RAINFALL-RUNOFF MODELING
IN THE UNGAUGED CAN LE CATCHMENT,
SAIGON RIVER BASIN

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RAINFALL-RUNOFF MODELING
IN THE UNGAUGED CAN LE CATCHMENT, SAIGON RIVER BASIN

by

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Dedicated to my parents with love
Kính tặng cha mẹ vợ vàn kính yêu
Abstract

In this study a rainfall – runoff model is developed for the Can Le catchment in the upper stream of the Sai Gon river Basin (Viet Nam). The model will serve for simulation of catchment runoff into the Dau Tieng Dam reservoir and use as flood forecasting tool at the Can Le catchment. In modelling many approaches are known and finding a suitable approach by far is trivial. Can Le catchment is regarded as an ungauged catchment since data from this area is not systematically collected.

The study is pursued as follows:

(1) Various model approaches including empirical, conceptual and physically based are compared and three suitable approaches are selected and tested;(2) The possible role of Geographic Information System (GIS) and Remote Sensing (RS) for data preparation and model parameterization in ungauged catchments are explored and remote sensing imagery and modelling are integrated; (3) Fields data for model parameterization, calibration and validation is collected during a field campaign and simulation results are critically evaluated.

Model approaches selected are:

Soil Moisture Accounting (SMA) model which is embedded in the HEC-HMS software suite. SMA is a lumped conceptual approach that allows continuous stream flow simulation and a number of model parameters are estimated using GIS techniques.

Geomorphologic Instantaneous Unit Hydrograph (GIUH) was selected as a lumped empirical model. Coupling of quantitative geomorphology and hydrology is at the core of this approach. The obtained Unit Hydrograph based on Horton’s morphometric parameters including bifurcation, length, area ratios explains this approach. The new functionality in ILWIS namely “DEM-hydro processing” is used in order to extract these ratios from the Digital Elevation Model.

Representative Elementary Watershed (REW) approach: The novel approach is recently developed and appears in hydrological society as a new blueprint for physically based hydrologic modeling. In the approach, a watershed is discretized into a number of sub-watersheds through specific Digital Elevation Model (DEM) analyses. Each REW is subdivided into five sub-regions including the saturated zone, the unsaturated zone, the channel reach, the concentrated overland flow zone and the saturated overland flow zone. Balance equations of mass and momentum are derived for each zone of each REW and they are directly applied to the sub-catchment scale. Applying the approach to an ungauged catchment is not reported in literature and is a major challenge to this study.

To supplement the limited data in the area, various satellites imageries have been used. The sources come from ASTER, SRTM (Shuttle Radar Topography Mission) to TRMM (Tropical Rainfall Measuring Mission) and METEOSAT 5.
A field campaign to obtain possible data was executed between September and October 2005. The data collected included discharge (and stage – discharge curve), meteorological data, soil, land use information that all are crucial for validation and calibration of the selected model approaches.

An intercomparison is made for the three applied approaches in order to propose a suitable model approach that is the overall objective of this study. In addition, model performance and model uncertainties due to various sources such as improper data input, incorrect model parameterization are also highlighted in the end of this study.

**Keywords:** Ungauged catchment, HEC-HMS SMA, REW, GIUH, GIS, RS, DEM, model parameterization, model uncertainty, Can Le catchment, Sai Gon river.
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<th>Description</th>
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<tbody>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>CN</td>
<td>Curve Number</td>
</tr>
<tr>
<td>d</td>
<td>Agreement index</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GIUH</td>
<td>Geomorphologic Instantaneous Unit Hydrograph</td>
</tr>
<tr>
<td>HEC-DSSVue</td>
<td>Hydrologic Engineering Center Data Storage System Visual Utility Engine</td>
</tr>
<tr>
<td>HEC-HMS</td>
<td>Hydrologic Engineering Center - Hydrologic Modeling System</td>
</tr>
<tr>
<td>ILWIS</td>
<td>Integrated Land and Water Information System</td>
</tr>
<tr>
<td>IWRM</td>
<td>Integrated Water Resources Management</td>
</tr>
<tr>
<td>m.a.s.l</td>
<td>meter above sea level</td>
</tr>
<tr>
<td>NA</td>
<td>Not applicable</td>
</tr>
<tr>
<td>NSE</td>
<td>Nash-Sutcliffe efficiency</td>
</tr>
<tr>
<td>pdf</td>
<td>probability density function</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of determination</td>
</tr>
<tr>
<td>R_A</td>
<td>Area ratio</td>
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<tr>
<td>R_B</td>
<td>Bifurcation ratio</td>
</tr>
<tr>
<td>REW</td>
<td>Representative Elementary Watershed</td>
</tr>
<tr>
<td>R_L</td>
<td>Length ratio</td>
</tr>
<tr>
<td>RS</td>
<td>Remote Sensing</td>
</tr>
<tr>
<td>SCS</td>
<td>Soil Conservation Service</td>
</tr>
<tr>
<td>SMA</td>
<td>Soil Moisture Accounting</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
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<tr>
<td>TRMM</td>
<td>Tropical Rainfall Measuring Mission</td>
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1. Introduction

“Water is essential for life”. We are all aware of its necessity, for drinking, for providing food, for washing, etc. – in essence for maintaining our health and dignity. Water is also required for providing many industrial products, for generating power, and for moving people and goods – all of which are important for the functioning of a modern, developed, and developing society. In addition, water is essential for the integrity and sustainability of the Earth’s system” (The United Nations - World water development report, 2003)

However, water availability is very concerned in the last decades. Demand and competition for water resources continue to grow almost everywhere. The main reason can be explained by the increase of the world population leading to higher demand on water in many activities such as agriculture, industry, energy supply, etc. In addition, the decrease of water quality and quantity due to such activities make this resource becoming limited and nowadays is considered as “Water crisis”

Many organizations appeal to solutions on this problem, especially from the United Nations (1992). Integrated Water Resources Management (IWRM) was introduced as a concept to optimise water resources management and applications are found in recent publications, such as Global Water Partnership (2005), Zaag (2005).

Singh (1995) mentioned that the IWRM should be accomplished within a spatial unit called catchment through a tool of modelling. Other authors (eg. Cuddy and Gandolfi, 2004) refer to IWRM as “An innovative modelling concept for integrated water resources management linking hydrological functioning and socio-economic behaviour”. Therefore, fundamental to integrated water management is catchment modelling.

