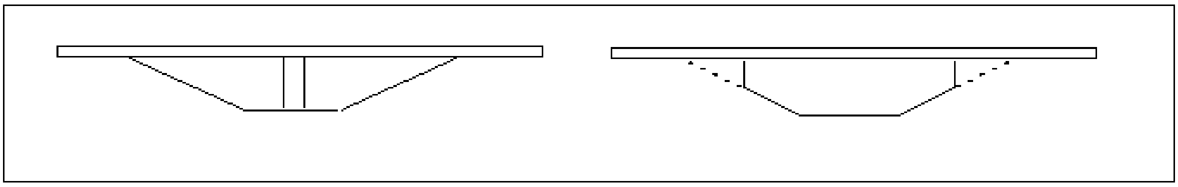


Figure 5-9: Pillar bridge (left) and Abutment bridge (right) entered in the SOBEK-flow schematization (Delft Hydraulics 2008)

Additionally the culverts were included in the network. The type entered was rectangular. The flow through this underground pipe is controlled by the begin and end bed level, the size, shape and the friction. Figure 5-10 shows a side view of the culvert type in the 1D SOBEK-flow model:

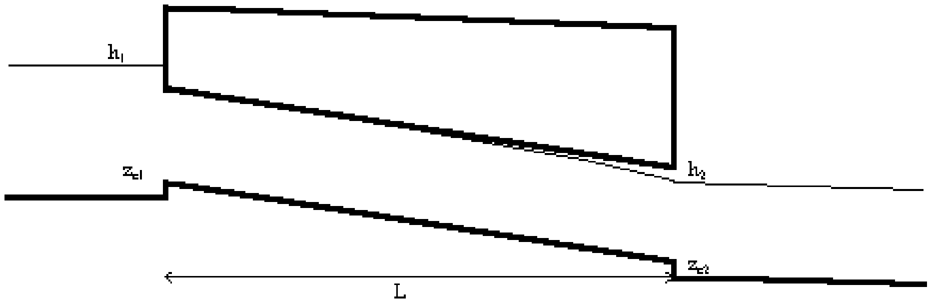


Figure 5-10: Side view of a rectangular culvert in the SOBEK-flow schematization (Delft Hydraulics 2008)

Where:

L is the length of the culvert

h_1 upstream water level

H_2 downstream water level

Z_{c1} bottom level of the culvert at the upstream part

Z_{c2} bottom level of the culvert at the downstream part

5.5. Model output

Model output in SOBEK can be visualized dynamically in user defined time steps specified in the “output parameter” section. Various types of output can be selected before the model outputs are achieved such has flood depth, velocity, duration etc. In order to create static maps, the desired output files (ASCII file format) of the SOBEK-flow model are exported into a GIS. The GIS used in this study was ILWIS Academic 331. In this raster GIS an import script (See Appendix 10) was used to import SOBEK result maps into the ILWIS user interface.

5.6. Flow model results

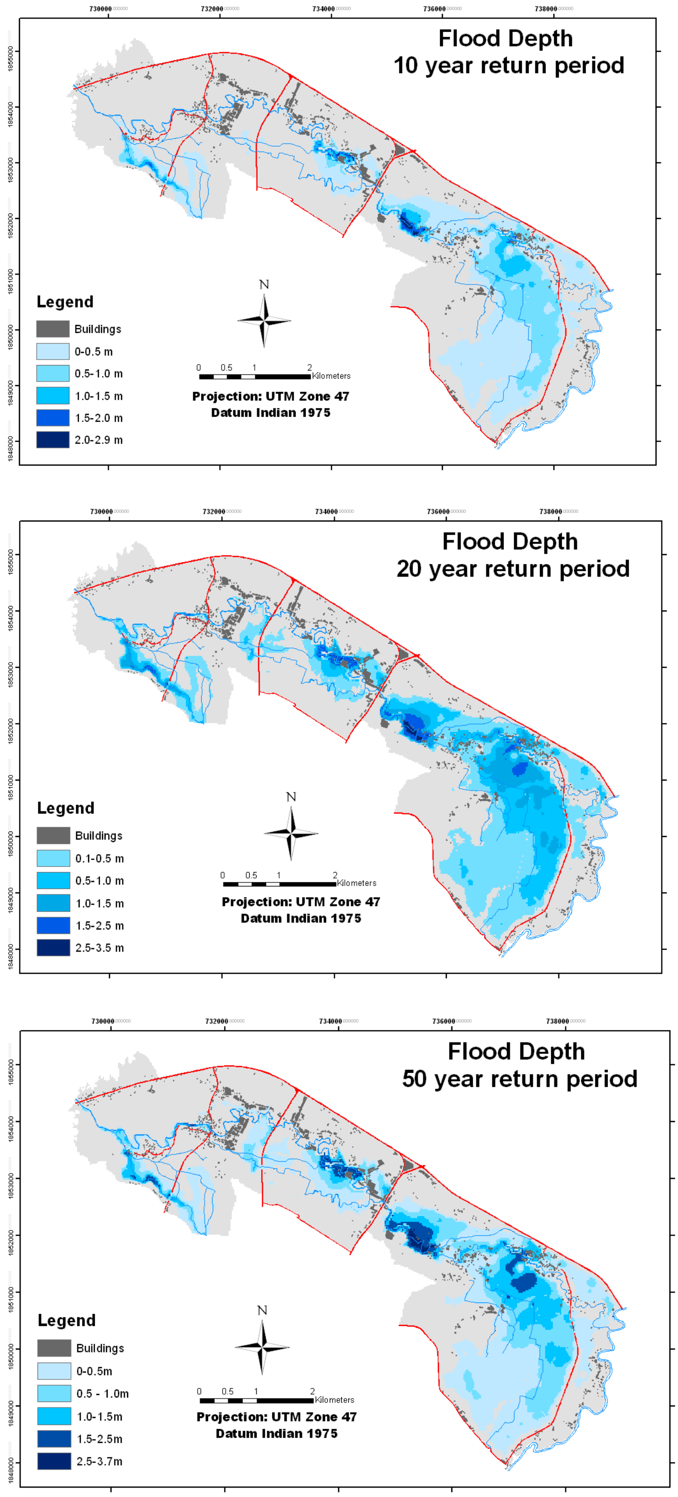


Figure 5-11: Flood depth maps generated in SOBEK-flow

The designed flash flood scenario lasted for 6 hours, however to accommodate the sedimentation of finer particles within the Water Quality model the simulation time was extended to 18 hours. The depths illustrated are the state of the inundation at the maximum depth. The flood depths are represented from shallow-deep with a light-dark blue colour ramp. The 10 year return period has a maximum depth of 2.9 m, while the 20 year return period is 3.5 m and the 50 year return period has a maximum depth of 3.7 m. In all the return period flood depth illustrations, the most widely flooded area is the south-eastern portion of the study area extent. The building shape file has been added to these figures to establish a visual relationship between inundated areas and settlement locations (See Figure 5-11).

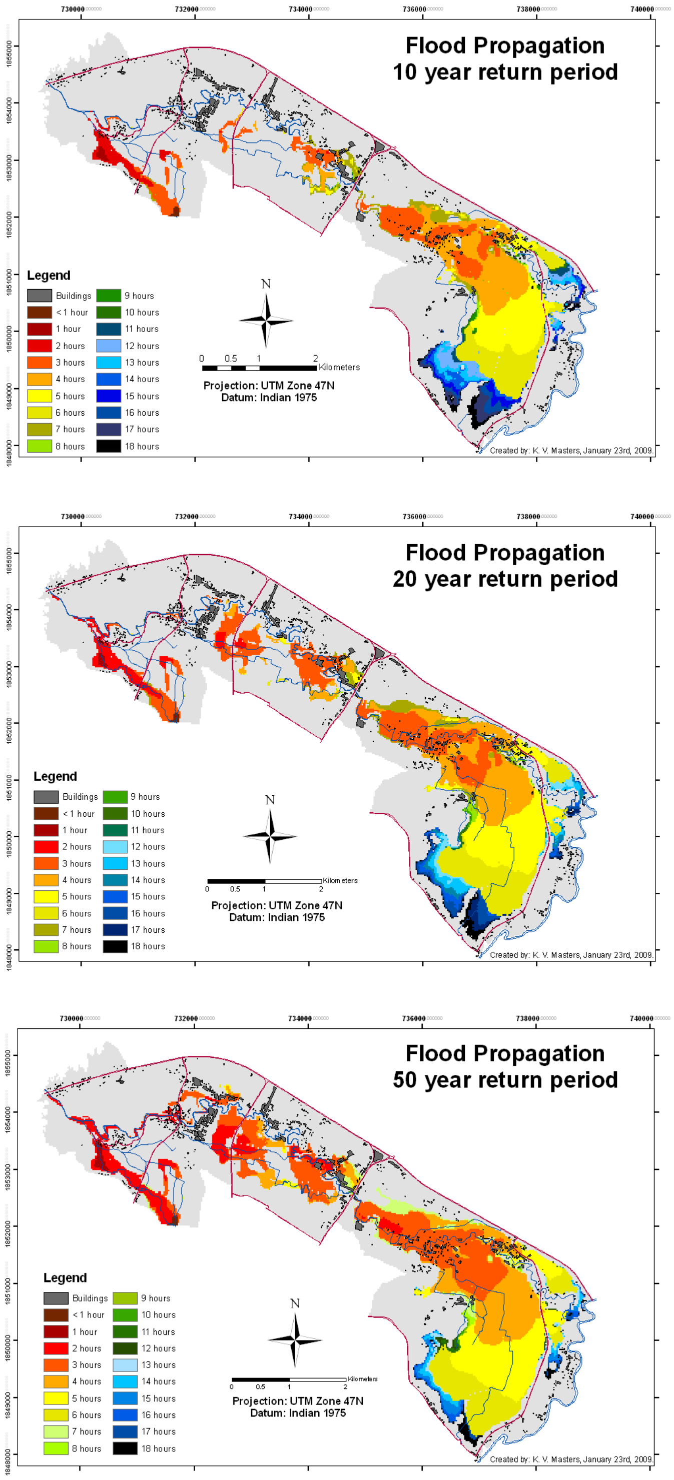


Figure 5-12: Flood propagation maps generated in SOBEK-flow

The flood propagations maps show the behaviour of the flood waters in hourly time steps. As the return periods go from 10-20 year the flood propagation becomes more prominent within the central part of the study area (See Figure 5-12).

The propagation maps along with the depth of inundation and flow velocity are factors that describe the risk and/or hazard level at particular inundation sites. These types of maps are also ideal for the design of warning systems. For the purpose of this study, the flood propagation maps were used to understand the behaviour of the designed floods and to provide a pre-interpretation of probably areas of deposition.

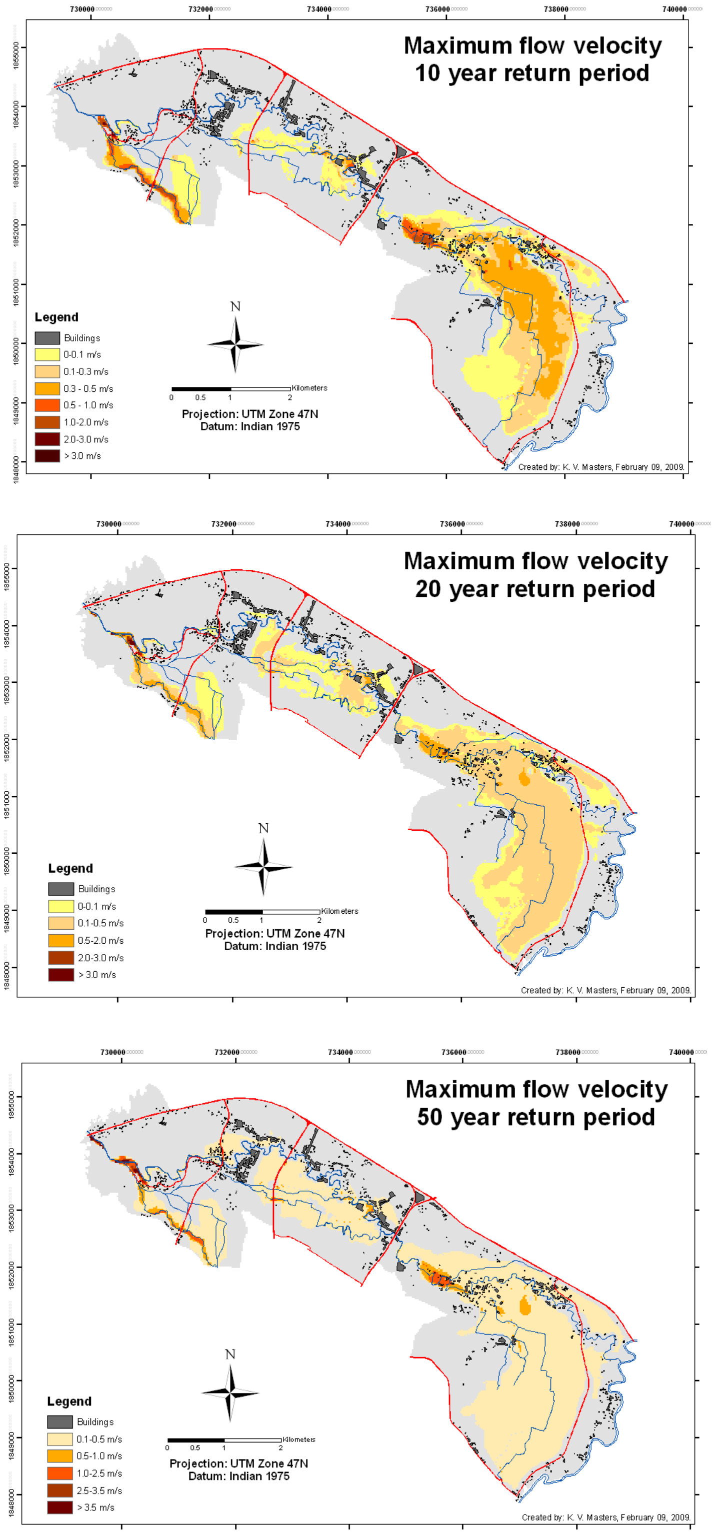


Figure 5-13: Flow velocity maps generated from SOBEK-flow

The characteristics that define a flash flood event are high intensity and short duration. Floods expected to result in considerable geomorphic change in lowland areas are those that generate discharge many times above that usually experienced by the river (Baker, Kochel, and Patton 1988). For the 10 and 20 year return floods the velocity reaches 3.0 m/s, while the 50 year flood experiences a maximum velocity exceeding 3.5 m/s (See Figure 5-13). The maximum velocities are most likely experienced within the channel because it is a defined course and the hub for high intensity flows which later overtop channel banks. The overland flow velocity is significantly lower than that of the channel. This is due to land cover types and possible