Catchment models are in general designed to meet one of two primary objectives. The first is to gain a better understanding of the hydrologic behaviors of a catchment and of how changes in the catchment may affect these behaviors. The second objective of catchment modeling is the generation of synthetic hydrologic data for facility design like water resources planning, flood protection, mitigation of contamination, or licensing of abstraction or for forecasting. They are also providing valuable information for studying the potential impacts of changes in land use or climate.

In catchment modelling, if we consider water quantity and water availability, traditionally, simulating the relation between precipitation and discharge at the river’s outlet should be carried out. Rainfall – runoff modelling is a major part of this job. Therefore, rainfall – runoff modelling is considered as standard tool routinely used today for the investigation and application in catchment hydrology.

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1 The IWRM is concerned with the interactions of physical, ecological, economic and social system as they affect the operation, planning and decision making processes.
However, due to catchment heterogeneity, (highly) dynamic and non-linear hydrologic behaviour, it is not easy to quantify the runoff of the system adequately. Appropriate modelling requires a certain level of understanding the physical characteristics. It becomes even more difficult if data from the catchment is not available that commonly is referred as an ungauged catchment. Moreover, this is not restricted for certain areas but is observed throughout the world as emphasised by Sivapalan et al (2003) “many parts of drainage basins in the world are ungauged or poorly gauged, and some countries existing measurement networks are declining”.

1.1. Problem description

In Viet Nam, conflicts in water resource management are also increasing in the recent years. Based on report of the World Bank (1996) and Pho et al (2003), Vietnam would seem to have an advantageous surface water situation, given the extensive network of rivers, favorable topography and rainfall patterns and in relation to its population size. However, in recent documentation prepared by The Ministry of Environment and Natural Resources (MONRE), the World Bank and the Danish International Development Assistance (DANIDA) (2003), Viet Nam is facing many water issues such as water pollution, floods, droughts.

An example is made for Dau Tieng Dam, the biggest irrigation dam of Vietnam. The Dam has played an indispensable role for the region of Tay Ninh, Binh Duong, Long An, and Ho Chi Minh city (figure 3.1) that are considered as key economic areas of the Southern Zone of Viet Nam. The dam initially was designed for flooding prevention and irrigation, and later served to prevent salt water intrusion in the low stream area (Hung, 1995; Tuan, 1998). In the last few years, due to a rapid increase of industry, urbanization, especially downstream of the Dau Tieng Dam, some environmental problems such as water pollution, groundwater over-exploitation have been occurred (Triet and Hung, 2002). The Dau Tieng Dam, again, plays a role for the region as “water regulator” to prevent salt water intrusion and to supply water plants in the Saigon river basin, and also a new functionality of increasing ability of the river’s self-purification. (Anonymous, 2002)

However, water availability of the Dam is recently very concerned. For example, in 2004, the director of Dau Tieng Water Resources Exploiting Company said “Dau Tieng is lacking of about 600 millions cubic meter of water”! Last year, April 2005, due to salt-water intrusion in the downstream area required Dau Tieng to operate as their highest capacity (HUY, 2005a; HUY, 2005b) which was not recommended at the beginning of the dry season.

Due to the crucial role of Dau Tieng Dam for the region as well as having the situation of the reservoir under control requires a good estimation of inflow into the Dam. Therefore, there is an urgent need to assess the water contribution from the upper tributaries.

For these reasons, in this study, an attempt is made to setup a hydrologic model which can quantify the volume of water from the Can Le Catchment. Developing a rainfall – runoff model for the catchment is the solution to be carried out. The model will serve for simulation of catchment runoff into the Dau Tieng reservoir in general and will be used as flooding prediction tool at Can Le catchment in particular.

1.2. Objectives

1.2.1. Objectives

Overall objective: To develop a suitable rainfall – runoff model for the Can Le catchment

To fulfill the research, the following specific objectives are:

- Obtain the real world data for model development and calibration and explore the potential and/or the possible role of Geographic Information System (GIS) and Remote Sensing (RS) for data collection and model parameterization;
- Select and test a small number of rainfall – runoff model approaches;
- Compare the selected model approaches using various performance criteria and recommend which approach is suitable for the area and (possibly) the Sai Gon river basin.

1.2.2. Research questions

Follow up to the above objectives, a few questions are raised.

Objective 1: Obtaining the real world data
- Which data should be collected and how to acquire data in the fieldwork period?
- What is the quality of the data? (Spatial data and attribute data)

If data availability is insufficient, how to generate synthetic data?

Objective 2: Select and test different model approaches
- What are the differences in model structure, model assumptions, and limitations of these approaches?
- What boundary conditions are implied and what initial conditions must be defined?

Objective 3: To compare and recommend model approaches
- What criteria should be selected for model comparison?
- Which model performs “best” and is to be recommended?

1.2.3. Hypothesis and expected results

Hypotheses
- The more complicated structure a model becomes, the better it performs;
- Satellite retrieved rainfall distribution will improve the simulation results.

Expected results
- Simulated discharge versus observed flow;
- A comparison of 3 model approaches and their performances;
An “optimal” model approach is released for the Can Le catchment and (possibly) the Sai Gon river basin and proposed for usage.

1.3. Overall framework

To conduct this study, 3 main stages were identified. They are: pre-fieldwork, fieldwork and post-fieldwork. Several activities for each period are shown in the overall framework (Figure 1.1).

The pre-fieldwork serves for proposal writing and fieldwork preparation stage. In this period, the strategy for rainfall – runoff modelling for ungauged catchment was developed. Also, DEM processing to extract the Can Le catchment as well as preparing a classified land cover map were done.

For the field campaign, discharge measurements were identified as a main activity to obtain reliable data for model calibration. In addition, other activities like data collection, field survey etc. were carried out.

In the last period, a number of activities have been done. Data processing, model development including model parameterization and operation, etc. are attributed as well as the indispensability of thesis writing.

Figure 1.1: Time-based overall framework.

1.4. Thesis outline

The thesis outline is as following

Chapter 2- A literature review covers and gives an overview of typically related references that are applicable for this study.

Chapter 3 discusses the study area and fieldwork activities and includes a description of the main characteristics of the catchment and data collected during the fieldwork period.

Chapter 4 describes the research methods to accomplish this study.
Chapter 5 shows results of data preparation (rainfall) and model simulation.

Chapter 6 covers the most important part of this study. This section comments on the model approaches, pro’s and con’s of each model in the context of the catchment. Output is discussed. In addition, model performance and model uncertainties due to various sources such as improper data input, incorrect model parameterization are emphasized;

Chapter 7 concludes this study and achievements and limitations are summarised and few recommendations for further investigation are proposed.
2. Literature review

In this chapter a review on typical topics involved in this study is presented. The chapter is started by briefly summarising on the catchment hydrologic cycle and catchment runoff generation; it is followed by giving an overview on rainfall – runoff modelling and rainfall – runoff model classification. The applications of Remote Sensing (RS), Geographic Information System (GIS), and Digital Elevation Model (DEM) in hydrology are discussed through introducing a number of typical literatures involved in these fields. A brief review on the three selected model is presented subsequently. References on model comparison or model evaluation in rainfall – runoff modelling are listed in the Section “Model evaluation”. Previous studies at the Can Le catchment are presented in the end of this chapter.

2.1. The catchment hydrologic cycle

Catchment modelling requires a clear understanding the hydrologic cycle at catchment scale. The catchment hydrologic cycle involves many processes. Many hydrologists investigated this cycle by a number of studies. A summary of the cycle is given by Chow et al (1988) or detail description of some processes can be found in the book of Kirby (1978). To summary the processes, a brief description is presented and is illustrated in figure 2.1.

Precipitation is the most essential process for the generation of runoff at a catchment scale. The distribution of precipitation varies spatially and temporally the nature. Precipitation can be in the form of snow, hail, dew, rain and rime. In this study precipitation is considered in the form of rain only.

Rainfall travels in a catchment in different directions. Due to vegetation, part of rainfall is intercepted by vegetation canopy. Interception is known as a loss function to catchment runoff depending on vegetation type, vegetation density. The rest of rainfall moves down the vegetation as stem flow, drip off the leaves, or directly falls to the ground as throughfall.

Rainfall remains at the land surface as depression storage and either evaporates, infiltrates or is discharged as overland flow.
By infiltration of rainwater, the water moves primarily in downward direction by unsaturated subsurface flow and recharges the saturated zone. This process is termed percolation or natural recharge and fills the aquifers of groundwater system. In some cases at the shallow subsurface layer where the lateral hydraulic conductivity is higher than the vertical one, the direct infiltration partly goes toward the channel through interflow or throughflow.

The groundwater pattern is influenced by the catchment characteristics, especially the topographic factors of the catchment, before being discharged to the channel network system. Aquifers of the groundwater system also can discharge groundwater across the catchment boundary.

Evaporation and transpiration at the land surface cause the decrease of water storage in the subsurface. As a consequence unsaturated flow in upward direction is generated that is called capillary rise.

Figure 2.2: Schematic of major processes of the catchment hydrologic cycle (after Rientjes, 2004)

### 2.2. Catchment runoff generation

Going to a bit detail of the catchment hydrology with respect to the aim of this study, the rainfall – runoff modelling, it is useful to look at the runoff generation of a catchment. The topic is discussed by a number of authors, one can refer to, for example, publications given by Dunne (1982), Rientjes (2004, p.24-39). Basically, the runoff generation at a catchment scale in general or hillslope scale in particular includes 2 main components: (1) surface runoff, (2) subsurface runoff. There are a number of flow processes within each main component as illustrated in figure 2.2 and more detail in figure 2.3.
The surface runoff: Flow processes include overland flow, stream flow, and channel flow which is defined as water flow over the land surface based on the differences on slope gradient. The overland flow is known as infiltration excess overland flow (Horton overland flow) or saturation overland flow (Dunne flow). The Horton overland flow is generated when the rainfall intensity exceeds the infiltration capacity of the soil or by a saturation mechanism where the soil becomes saturated by the perennial groundwater rising to the surface or by lateral or vertical percolation above an impeding horizon (Dunne, 1982). The overland flow is observed as sheet flow which then generates the rill flow. A number of the rill flow will contribute or create the stream flow which then converges into channel flow.

Subsurface runoff: Flow processes include unsaturated subsurface flow, perched subsurface flow, macro pore flow and groundwater flow. Subsurface runoff is generated since water discharged from the surface into the subsurface system. The unsaturated subsurface flow mostly is in vertical direction while the perched flow moves in lateral direction. The perched flow is generated where the shallow soil layer has much more higher hydraulic conductivity as compared to the lower one. The macro pore flow occurs where the subsurface system has macro pores such as voids, natural pipes, cracks, etc. the flow rapidly contributes to the groundwater system. Ground water flow is produced in the saturated zone which is fed through percolation of infiltrated water or from neighbouring system. The ground water contributes to the channel system as rapid groundwater flow in the upper part of the initially unsaturated subsurface domain or as delayed groundwater flow in the lower part of the saturated subsurface domain.

![Figure 2.3: Cross-sectional presentation of hillslope flow process (after Rientjes, 2004)](image)

2.3. Rainfall – runoff modelling

The processes described in the previous part are not simple to qualify because most hydrologic systems are extremely complex. Thus we may hope to find an abstraction of the processes instead of understand them in all detail. Rainfall – runoff modelling is a tool for this purpose.
In order to simulate the transformation from rainfall to runoff, rainfall – runoff models have been developed already a long time ago and reference is made to the work of Todini (1988) for historical review of rainfall - runoff modelling or Singh and Woolhiser (2002) for review on catchment models. With respect to development over the past decade, Beven (2000, p.ix) wrote “it is now virtually impossible for any one person to be aware of all the models that are reported in the literature ” and can be interpreted as that much efforts have been devoted to this issue.

Hydrologists have tried to classify rainfall – runoff models according to their specific approaches as well as their characteristics (Dooge, 1977; Refsgaard, 1996; Rientjes, 2004; Singh, 1988; Wood and O'connel, 1985). Basically, when we consider deterministic rainfall – runoff models and mathematical solutions, we could classify them into 3 main types:

- Physically based (or theoretical, white box) models are based on physical laws that include a set of conservation equations of mass, momentum, energy and specific case entropy to describe the real world physics that governs nature. The first two equations are most popularly applied in current models. Examples of this approach are SHE (Abbott et al., 1986), REW (Reggiani and Rientjes, 2005).

- Conceptually based (grey box) models consider physical laws but in a simplified form that is able to explain the hydrologic behaviour by empirical expression. Examples of this approach are Tank (Sugawara, 1995), Sacramento (Burnash, 1995), TOPMODEL (Beven et al., 1995), HBV (Bergstrom, 1995).

Empirically based (black box) models do not aid in physical understanding. However, they contain parameters that may have physical characteristics that allow the modelling of input-output patterns based on empiricism. Examples of this approach are unit hydrograph, rational method, etc. which are well described by Singh (1988).