5.7. Water Quality results

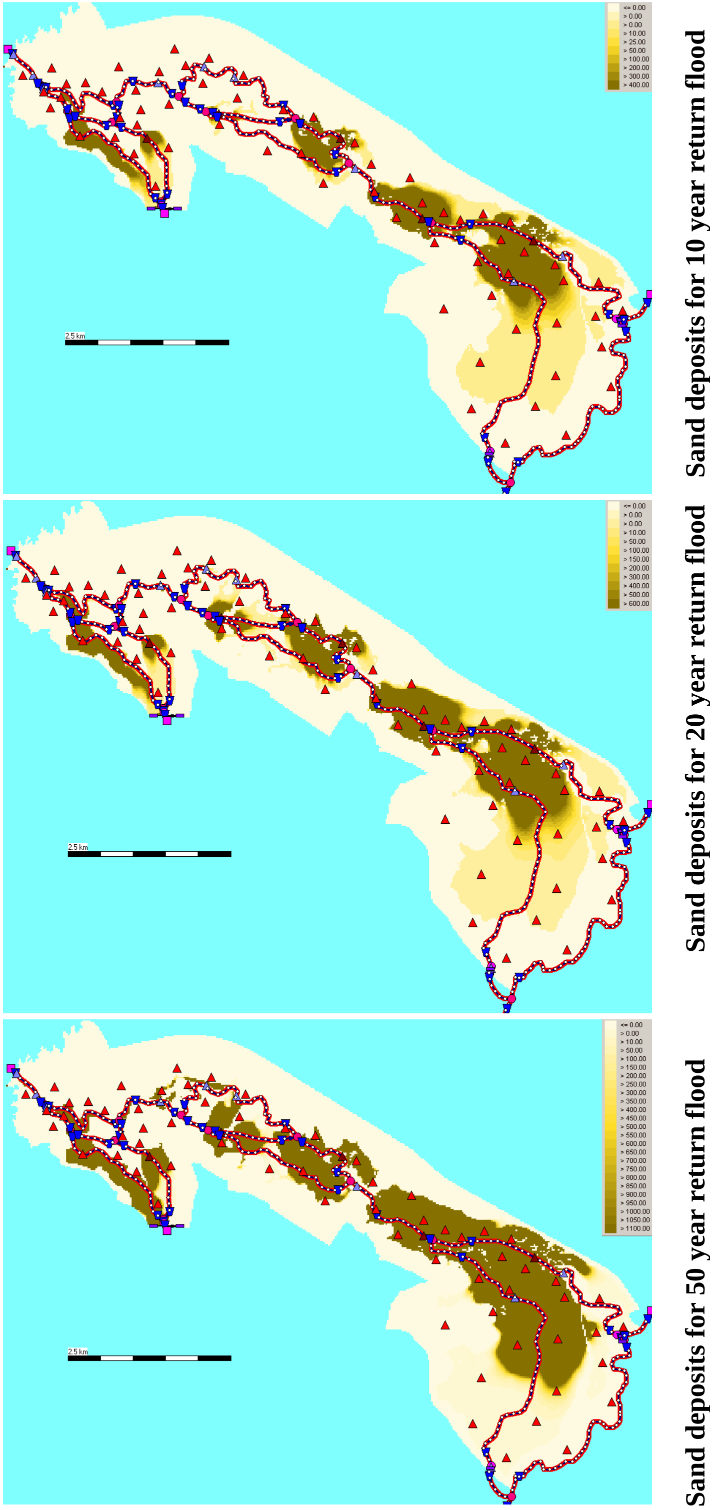


Figure 5-14: Amount of freshly deposited sand (g/m^2). The sedimentation velocity of sand is 30m/d (Delft Hydraulics 2007)

In this section the results are given for the water quality model in terms of the sediment fractions. They refer to the concentrations in one sediment layer (S1). The results of the concentration of the substances in the water column and thickness of the sediment layer were not considered in this study in order to give more emphasis to the spatial distribution of deposited sediments. The results of the sediment model consider the mass of the three fractions of sediment: sand, silt and clay. Illustrated in Figure 5-14 is the deposition of the sand fraction for the 10, 20 and 50 year design floods. This is represented on a light-dark yellow colour ramp. The sedimentation velocity of sand is 30 m/d. It is expected that most of the sand exiting the main catchment outlet will be transported in the channel and deposit near the channel at the instance of overbank flow. The 10 year sand deposits range from 10 g/m^2 to more than 400 g/m^2 while the 20 ranges from 10 g/m^2 to more than 600 g/m^2 and the 50 year sand deposits range from 10 g/m^2 to more than 1100 g/m^2.

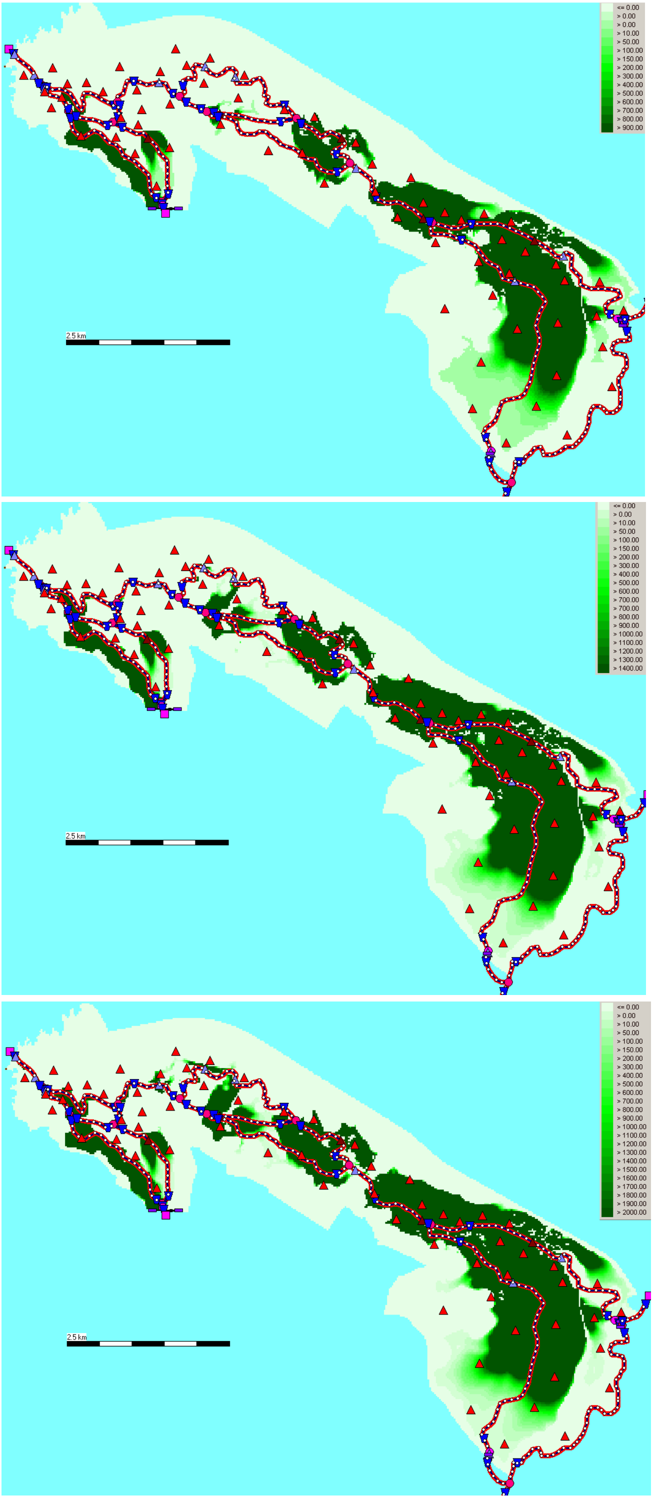


Figure 5-15: Amount of freshly deposited silt (g/m^2). The sedimentation velocity of silt is 7m/d (Delft Hydraulics 2007)

The results of the silt deposits are illustrated in Figure 5-15. The range of deposited silt is represented by a light-dark green colour scale. For the 10 year return scenario the amount of silt deposits range from 10 g/m^2 to more than 900 g/m^2. The limits of the 20 year deposits start from 10 g/m^2 and exceed 1400 g/m^2 while the 50 year deposits ends at > 2000 g/m^2.

The distribution of the silt deposits closely replicates the areas inundated as expected based on the sedimentation velocity (7 m/d).

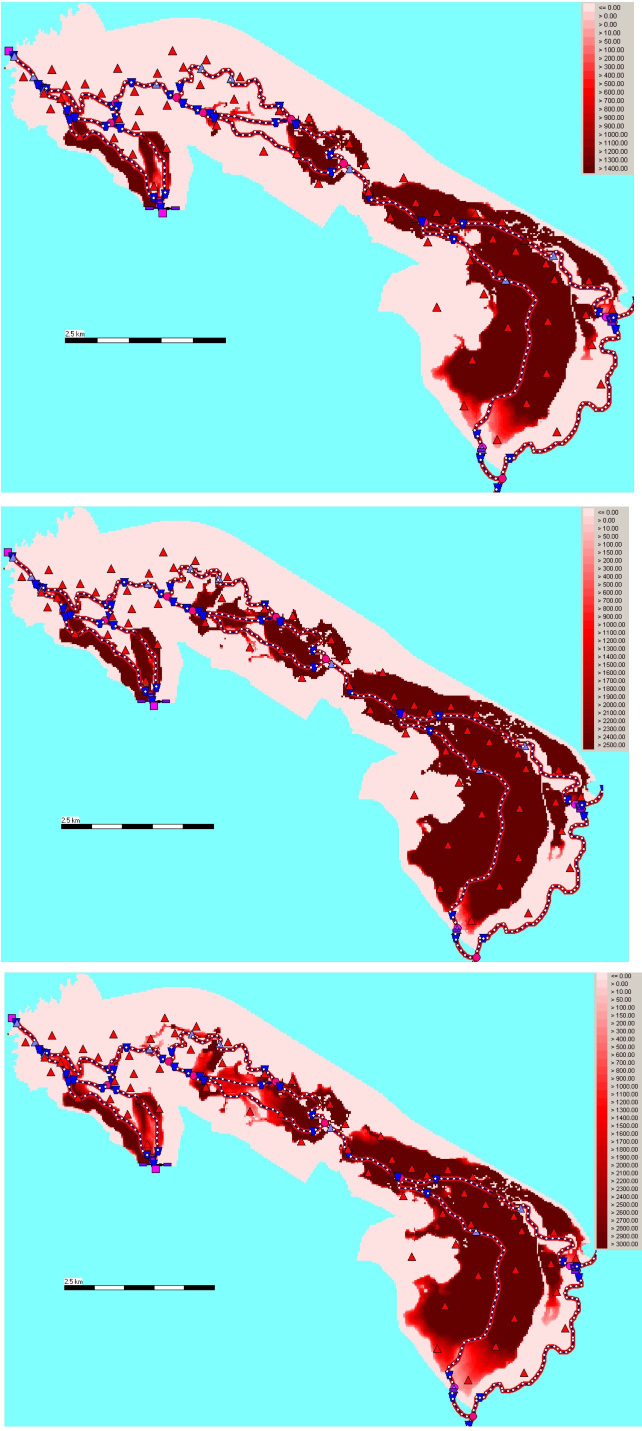


Figure 5-16: Amount of freshly deposited clay (g/m^2). The sedimentation velocity of clay is 0.3m/d (Delft Hydraulics 2007)

The clay deposits dominate the areas affected by deposition compared to the other two fractions. This is expected based on the review of the interviews carried out in the field. The residence explained a “muddy” deposition which was sticky.