In terms of spatial domains in catchment modelling, models can be classified as lumped, distributed or semi-distributed ones. The lumped model ignores spatial distributed of the catchment characteristics but there are represented by averaged single values. In contrast, distributed model approaches capture the system by partitioning the catchment into a number of smaller units. Semi-distributed model is something in between the first two that means the catchment is partitioned but in a coarser unit as compared with distributed model. This classification scheme is now also very popularly used because partitioning the system is not difficult by mean of some modern techniques like Geographic Information System (GIS) or available spatial distributed data through Remote Sensing (RS). In this respect, the next section will discuss about applications of GIS, RS in catchment modelling.

2.4. The role of remote sensing (RS), geographic information system (GIS), and digital elevation model (DEM) rainfall - runoff modelling

The very quick developments in RS and GIS technology have played a critical role of application of RS and GIS in watershed modelling in general and rainfall – runoff modelling in particular. The reason is that RS and GIS have contributed critical information as input of the models. Actually, nowadays, we hardly find any rainfall – runoff models that do not utilise RS and GIS data. Several
scientists have introduced RS and GIS as powerful tools in rainfall – runoff modelling, are mentioned as hereunder. 

Van De Griend and Engman (1985) when looking at the behaviour of saturated areas in a spatial manner also mentioned the potential of RS in catchment modelling. Schultz (1988; 1996) has contributed the introduction of different applications of RS in hydrology, from different satellite sources to different issues like runoff modelling and flood forecasting. Kite and Pietroniro (1996) reviewed a number of parameters in hydrologic modelling which are currently available from RS and presented one example based on the SLURP conceptual models. De Troch et al (1996) reviewed applications of remote sensing for hydrological modelling, of which RS data sources, applications on precipitation, evapotranspiration, soil moisture etc. retrievals, as well a number of RS experiments in hydrology were reported. Although there are many other recent applications of RS in hydrology, it is out of the scope of this thesis to describe them in detail. 

In case the catchment is ungauged, an exploration on data sources from satellite images as also can be referred to the Laskhmi (2004). Especially potential sources contributed from “free” or public domain satellite data have been utilised in many applications, for example SRTM (Rabus et al., 2003) for DEM generation, TRMM (Rabus et al., 2003), METEOSAT (Barbera et al., 1995; Levizzani et al., 1999) for rainfall estimation.

GIS processing becomes a critical step in hydrologic modelling since it contributes to generating model parameter distribution in spatial manner. Typical examples on applying GIS in rainfall – runoff modelling can be found in Maidment (1993), Meijerink et al (1994), Schumann et al (2000), Maidment and Djokic (2000). In these applications, the GIS processing steps such as data storing, map overlaying, map analysis etc. have helped to derive hydrologic parameters from soil, land cover, rainfall maps etc. 

With respect to GIS processing products, Digital Elevation Models (DEM) are more important in rainfall – runoff modelling. The development of DEM processing algorithms as well as relevant softwares to extract hydrologic information from DEM is increasing and makes it widely applied. For example, Tarboton et al (1991) introduced criteria to properly extract drainage networks, Moore et al (1992) reviewed many application of DEM in different disciplines including hydrology, while he also (Moore, 1996) introduced different algorithms to extract catchments from DEM. 

DEM is popularly processed in Arcgis, Arcview (with Hec-Geo-HMS extension) (Doan, 2000), ILWIS (Maathuis, 2005), Tardem (Tarboton, 1997), etc. to extract hydrologic parameters or physical characteristics of a catchment and can serve for model simulation.

2.5. Review on the selected model approaches

One of the objectives of this study is to select and test different model approaches to determine which perform best. Also, follow up to the classification scheme mentioned in section 2.3, three approaches are following:

1. Empirically model based on the Geomorphological Instantaneous Unit Hydrograph (GIUH) concept;
2. Conceptual model as based on Soil Moisture Accounting (SMA) loss model a part of the Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) software;

3. Physically based model as based on the Representative Elementary Watershed (REW) approach.

2.5.1. Geomorphological Instantaneous Unit Hydrograph (GIUH)

Coupling of quantitative geomorphology and hydrology is at the core of this approach. The model links geomorphological characteristics of a catchment to its response to rainfall (for example hydrograph related to topographic factors can be seen in figure 2.4). In this approach, the Horton’s morphometric parameters (Strahler, 1964; Strahler, 1969) including area ratio \(R_A\), bifurcation ratio \(R_B\), length ratio \(R_L\) are mainly used to develop the Geomorphological Instantaneous Unit Hydrograph (GIUH).

The GIUH was first initiated by Rodríguez-Iturbe and his colleagues (1979) and restated by Gupta et al (1980) and it is defined as “the probability density function of a drop’s travel time in a basin”. Thus, the goal of GIUH theory is to derive this density function based on geomorphologic parameters.

In order to determine the GIUH, the input data is considered as rainfall drops which are randomly and uniformly distributed over the watershed. Hereunder, a travel path of one particle is analysed.

The path consists of the route through hillslope areas and channels leading to the outlet. The probability of this water particle follows a certain path among all possible paths from stream of lower order to those of higher order. This order is computed based on the Strahler order scheme. The transition of the drop can be referred to as a change of state. The state is defined as the order of the stream in which a rainfall drop is located at time \(t\). If the rainfall is in a hillslope area, it will drain directly to the stream. After it comes to the stream, it will moves to the higher order stream. In another word, the movement of a water particle is a series of transitions from one state to another. From now on, \(r_i\) is denoted when the drop in channel state of order \(i\), and \(a_i\) is denoted when the drop in hillslope state of order \(i\). A watershed has its order ranging from 1 to \(\Omega\) (\(\Omega\) is the highest order). A water particle will follow from a point to the catchment outlet through a determined drainage network and hillslope areas. Additionally, it is assumed that only those rainfall particles falling on the hillslope areas will be taken into account and those falling onto streams will be neglected. Given that a particle starts in any one of the hillslope areas, it is governed according to the following rules:

1) The only possible transitions out of the state \(a_i\) are those of the type \(a_i \rightarrow r_i\); \(1 \leq i \leq \Omega\):

2) The only possible transitions out of the state \(r_i\) are \(r_i \rightarrow r_j\); \(j > i\); \(i = 1, 2, \ldots; \Omega\):
3) A state $r_{t+1}$ is defined as an ending state, and transitions out of $r_{t+1}$ are impossible.

Here above is a short description of the GIUH theory, it is further explained and given detailed calculation in section 4.4.1

The concept so far has been improved and successfully implemented as a hydrological model to simulate rainfall – runoff relation and to forecast floods (Al-Wagdany and Rao, 1998; Jain et al., 1997; Rodríguez-Iturbe, 1993; Tuong, 1997). Simulation results showed that approach is a very promising tool to estimate event discharges, even for ungauged catchment (Bhaskar et al., 1997).

When Rodríguez-Iturbe and Valdez (1979) suggested it is adequate to assume a IUH is a triangular, it could be the most convenient of the GIUH that accounts for the peak flow ($q_{pg}$) and the time to peak ($t_{pg}$) in a very simple form. They are defined:

$$q_{pg} = 1.31 R_L^{0.43} \frac{V}{L_{\Omega}} \text{ (hour$^{-1}$)} \quad \text{(eq.2.1)}$$

$$t_{pg} = 0.44 R_L^{-0.38} \left( \frac{R_L}{V} \right)^{0.55} \left( \frac{L_{\Omega}}{V} \right) \text{ (hour)} \quad \text{(eq.2.2)}$$

Where:

$L_{\Omega}$ - is the length in kilometres of the highest order stream;

$V$ – is expected velocity stream flow in meters per second.

In the (eq.2.1), (eq.2.2), while the velocity is estimated, remaining information is extracted based on the topological characteristics of the catchment.

The GIUH has developed for quite along time ago (27 years). There are numerous publications on this topic. They include the improvement of analytical solution, parameterization of the dynamic velocity, etc. In this study, the main references for model development made are based on the work of Rodriguez-Iturbe and Valdez (1979), Gupta et al (1980), Bras and Rodriguez-Iturbe (1989)

2.5.2. Soil Moisture Accounting (SMA) and Hydrologic Engineering Center - Hydrologic Modeling System (HEC- HMS)

SMA, a loss model within the HEC-HMS software suite, was designed to compute runoff discharge on a continuous time base. This model was successfully applied for long term rainfall – runoff modelling and reference is made to the work of Fleming (2002) Fleming and Neary (2004).

The model operates as the Precipitation - Runoff Modelling System – PRMS (Leavesley and Stannard, 1995) whose system domains are expressed by the inflow, outflow, and capacities of each of the storages. The model is conceptualised as a series of reservoirs, controlling the volume of water lost or added to each of these storage components.

River flow is produced from three sources in this model. The first source from overland flow when excess precipitation is transformed to stream flow at the basin outlet if the canopy storage zone is filled; or when the available infiltration rate is exceeded, and the surface storage zone is filled. A number of methods can be used to transform excess precipitation into surface runoff (i.e. SCS Unit Hydrograph, Clark Unit Hydrograph). Later, two others sources, groundwater storage in 2 zones are
The model simulates the movement of water through and storage of water on vegetation, on the soil surface, in the soil profile, and in groundwater layers which is illustrated in figure 2.5. Five zones of a catchment are simulated including canopy interception storage, surface depression storages, soil profile storage, groundwater layer-1 storage, and layer-2 storage.

To run this model, several parameters should be known or estimated that will be presented in section 4.4.2

2.5.3. Representative Elementary Watershed (REW)

Since the Representative Elementary Watershed (REW) concept was introduced by Reggiani et al (1999; 1998; 2000), so far only few applications are shown in rainfall – runoff modelling (Fenicia et al., 2005; Reggiani and Rientjes, 2005; Zhang et al., 2005). For example, in the case of applying REW to the Geer catchment in Belgium of 490 km², the model was successful to simulate the discharge that corresponds to observed data with Nash-Sutcliffe efficiency of 86% (Zhang et al., 2005). Considering the Freeze-Harlan blueprint (Freeze and Harlan, 1969) for distributed physically based hydrologic model, this approach can contribute as an alternative solution (Beven, 2002; Reggiani and Schellekens, 2003; Reggiani and Schellekens, 2005). A brief description of this approach hereunder:

A watershed is discretized into a number of sub-watersheds (catchments) through a specific Digital Elevation Model (DEM) technique (using TARDEM). The sub-watersheds are termed Representative Elementary Watersheds (REWs) (Figure 2.6)
and each REW is subdivided into five sub-regions according to the major hydrological processes, geometry and time scales. The five sub-regions are: the saturated zone, the unsaturated zone, the channel reach, the infiltration excess overland flow zone and the saturated overland flow zone.

A schematic of 3 REWs with 5 zones is shown in figure 2.7 and detail of a REW indicated in figure 2.8 by the indices s,u,r,c,o respectively. The volume of a REW is delimited at the bottom by a horizontal impermeable surface, on top by the land surface, and laterally by a vertical prismatic mantle.

In the context of the REW approach, balance laws for mass, momentum, and energy are mapped from the microscale or point scale to the megascale (or REW scale) by integration in space (Reggiani and Rientjes, 2005). Balance equations of mass and momentum are derived for each zone of each REW and they are directly applied to the sub-catchment scale. For the closure of the balance equations watershed-scale hydrologic relations such as Darcy’s law, Chezy’s formula, and the Saint Venant equation, etc. are needed although some particular methods such as Hardy-Cross procedure for looping the REWs as a network, Inoue algorithm for groundwater table interpolation, etc also applied. The resulting conservation equations constitute a system of coupled Ordinary Differential Equations (ODE) leading to a simplification of the mathematical model. Those relations are also developed directly at the REW scale and are applied to the specific zones.

Figure 2.7: Three-dimensional view of an ensemble of three REWs, including a portion of atmosphere (Reggiani and Rientjes, 2005; Reggiani and Schellekens, 2003)

Figure 2.8: Detailed view of the five subregions forming a REW (Reggiani et al., 1999)

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2 Additional perched zone (p_zone) is recently added in REW version 8.0, see section 4.4.3
2.5.3.1. Model evaluation

In the field of rainfall – runoff model comparison, several authors investigated models’ behaviours usually within their specific approaches. For example, Al-Wagdany and Rao (1998) compared velocity parameters of three GIUH models. Gan et al (1997) distinguished 4 conceptual models including PITMAN, SACRAMENTO, XINANJIANG, SMAR to find out which model performs best by looking at their structures, objective functions, etc. Perrin et al (2001) did an intensive comparative performance assessment of the structure of 19 lumped models carried out 429 catchments. The World Meteorological Organization (WMO), held a project of doing an intercomparison of hydrological models to be applied in real-time forecasting, most of them are conceptual models (Askew, 1989; Reed et al., 2004). Rientjes (2004) gave a comparison of model structure concept, data requirement, model performance etc. of 4 physically-based models including MIKE-SHE, IHDM, THALES, DBSIM. Refsgaard and Knudsen (1996) reviewed on model comparison of 3 conceptual and physically based models including NAM, MIKE SHE, WATBAL based on validation schemes.