A red colour ramp from light-dark illustrates the amount of clay deposits in the study extent (See Figure 5-16). The clay deposits for the 10 year scenario flood range from 200 g/m^2 to more than 1400 g/m^2. The 20 year deposits start at 400 g/m^2 and end at more than 2500 g/m^2. The 50 year design flood deposits range from 600 g/m^2 to more than 3000 g/m^2. The deposition of clay particles occurred while the flood waters began to recede due to the sedimentation velocity (0.3 m/d).

5.7.1. SOBEK-flow sensitivity analysis

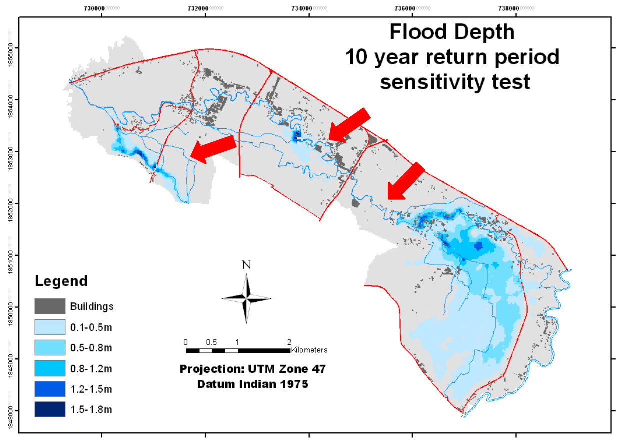


Figure 5-17: Flood depth map without bridges and culverts

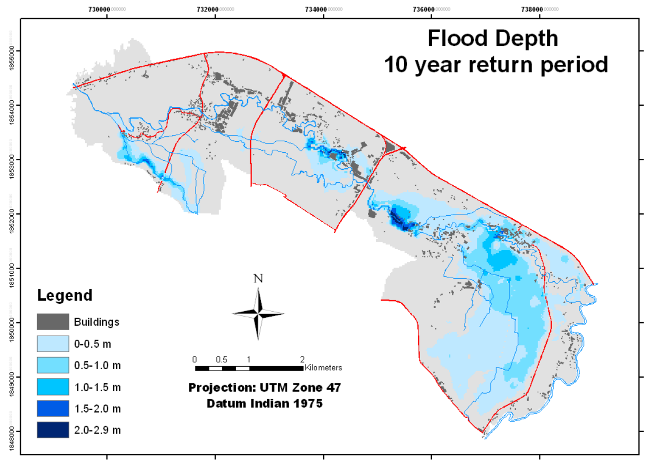


Figure 5-18: Flood depth map with bridges and culverts

The SOBEK-flow sensitivity test was done with the exclusion of the bridges and culverts in the schematization. This was a test of the model behaviour without the inclusion of (perceivably) necessary model structures. The red arrows indicate areas that are not flooded when the simulation is done without the effect of the engineering features (See Figure 5-17) in comparison to a simulation with these features (See Figure 5-18). The flood depths also vary as a result of the exclusion of these features. The maximum flood depth of the simulation without the bridges and culverts is 1.1 m lower than the simulation carried out with the bridges and culverts.

5.7.2. SOBEK-2DWAQ sensitivity analysis

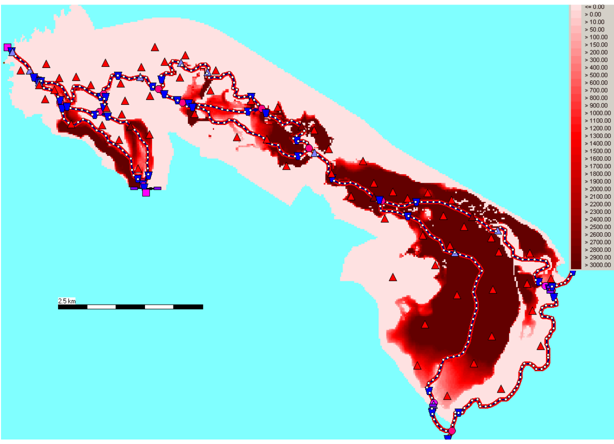


Figure 5-19: 20 year return flood clay deposits

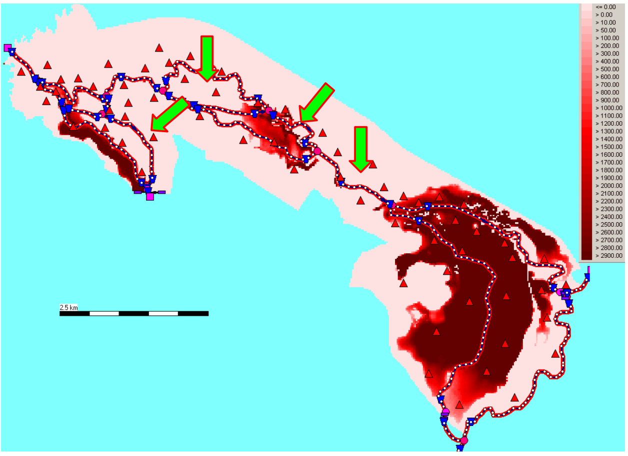


Figure 5-20: 20 year return flood clay deposits without bridges and culverts in the schematization

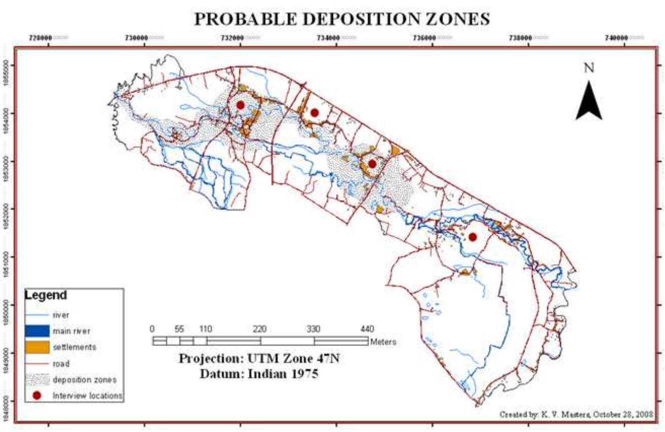


Figure 5-21: Probable deposition zones

The clay deposits from the 20 year return flood were used for the sensitivity analysis of the water quality model. The first simulation was done with all the schematization inputs originally defined (See Figure 5-19). The green arrows in Figure 5-20 highlight areas with a notable decrease in the spatial distrution of clay deposits.

From group interviews done during field data collection a probable depositon map was generated (See Figure 5-21). This map shows an underestimation in the areas most likely to experience depositon compard to that of the simulated results. This finding illustrates the limitation of the validation methodology implemented in this study. Group interviews are not as detailed as other possible methods to check model accuracy. This is further discussed in Chapter 6.

6. Discussion

6.1. The LISEM Model

The LISEM simulation in this study was an addition to the work carried out by Prachansri (2007). The results serve as the input boundary conditions for the SOBEK-flow model. In Prachansri's study the discharge simulation achieved from the LISEM model assumed no baseflow. However, a river's streamflow is generated by a combination of baseflow, interflow and saturated overland flow (Maidment 1993).

During the fieldwork phase of this study, velocity measurements were obtained at the outlet of the catchment at the same time daily. An average streamflow of $\pm$ 10m^3/s was observed on days which had little or no influence of previous rainfall occurrences. As a result, this measured discharge was classed as baseflow. Figure 6-1 illustrates the relationship between rainfall, baseflow and stormflow. After the stormflow subsides the river conforms to the original capacity of the river (baseflow). Therefore, in an attempt realistically replicate the behaviour of this river system and represent probable events in this area a baseflow was added to the simulated results.

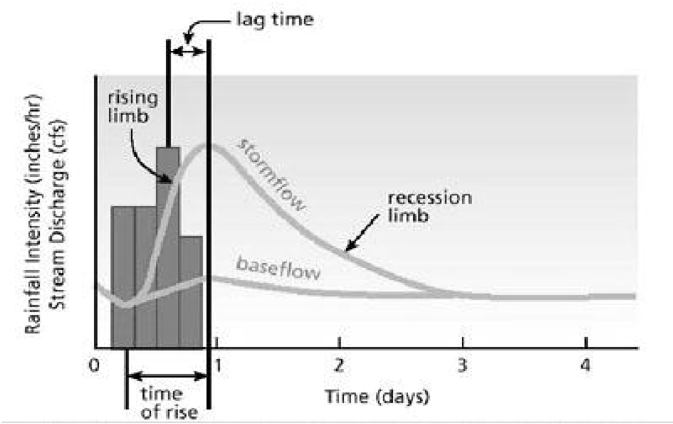


Figure 6-1: The relationship between stormflow and baseflow (US-EPA 2008)

Prachansri's LISEM model was calibrated meticulously. However, due to the addition of the baseflow parameter it was necessary to recalibrate the model. In theory, it should not be necessary to calibrate fully physically based models. However, models are never fully physically based and many authors have confirmed the need to calibrate process based erosion models to achieve an acceptable predictive quality e.g. (Jetten, de Roo, and Favis-Mortlock 1999). Limitations in both model structures and data availability on parameter values, initial conditions and boundary conditions, will cause difficulty in the application of a hydrological model lacking some form of calibration. "All model calibrations and subsequent predictions will be subject to uncertainty" (Beven 2001). This uncertainty is understandable since no rainfall-runoff model is a "true" replication of what occurs in reality due to sources of error which can start from field measurements and propagate throughout the results.

The peak discharge occurs slightly early, as can be seen in Figure 4-5 and Figure 4-6. A possible reason for this is the time of observation. The observed discharge was recorded every three hours, therefore, the "true" momentary peak discharge may have been missed. Additionally, the measured hydrograph shows a combination of runoff and baseflow increase, and LISEM assumes a constant, steady state baseflow. A combination of these factors could be the rationale for the early measured peak compared to the simulated.

One of the crucial steps in modelling and understanding how the model behaves is to perform a sensitivity analysis. Many modellers believe that at the instance all input parameters are defined, the output is the "true" representation of the earth which they model. As scientist there needs to be some intuitive understanding to what kind of output is desired and how the change in values can affect the results. The K_{sat} and Manning's n values were selected as the parameters to test the model sensitivity. The results of this sensitivity analysis illustrates that the model is more sensitive to changes of the K_{sat} parameter. A series of parameters with different combinations of values could very well yield the same results (Jetten 1998). Hence, a more detailed sensitivity analysis would be more advantageous.

6.2. The SOBEK-flow model

"Reliability of model results is primarily based on the accuracy of the DTM" (Tennakoon 2004). The most crucial input parameter in the SOBEK-flow model that aids in flood routing is a detailed Digital Surface Model (DSM) containing all major surface features. A DSM illustrates the elevations of the top surfaces of buildings, vegetation and other features elevated above the bare terrain. Inversely a Digital Elevation Model (DEM) usually implies elevations of the terrain without vegetation and manmade features. The definition of Digital Terrain Model (DTM) is also synonymous to that of a DEM (Maune 2001). In many studies these terms are used interchangeably to describe elevation models of various types. In this study, an existing "DEM" constructed with road, embankment and terrain elevations were enhanced with the addition of building elevations. Considering the inclusion of manmade features in the construction of this elevation model, it was classed as a DSM.

Ideally, a high resolution DSM such as LIDAR data, with a pixel resolution of 1 meter, would be preferred. However, the computational time would be too lengthy. While a high level of detail is desirable there should also be a compromise between computational time and resolution. A 25 meter DSM was chosen for this research due to the addition of sedimentation processes, which would be calculated per cell increasing simulation time. Bearing in mind the main aim of the study, is to test a methodology rather than for decision making purposes, this was considered acceptable.

The SOBEK-flow model produces user defined outputs such as depth, duration, velocity and propagation. In order to understand the processes of sedimentation and re-suspension the characteristics of the medium which transports the sediments must also be examined. For this purpose maximum depth, velocity and propagation maps were generated (See pages 54-56). The depth and propagation map describes the behaviour of flow in both vertical and horizontal dimensions respectively. The velocity map, on the other hand illustrates the intensity of each flood event. At this stage in the research, some assumptions were made about the areas of probable deposition, which did not correlate with the validation methodology implemented. This is further discussed in 6.3.

The sensitivity of the SOBEK-flow model was tested by simulating the 10 year return flood without the effects of bridges and culverts. A notable change occurred. The simulation without engineering features had less inundation coverage compared to that of the simulation with these features (See Figure 5-17 and Figure 5-18). The maximum depth of the simulation without the bridges and culverts is 1.1 m less than that of the simulation with these features. The exclusion of such features in a vulnerability estimation for example could cause serious underestimations.

6.3. The SOBEK -2DWAQ model

The results of the SOBEK-2DWAQ model were divided by sediment type i.e. Sand, silt and clay. The spatial distribution of each sediment type was determined by the spatial distribution of the medium that is loaded with sediments and the time scale of sedimentation against the time scale of hydrodynamics. The flash flood event ended after 6 hours. However, the simulation time was prolonged to allow the sedimentation of the finer particles i.e. silt and clay. These sediment fractions have a sedimentation velocity of 7m/d and 0.3m/d respectively versus sand which was 30 m/d. These sedimentation velocities were derived from studies carried out by Delft Hydraulics, which successfully applied the Water Quality model (Delft Hydraulics 2007).

To test the sensitivity of the SOBEK-2DWAWQ model, the clay deposit simulation (20 year return flood) was generated with and without the engineering features in the schematization, namely the bridges and culverts. Areas which experience deposition with the inclusion of these structures are not affected when the structures are absent. This indicates how sensitive the model is to such features. In additon, many hydrodynamic and sediment transport models are used to aid municipalities in decision making. A prime example of simulating the SOBEK model without the necessary engineering features could mean underestimating evacuation zones.

When attempting to replicate the way the earth behaves with a model, accuracy assessment is of great importance. This aspect was lacking in the study. The validation method implement was not detailed enough to crosscheck the model outputs. In group interviews one opinion is sometimes influenced by others. This means, the group came to a consensus about the answers given regardless of the locality of their dwelling. A more detailed participatory GIS method is desired. For future studies bore hole profiles would be useful to examine the various events which have occurred in the area, their depths and soil type.

7. Conclusions and recommendations

7.1. Conclusions

The main objective of this research was to estimate sediment deposition from flash flood waters in the downstream area of the Nam Chun watershed, taking into account the soil erosion occurring within the upstream catchment. The specific objectives were divided into a three step methodology in order to achieve the main objective. These were to estimate the discharge and sediment concentration from the upland catchment for designed flood events, characterize the propagation of flood waters over a downstream flood plain and finally to test the application of the SOBEK-2DWAQ model to simulate the transport and deposition of sediments in a downstream flood plain. The following conclusions were derived based on the results obtained in this study:

- The results obtained from this study illustrate the possibility to have a successful connection between the upstream catchment model LISEM with the downstream SOBEK-flow and SOBEK-2DWAQ models for the spatial temporal evaluation of sediment deposition from flash floods.

- SOBEK-2DWAQ model is applicable to model 2-Dimnesional sediment transport and deposition from high velocity flood events.

- The SOBEK-flow and 2DWAQ model yield notable changes in simulated results when bridges and culverts are not included in the schematization compared to simulations with these features.

  - In the SOBEK-flow model simulated water depths are lower with the exclusion of bridges and culverts than that of simulations including these structures.
  - Areas which are inundated with the inclusion of bridges and culverts in the schematization are not flooded when these structures are omitted.
  - In the SOBEK-2DWAQ model the spatial distribution of simulated sediment deposits are less when the bridges and culverts are excluded from the schematization compared to the simulation with these structures.

- The final results of the sediment deposition model could be constructive for decision making processes on watershed and flood plain management. These include, watershed conservation regimes, improved urban planning strategies in the flood plain and an introduction of flood defence and warning time systems.

7.2. Limitations of study

- The main limitation concerning the LISEM model was the availability of data. The fieldwork time allotted was not sufficient for carrying out detailed measurements necessary to calibrate the model. Also, the rainfall data available at the municipal offices (daily) were not ideal for use in LISEM. This presented the use of data from previous researches and the inclusion of design storms in the study.

- The rainfall information used in the LISEM model was considered uniform for the entire catchment because the rainfall data was collected from one location. This hinders the spatial variability of rainfall within the watershed.