A number of criteria used in this study to perform models’ comparison will be listed in section 4.5 to recommend which model is suitable for application in the area.

2.6. Previous studies in the area

In 1995, after 10 years operation (since 1985), the Dau Tieng Dam was assessed by Hung (1995), who focused on its impacts on environment/society in both negative and positive context. Tuan (1995) preliminarily investigated flows from upper streams of Dau Tieng Dam and also assessed the Dam’s capacity, water quality, etc. Hai et al (1999) did a very intensive investigation on geological environment of Saigon river (below Dau Tieng Dam) and mentioned the impact of Dau Tieng Dam. Again, Tuan (2002) used a Tank model to assess the monthly runoff generation, for the whole catchment of Dau Tieng Dam. The model was applied for the period from 1977 to 1981 and obtained the Nash-Sutcliffe efficiency of 0.85.

Lieu (1992) published his group’s research on soil of the East Southern of Vietnam that was not only about soil characteristics but also orientation of land use planning.

Closer to the Can Le Catchment, Co et al (2001) investigated the geological characteristics including geology, geomorphology, mineral, etc. to produce various maps at 1:50,000 scale for the whole Loc Ninh region that covers the study area.

Hai et al (2003) produced a GIS database for Binh Phuoc province at 1:50,000 scale including more than 20 thematic layers such as land use, soil, topology, road, etc. and linked to their attributes in the form of linking table or sheets.

However, in the case of the Can Le catchment, so far the data was not systematically collected especially discharge data. The catchment is regarded as an ungauged catchment following the definition3 of Sivapalan et al (2003).

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3 “An ungauged basin is one with inadequate records (in terms of both data quantity and quality) of hydrological observations to enable computation of hydrological variables of interest (both water quantity and quality) at the appropriate spatial and temporal scales, and to the accuracy acceptable for practical applications.” (Sivapalan et al, 2003)
3. Study area and fieldwork activities

This chapter presents an overview of the study area. This section is followed by reporting the field campaign between September and October 2005 that included data collection, field measurement, and field survey. The chapter is illustrated by some figures which were processed based on field data collected.

3.1. Study area

The study area covers a tributary river of the man Can Le River. The area is about 203 km$^2$, almost a half of the overall upstream contributing area. The study area is also called Can Le Catchment.

The Can Le catchment is located in the South of Viet Nam (figure 3.1). It is a tributary of Sai Gon River, a second biggest river in the South East, which contribute to the Dau Tieng Dam. The catchment is identified by its corner coordinates of (11°40′10″N, 106°41′25″E), (11°53′52″N, 106°33′15″E).

This section will give an overview of the main characteristics of the catchment

Figure 3.1: Study area in the context of its region.
3.1.1. Climate

According to Hai (2004), Vietnam in general and Binh Phuoc in particular, located at the sub-equator, has a tropical, monsoon climate, two distinguished seasons, a rainy and dry ones with yearly averages of several climate parameters as hereunder:

- **Temperature**: 25.8 – 26.9°C
- **Humidity**: 78.9 – 82.2%
- **Sunny hours**: 7.8 – 8.6 hours/day
- **Rain**: 2045 – 2325 mm (from May to November)
- **Rain days**: 112 – 145 days
- **Evaporation**: 1.113 - 1.447 mm.
- **Wind speed**: 3.5 m/s (East Northern in dry season), 3.8 m/s (West Southern in rainy season)

3.1.2. Topology

From figure 3.2, one can see the area having the main floodplain about 50-70 m.a.s.l, next to a transition of about 90. m.a.s.l and then bounded by a range of hilly uplands ranging from 120 to 220 m.a.s.l. In the mountainous areas, the topology is more dissected as shown in figure 3.3.

3.1.3. Drainage characteristics

Most of the catchment runoff of the catchment starts at the highland areas and travels downstream to the outlet of the catchment. The drainage density is about 632.3 m/km²; and the catchment’s longest flow path is 31.19 km;

The drainages are classified into 4 order levels according to Strahler’s classification. The catchment is not a complete 4th order catchment and here it is still considered a contribution of a 3 order catchment. (Figure 3.4)
3.1.4. Land use, land cover

The main economic activity in the area is agriculture. Using ASTER image of December 2004 and field work experiences in September 2005, the land cover map is reclassified to a land use map shown in figure 3.5 (see section 4.2.1 for more detail about land use classification). Due to the specific characteristics of agriculture in the areas, except the uniformly rubber (entitle agriculture_tree) or growing rubber (entitle agriculture_tree_small), the remaining parts are very scattered with different kind of crops like cassava, rice, bean, peanut (entitle agriculture_crop) and some places mixed of crops and cashews (entitle agriculture_mixed) as well as bare soil.

![Drainage networks and its Strahler’s orders of the Can Le catchment](image1)

![Land use map of the Can Le catchment](image2)

3.1.5. Geology

Based on the work of Co et al (2001), hereunder a number of formations in the study area are summarised:

- Mainly formed in Can Le catchment is the Loc Ninh formation (N_2^ln). The basalt of the Loc Ninh formation is typical represented for effusive - centred basalts and creating the topology with arch – shape. The thickness of this formation is 80-100m (in centre arch) and 10-20m (in the edge arch).

- The Dak Krong (J_1^dk) is the second largest formation in the area. It lies under basalt sediments in the flat plain area. This formation includes 3 main layers of (1) sandstone, siltstone and shale with lime; (2) sandstone, siltstone with lime; (3) Clay shale, siltstone and not-yet differentiated sandstone with lime. Total depth is more than 750m.
There is a meridian fault in the center of the catchment which separates the previous formation with the Chau Thoi formation (T2ct). This formation (Khuc et al., 2000) includes basalt conglomerate in layer 1, arkose bearing effusive fragment, interbeds of conglomerate in layer 2 and sandy siltstone, clay shale, lenses of marl in the last layer.

The next dominant formation is the Holocenic (aqIV1,2) that appears in almost all river valleys but is not continuously developed. Main components found include sand, silt with clay in grey colour and loosen structure. Its depth ranges from 1-6m.

The geological stratigraphic units of the Can Le catchment are illustrated in figure 3.6.