- The primary limitation in this study was the lack of knowledge and SOBEK-desktop help regarding the SOBEK-2DWAQ model. Hence, considerable time was utilized for troubleshooting and enquiring with SOBEK support for assistance.

7.3. Recommendations

- The present grid used in this study is 25*25 m^2. To achieve a better description of the spatial distribution of sediments in the flooded areas, the grid can be refined to 10*10 m^2.

- The suspended sediment concentrations defined in the boundary conditions are constant in the present model schematization. This is not so in reality, suspended sediment concentrations are a function of discharge and time and this should be reflected in the model.

- The sensitivity of the model should be carried out more thoroughly. This may give more clarity of the effects of flooding in the water quality. The Table 7-1 below list parameters which should be considered in future studies:

Table 7-1: Parameters for water quality sensitivity analysis

Parameter	Effect
Sedimentation velocity	Spatial distribution of sediments Overall sediment mass balance
Density & Porosity	Thickness of sediment layer
Hydrodynamic simulation	Spatial distribution of sediments Overall sediment mass balance

7.3.1. Further Studies

Combined flood and sediment transport modelling for risk assessment

Many flood risk assessment studies are carried out yearly in areas that also experience large amounts of sediment deposits as a consequence of these flood events. This is an added element that affects the morphology of floodplains and the livelihood of those living in the area. It is an aspiration that a continued study is carried out in the Nam Chun Watershed concerning flood events and sediment deposition risk. As stated numerous times throughout this work, a flood event is not merely water at a certain depth with a particular velocity, but also the sedimentation processes occurring concurrently.

Sediment transport modelling as support for decision-making

Sediment deposition performs various functions: it shapes flood plains making river beds shallower and more prone to flooding, blocks drains and affects water quality. These factors provide an avenue for improved upland conservation practices and lowland urban planning strategies in such areas. Further studies should be carried out to develop these strategies with the aid of Remote Sensing and GIS bearing in mind results that are suitable for presentation to a municipality.

Water Quality Evaluation

In the upland catchment of the Nam Chun Watershed the farmers use a host of pesticides. These contaminants can be washed to the downstream area and affect the water quality. Contaminants are usually attached to clay particles which is the main fraction deposited in this area. The interviews carried out in this area also consider water quality issues even though they were not addressed in this research. The residence affected by sediment deposition also mentioned that the tap water would also appear to have sediments after a flood event. This is cause for concern and future study.

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Appendices

Appendix 1: Group interview questionnaire

Questionnaire: Evaluation of the probable extent of sediment deposition and identification of associated effects in Lom Sak, Phetchabun, Thailand

GPS Location: X: Y:

1. Are there problems with soil washed from the mountain areas to the downstream areas during a normal rainstorm?

   ☐ Yes ☐ No

2. After a flood event, is there any damage to your property because of soil left behind?

   ☐ Yes ☐ No

If yes, what type of damage

____

____

3. Are there water quality issues after a flood event?

   ☐ Yes ☐ No

4. Are the farm lands damaged as a result of sediments deposited from a flood event?

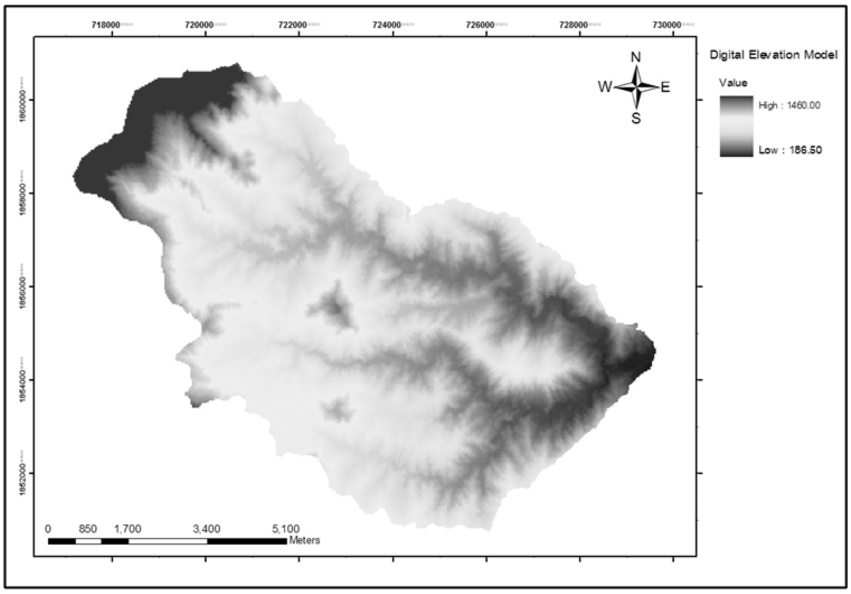
   ☐ Yes ☐ No

5. Which areas in your village experience the greatest problem of sediment deposited after a flood?

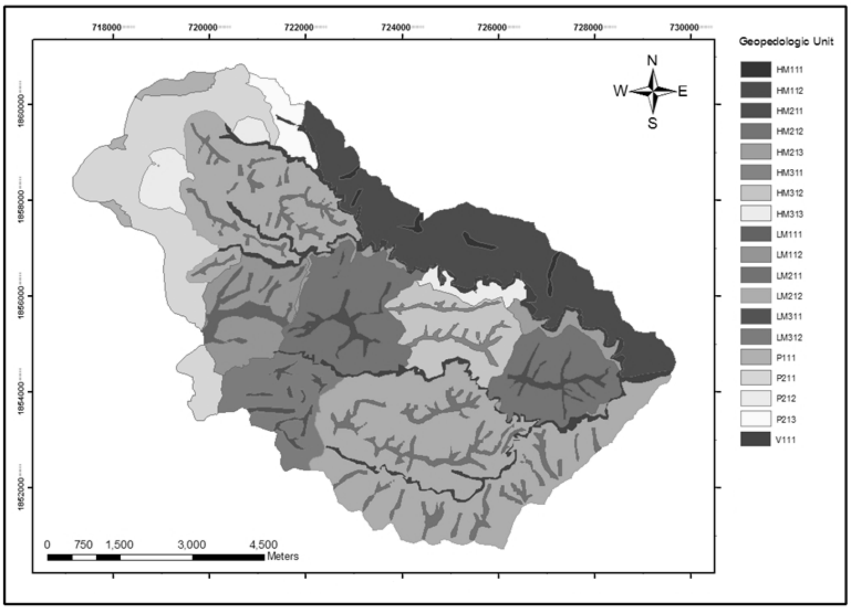
____

____

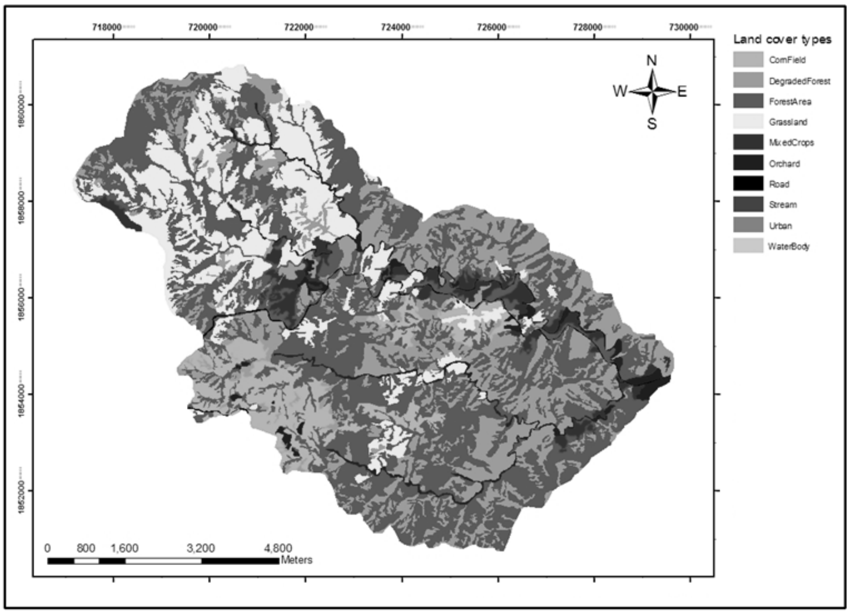
Appendix 2: Basic LISEM input map-DEM



Appendix 3: Basic LISEM input map-Geopedologic



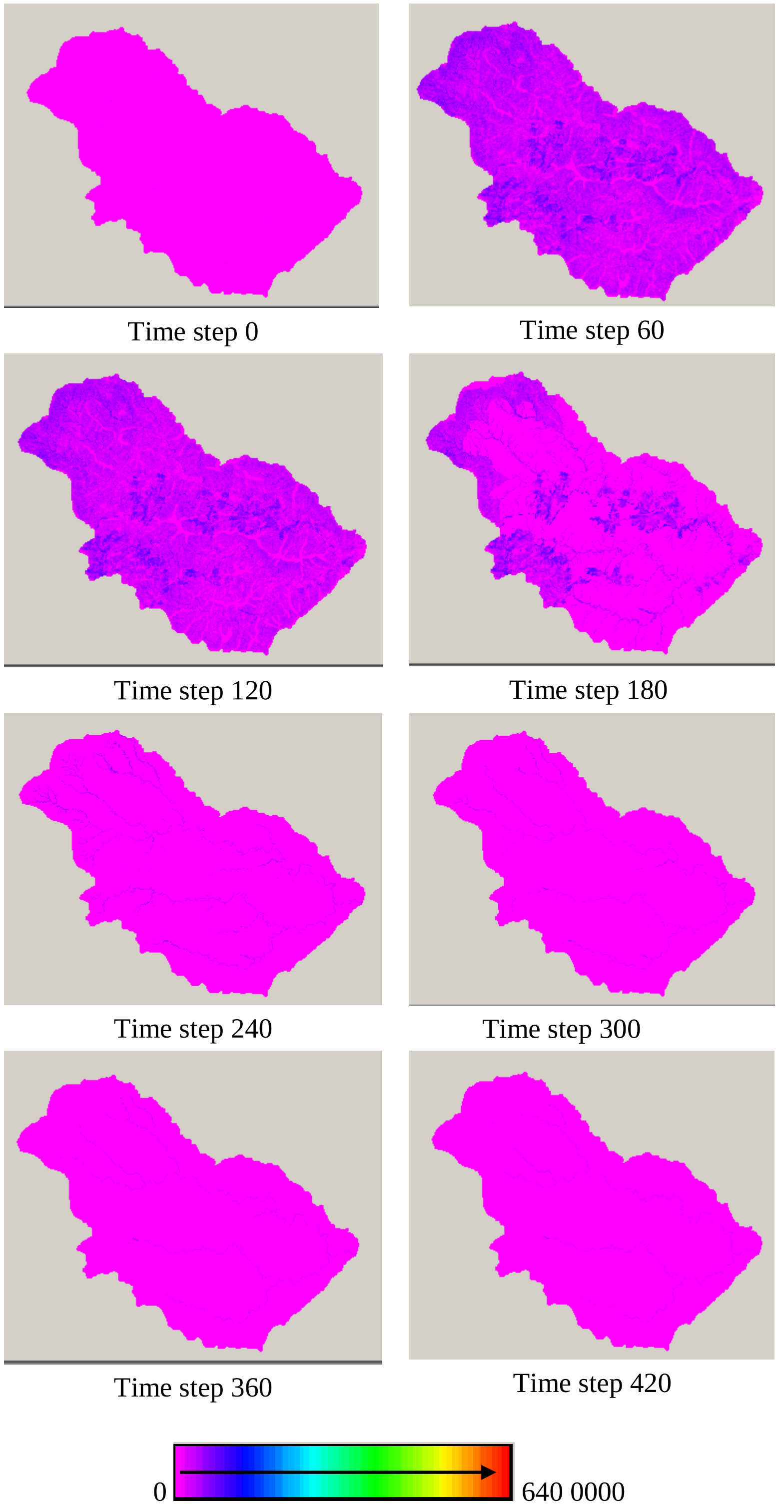
Appendix 4: Basic LISEM input map-Land cover types



Appendix 5: Rainfall frequency analysis

Date	Year	Max Rain	Total 5 days prior	Total 5 days post	Rain-Pre	Rain-Post
26-Oct	1970	67.7	6.5	2.9	6.5	0.1
14-Jun	1971	76.8	8	16.7	5.8	0
30-Jun	1972	67.8	0	47.4	0	33.5
4-Apr	1973	60.3	0	1.6	0	1.6
20-May	1974	54.8	43.7	57.4	32	0
17-Jul	1975	60.5	39.7	32.2	7.1	2.9
25-Aug	1976	56.5	31.7	50.2	1	7.2
5-Sep	1977	109.1	21.1	25	14.8	2.6
8-Jul	1978	97.5	31	41.5	18.3	16.1
20-Jun	1979	54.2	37	0	31	0
17-Sep	1980	80.4	30.7	83.6	12	60.3
10-Aug	1981	50.4	21.7	8.4	5.5	0.2
7-Sep	1982	76.4	50.3	84.3	43.8	60.7
3-Oct	1983	95.5	14.1	6.5	1.5	1.8
11-Jun	1984	109.2	56.9	3.4	18.3	0
16-Oct	1985	91.9	25.2	29	0.1	11.8
26-Aug	1986	51	12.1	1.5	10.9	1.5
7-Sep	1987	89.1	26.9	21.8	24.6	16.2
10-May	1988	71.4	63.8	43.6	0	20.2
13-Oct	1989	95.6	12.7	42.7	0	29.8
8-Mar	1990	93.2	12.3	48.9	12.1	4.9
18-Aug	1991	129.2	56.9	19.1	29.3	8.4
4-Aug	1992	63.7	7.8	31.4	0	23.7
29-May	1993	42.8	0.4	87.9	0	5.6
9-Jun	1994	93.3	50.1	4	0	4
25-Jul	1995	70.8	44	18.2	10.7	0
14-Sep	1996	77.3	95.7	89.3	63	7.6
30-May	1997	71.8	0	1.6	0	1.6
13-May	1998	62.8	2.3	46.7	1.3	0
26-Sep	1999	60.9	30.5	2.4	0	0
24-Aug	2000	72.2	37.4	15	11.5	2.2
30-May	2001	61.7	0	24.5	0	0
19-Aug	2002	105	8.9	137.7	4.8	56
12-Jul	2003	55.6	28.5	1.8	1	1.8
15-Jun	2004	61.1	37.7	15.2	17.6	8.8
27-Sep	2005	75.7	4.2	1.1	4.2	1.1
9-Oct	2006	109.8	10.6	8.4	3.1	0.8
4-Oct	2007	115.6	42.9	105	42.9	4.2

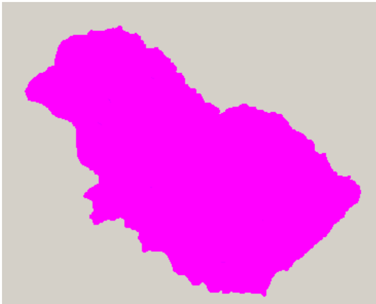
Appendix 6: Spatial temporal distribution of sediment concentration for the 20 year return flood



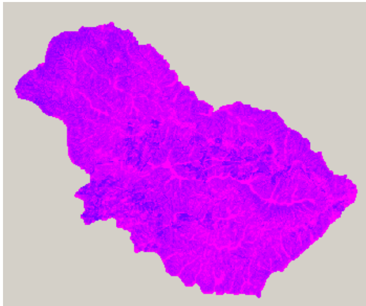
Increasing sediment concentration (g/m^3)

(time step = 1 min)

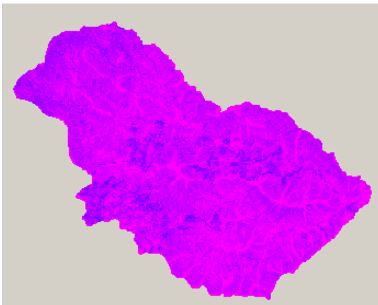
Appendix 7: Spatial temporal distribution of sediment concentration for the 50 year return flood