3.1.6. Soils

Most of the area is covered by soil developed on basalts that originated from volcanic activities in the past. According to the GIS database of Binh Phuoc province (Hai and Tu, 2003), apart from the river alluvial soils which are mainly clay loam, the rest consist of clay. This clay is in the first 1-2 meter the weathered products from basalts/shale. The next layer about 3-10m is mainly conglomerate/laterite mixed with clay overlaying the main clay layer (Figure 3.7).

3.2. Fieldwork activities

Three different activities were carried out during the fieldwork period: data collection, field measurement and field survey.

3.2.1. Data collection

Several materials were collected during this time

1. Maps:
   - Geological map of the area of 1:50,000 scale;
- Geomorphological map of the area of 1:50,000 scale;
- Soil map of the area of 1:50,000 scale (not in detail);
- Hydro-geological map of the area of 1:50,000 scale (not in detail);

2. Reports
- Geological survey report of the area;
- Geomorphological survey report of the area;
- Hydro-geological survey report of the area;
- Soil sheets of dominant soils in the area;
- Well drilling reports of surrounding areas of Binh Phuoc province.

3. Images
- Aerial photographs of most of the study area at 1:33,000 scale (in 1993)

3.2.2. Field measurement

1. Rainfall station

The station was set up at a clear place, in the centre of the overall upstream catchment. Only one tipping bucket was used to collect rainfall. Additionally, rainfall was collected at four surrounding national stations, of which two is hourly recording and others are 2 times/day. Locations of the rain gauge and the other stations are shown in figure 3.8.

Figure 3.8: Rain gauge locations

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4 2 times/day: at 7AM and 7PM.
2.  Discharge station

In the beginning of the fieldwork period, the outlet was chosen for a bigger catchment (400km²). However, another outlet upstream was chosen due to given feasibility for discharge measurement. This selected catchment is about 203 km². (Figure 3.9)

The station was first located at Can Le Bridge. However, after one big storm, observing that the flow velocity was very turbulent, a new site, upstream of the bridge was selected to set up the second station. At this site, after concluding that the flow was stable enough to make a permanent station, a standard staff was also set up to observe water level. The method to measure discharge is according method described by Herschy (1995) and Gioi et al (1990). To measure the discharge, flow velocity and cross section is needed.

Here, the flow velocity was measured at 0.2, 0.6 and 0.8 of the depth from the surface if there was sufficient depth; otherwise it was measured at 0.6 alone using current meter. Due to the turbulent flow, the rapid flow raised and receded very quickly, the velocity was measured only in center of the stream. Later the velocity is multiplied by a factor of 0.85 which accounts for the lower velocity at the bank of the stream (Gioi et al., 1990).

The cross section of the river at the station was determined using traditional theodolite equipment. A complete discharge station is sketched in figure 3.10. The maximum width at the cross section is 25.57 m, and the maximum depth observed during the fieldwork period is 4.35 m (based on a supposed base line, h=0 in figure 3.10). The cross section is relatively accurate. Therefore it is convenient to calculate the area by partitioning the cross section into a number of triangular shapes, and trapeziums.

Figure 3.9: The selected catchment (in red boundary) in the context of the proposed catchment (in green boundary)

Figure 3.10: Cross section at Can Le discharge station
The discharge data of several storms was calculated. According to the deviation of the discharge, based on a method given by the International Institute for Land Reclamation and Improvement - ILRI (1972), the minimum 43 pairs of stage-discharge are required\(^5\). Moreover, after the first storms, 59 paired points were obtained. Therefore, it is sufficient enough to establish the stage-discharge curve. Since then, only water level was recorded.

Figure 3.11 shows the stage-discharge curve and 3.12 is the discharge – stage curve and the fitted formula which is used to define the discharge for the later period.

\[
y = 0.0254x^{1.3081} \\
R^2 = 0.9864
\]

![Figure 3.11: Stage-discharge relation curve](image)

### 3.2.3. Field survey

The field activities include land cover and land use survey but also local people were interviewed. During the fieldwork period, surveys across the catchment were carried out (red dots in figure 3.13). Several objectives were set before implementing this work. They are:

- To know the groundwater level of in the area;
- To estimate the base of the first groundwater storage; and
- To obtain information about land cover and land use in the study area.

GPS Etrex, digital camera and field book were used to support this work.

Totally, 53 points were surveyed. The obtained information is reported in Appendix 2

\(^5\) Method to determine the number of observations necessary for establish a reliable stage-discharge curve is presented in appendix 1
3.3. Remarks on chapter 3

During the field campaign, the most important obtained data was the discharge. This data will serve for model calibration. Information on soil, land cover, groundwater is very useful for estimating the model parameters. However, the small number of rainfall measurements could be a problem for this study.

Figure 3.13: Field survey points during fieldwork period 15/9/2005 – 15/10/2005
4. Research methods

This chapter starts with a “conceptual framework” which describes an overall methodology applied to carry out this research. It is followed by “GIS and RS application” including land use classification, DEM processing, rainfall interpolation. The “stream flow analysis” briefly discusses method used to separate the contribution of base flow into the total runoff. The “model development” for the three selected models is sequentially presented that mostly is about model operation and parameterization for each model approach. The chapter is ended by introducing model performance criteria and a ranking scheme for model selection

4.1. Conceptual framework

A conceptual framework serves to describe the overall research steps. Firstly, two main data types required as input includes rainfall and DEM. Other input data such as soil, land cover, land use, meteorological data changes depending on the model approach. After having data, the three models are developed through model parameterization, and then these models are operated. The main output from these models is discharge at the outlet of the catchment. The output is compared with real discharge data (measured during fieldwork campaign) to calibrate the model. Model output is compared based on a number of criteria to see which model yields better result so that the best performing model is proposed.

Figure 4.1 Conceptual framework
4.2. Applications of RS and GIS

As mentioned in chapter 2, quite a few potential applications of GIS and RS have been reported in literature. In this thesis, the applications of these techniques are also explored. Three typical applications reported in this section include land use classification, DEM processing and rainfall interpolation. Other particular applications of GIS and DEM processing in model parameterisations are not presented in this section but in model development (section 4.3) in order to complete each approach systematically.

4.2.1. Land use map classification

Supervised classification is applied in order to obtain land cover and land use map. A number of steps are required to accomplish this job as shown in figure 4.2.