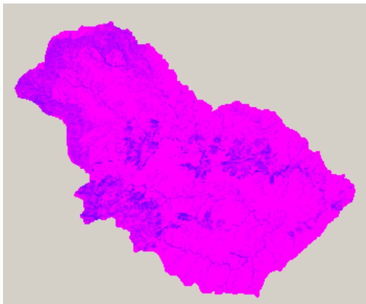
Time step 0



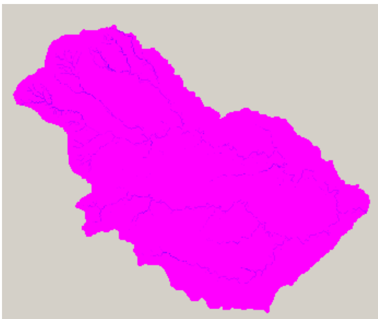
Time step 60



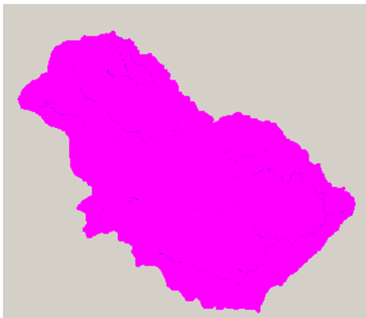
Time step 120



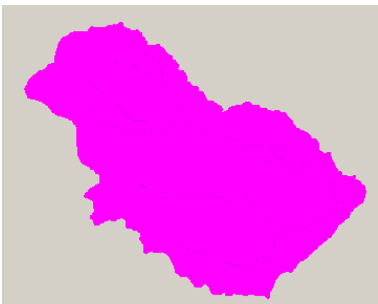
Time step 180



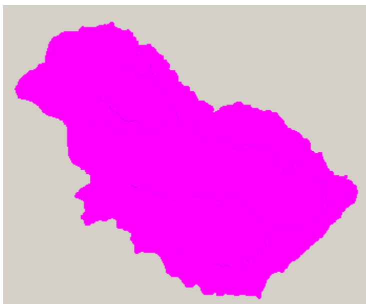
Time step 240



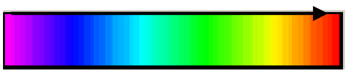
Time step 300



Time step 360



Time step 420

0  720 0000

Increasing sediment concentration (g/m^3)

(time step = 1 min)

Appendix 8: LISEM calibration rainfall (a) 260905 and (b) 180905

Time (mins)	Rain (mm/hr
0	0
60	0
120	0
180	0
240	0
300	0
360	0
420	0
480	1
540	0
600	0
660	1
720	30.5
780	0.5
840	0
900	0
960	0
1020	0
1080	0
1140	0
1200	0
1260	0
1320	0
1380	0
1440	0

(a)

Time (mins)	Rain (mm/hr
0	0
60	0
120	0
180	0
240	1
300	18
360	1
420	0
480	1
540	0
600	0
660	0
720	0
780	0
840	0
900	0
960	0
1020	0
1080	0
1140	0
1200	0
1260	0
1320	0
1380	0
1440	0

(b)

Appendix 9: Rankplot input dataset - Historical rainfall data for the Nam Chun Watershed

Year	Rainfall (mm)
1970	67.7
1971	76.8
1972	67.8
1973	60.3
1974	54.8
1975	60.5
1976	56.5
1977	109.1
1978	97.5
1979	54.2
1980	80.4
1981	50.4
1982	76.4
1983	95.5
1984	109.2
1985	91.9
1986	51
1987	89.1
1988	71.4
1989	95.6
1990	93.2
1991	129.2
1992	63.7
1993	42.8
1994	93.3
1995	70.8
1996	77.3
1997	71.8
1998	62.8
1999	60.9
2000	72.2
2001	61.7
2002	105
2003	55.6
2004	61.1
2005	75.7
2006	109.8
2007	115.6

Appendix 10: ILWIS Import Script

```
import arcinfonas(dm1c0000.asc, c00)
import arcinfonas(dm1c0001.asc, c01)
import arcinfonas(dm1c0002.asc, c02)
import arcinfonas(dm1c0003.asc, c03)
import arcinfonas(dm1c0004.asc, c04)
import arcinfonas(dm1c0005.asc, c05)
import arcinfonas(dm1c0006.asc, c06)
import arcinfonas(dm1c0007.asc, c07)
import arcinfonas(dm1c0008.asc, c08)
import arcinfonas(dm1c0009.asc, c09)
import arcinfonas(dm1c0010.asc, c10)
import arcinfonas(dm1c0011.asc, c11)
import arcinfonas(dm1c0012.asc, c12)
import arcinfonas(dm1c0013.asc, c13)
import arcinfonas(dm1c0014.asc, c14)
import arcinfonas(dm1c0015.asc, c15)
import arcinfonas(dm1c0016.asc, c16)
import arcinfonas(dm1c0017.asc, c17)
import arcinfonas(dm1c0018.asc, c18)

import arcinfonas(dm1maxc0.asc, v_max)

setgrf c??.mpr dtm25.grf
setgrf v_max.mpr dtm25.grf

del c??.grf -force
del v_max.grf -force

vel00 { vr=0:30:0.1 }:=ifundef(c00,0,c00)
vel01 {vr=0:30:0.1}:=ifundef(c01,0,c01)
vel02 {vr=0:30:0.1}:=ifundef(c02,0,c02)
vel03 {vr=0:30:0.1}:=ifundef(c03,0,c03)
vel04 {vr=0:30:0.1}:=ifundef(c04,0,c04)
vel05 {vr=0:30:0.1}:=ifundef(c05,0,c05)
vel06 {vr=0:30:0.1}:=ifundef(c06,0,c06)
vel07 {vr=0:30:0.1}:=ifundef(c07,0,c07)
vel08 {vr=0:30:0.1}:=ifundef(c08,0,c08)
vel09 {vr=0:30:0.1}:=ifundef(c09,0,c09)
vel10 {vr=0:30:0.1}:=ifundef(c10,0,c10)
vel11 {vr=0:30:0.1}:=ifundef(c11,0,c11)
vel12 {vr=0:30:0.1}:=ifundef(c12,0,c12)
vel13 {vr=0:30:0.1}:=ifundef(c13,0,c13)
```

```
vel14 {vr=0:30:0.1}:=ifundef(c14,0,c14)
```

```
vel15 {vr=0:30:0.1}:=ifundef(c15,0,c15)
vel16 {vr=0:30:0.1}:=ifundef(c16,0,c16)
vel17 {vr=0:30:0.1}:=ifundef(c17,0,c17)
vel18 {vr=0:30:0.1}:=ifundef(c18,0,c18)


velocity_max {vr=0:30:0.1}:=ifundef(v_max,0,v_max)

del c??.mpr -force
del v_max.mpr -force


import arcinfonas(dm1d0000.asc, x00)
import arcinfonas(dm1d0001.asc, x01)
import arcinfonas(dm1d0002.asc, x02)
import arcinfonas(dm1d0003.asc, x03)
import arcinfonas(dm1d0004.asc, x04)
import arcinfonas(dm1d0005.asc, x05)
import arcinfonas(dm1d0006.asc, x06)
import arcinfonas(dm1d0007.asc, x07)
import arcinfonas(dm1d0008.asc, x08)
import arcinfonas(dm1d0009.asc, x09)
import arcinfonas(dm1d0010.asc, x10)
import arcinfonas(dm1d0011.asc, x11)
import arcinfonas(dm1d0012.asc, x12)
import arcinfonas(dm1d0013.asc, x13)
import arcinfonas(dm1d0014.asc, x14)
import arcinfonas(dm1d0015.asc, x15)
import arcinfonas(dm1d0016.asc, x16)
import arcinfonas(dm1d0017.asc, x17)
import arcinfonas(dm1d0018.asc, x18)

import arcinfonas(dm1maxd0.asc, d_max)


setgrf x??.mpr dtm25.grf
setgrf d_max.mpr dtm25.grf

del x??.grf -force
del d_max.grf -force
```

```
depth01 {vr=0:20:0.1}:=ifundef(x01,0,x01)
depth00 {vr=0:20:0.1}:=ifundef(x00,0,x00)
depth02 {vr=0:20:0.1}:=ifundef(x02,0,x02)

depth03 {vr=0:20:0.1}:=ifundef(x03,0,x03)
depth04 {vr=0:20:0.1}:=ifundef(x04,0,x04)
depth05 {vr=0:20:0.1}:=ifundef(x05,0,x05)
depth06 {vr=0:20:0.1}:=ifundef(x06,0,x06)
depth07 {vr=0:20:0.1}:=ifundef(x07,0,x07)
depth08 {vr=0:20:0.1}:=ifundef(x08,0,x08)
depth09 {vr=0:20:0.1}:=ifundef(x09,0,x09)
depth10 {vr=0:20:0.1}:=ifundef(x10,0,x10)
depth11 {vr=0:20:0.1}:=ifundef(x11,0,x11)
depth12 {vr=0:20:0.1}:=ifundef(x12,0,x12)
depth13 {vr=0:20:0.1}:=ifundef(x13,0,x13)
depth14 {vr=0:20:0.1}:=ifundef(x14,0,x14)
depth15 {vr=0:20:0.1}:=ifundef(x15,0,x15)
depth16 {vr=0:20:0.1}:=ifundef(x16,0,x16)
depth17 {vr=0:20:0.1}:=ifundef(x17,0,x17)
depth18 {vr=0:20:0.1}:=ifundef(x18,0,x18)

depth_max {vr=0:30:0.1}:=ifundef(d_max,0,d_max)


del x??.mpr -force
del d_max.mpr -force
```