- ASTER image which was taken in December 2004 was used;
- The image was georeferenced to the coordinate system of the study area (WGS84, projection: UTM, zone 48N);
- Visualise the image by colour compositing of three bands 3, 2, 1 for red, green and blue respectively;
- The most important step in supervised classification is defining spectral characteristics of different classes by identifying sample areas. A sample of a specific class includes a number of training pixels, forms a cluster in feature space as shown in figure 4.3.

To support the supervised classification, field knowledge and unsupervised classification was utilised. The first one is to know what the main land cover types of the study area are. The later is to combine pixels into groups (classes) according to their spectral characteristics to see how it relates to the sample classes.

The land cover map is the result after applying the maximum likelihood classifier method.

The final overall accuracy of the map is 60%, which is not high. One of the main reasons is that the image was taken in the beginning of the dry season of 2004 and the fieldwork was carried out during rainy season of 2005. The small number of collected samples (57) could also contribute to the result. However, the three applying models are using this information as a lumped manner so that this accuracy is reasonably accepted.

- The land cover map is then reclassified into land use map by incorporating with a digitized urban, water areas, the produced map (figure 3.5.) is product from previous step after being filtered and smoothed.
Figure 4.2: Land use classification steps.

Figure 4.3: Sampling classes and combinations of different feature spaces in left side.
4.2.2. DEM Processing

As described in chapter 3, due to difficulties in choosing a typical catchment in the upstream of Dau Tieng Dam, firstly, SRTM is used to access several potential catchments. Secondly, the Can Le catchment was chosen for further investigation because its extracted drainage system is well represented as compared with the existing network (digitized from topographic map). (Figure 4.4) Then the SRTM DEM was combined with topographic map sources of 1:50,000 to generate the DEM of Can Le catchment.

![DEM Processing Diagram](image)

Figure 4.4: Two extracted catchments using SRTM (digitized river in red color), the right one chosen is properly representing the existing drainage network.

The DEM is optimised through integration of the existing digitised drainage to obtain a final DEM. This optimized DEM is processed through several steps such as fill sink, calculate flow direction,
flow accumulation, etc. (figure 4.5) to extract the Can Le catchment as well as the topological drainage network (figure 3.4). During the whole process (using ILWIS), a number of decisions have to be taken so that the extracted information is representative, e.g. defines width, depth of the existing drainage network when integrate it into the DEM, selects the multiple variable thresholds for drainage line initialization.

The optimised DEM is used for different model applications in this study. (1) In ILWIS, the DEM is used to calculate Horton’s statistics to apply the GIUH model; (2) In ARCVIEW, using HEC-GeoHMS extension, the DEM is processed to create a HEC-HMS base map and also other related information which are used to calculate several parameters in HEC-HMS (length, slope, etc. as shown in figure 4.13). When applying the REW model, the DEM processing package TARDEM is used to extract sub-catchments (REWs) so that the model will apply simulation in these REWs (figure 4.20).

![Figure 4.5: DEM processing steps to extract the drainage network and catchment (modified after Maathuis, 2006)](image-url)
4.2.3. Rainfall interpolation

Rainfall data was collected by one tipping bucket gauge from national stations (Chapter 3). By analysing the relation between rainfall data\(^6\) and discharge, it is recognised the non-uniformly distribution of rainfall in the area (see section 5.1). Several rainfall data sources were used to correct this data. Integration of satellite images and rain-gauge to have proper rainfall distribution is needed.

The first source, TRMM (Tropical Rainfall Measuring Mission), providing daily rainfall in the world within the satellites field of view, is assessed. Unfortunately, there were no suitable images related to the first events in the area (25/9/2005, 4/10/2005). For example, for the first storm, the image covered neighbouring areas, other images were taken before/after the events (Figure 4.6).

![TRMM OVER PASS](image)

**Figure 4.6:** TRMM passed over on 25 September, 2005

Another source, METEOSAT-5, providing images every 30 minutes was selected and successfully applied. The spatial distribution of the Digital Numbers (DN) or DN values of infrared band\(^7\) is used to interpolate rainfall data from the tipping bucket and the nearest national station based on their weight ratios.

An example for this method is illustrated by examination of the event on 25 September 2005 (10.30 AM, UTC). Others events are processed in the same way.

The ratio is identified by matching the DN value at the tipping bucket gauge with the one at the closest rainfall station\(^8\) (hourly) (figure 4.7). The 10 surrounding pixels of the tipping bucket are implied as 10 stations (figure 4.8). Each of this “station” has their own grey DN values. The DN values are used to calculate the corresponding rainfall intensity based on formula “\(y = -4.1x + 131.8\)”

---

\(^6\) Rainfall data from the tipping bucket

\(^7\) Due to limitation in retrieving the radiometry of the images, only DN values of the IR band was used.

\(^8\) Dong Phu (hourly) and some cases using Loc Ninh station (2 times/day)
(figure 4.6), where “y” is rainfall intensity and “x” is DN value. After having rainfall intensity at each pixel within the Can Le catchment, the station having lowest DN value or highest rainfall intensity during this time is set with weight ratio equal to 1 and other “stations” have corresponding weights (table 4.1). These weights are used to calculate time series rainfall for other “stations” based on the time series data of Can Le station.

The final rainfall is calculated by aggregating all the rainfall of the “stations” for the Can Le catchment in a lumped manner. The results are presented in chapter 5 (section 5.1).

![Figure 4.7: Linear regression between rainfall intensity and infrared DN value of two data sources](image)

![Figure 4.8: One pixel is implied as one station having their own grey DN (Infrared band of Meteosat 5 image on 25 September, 2005 at 10.30 UTC)](image)

9 Yield results in column (2), table 4.1
10 It is assumed that the rainfall has the same duration over the area and only difference is having intensity.
Table 4.1: Weight and rainfall intensity for each station in Can Le catchment

<table>
<thead>
<tr>
<th>Stations</th>
<th>DN (1)</th>
<th>Rainfall (mm/hour) (2)</th>
<th>Weight (%) (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can Le</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>26</td>
<td>25.2</td>
<td>0.43</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>21.1</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>49.8</td>
<td>0.86</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>41.6</td>
<td>0.72</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>53.9</td>
<td>0.93</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>45.7</td>
<td>0.79</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>58</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
<td>53.9</td>
<td>0.93</td>
</tr>
<tr>
<td>9</td>
<td>19</td>
<td>53.9</td>
<td>0.93</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>49.8</td>
<td>0.86</td>
</tr>
<tr>
<td>Dong Phu</td>
<td>30</td>
<td>8.8</td>
<td>0.15</td>
</tr>
</tbody>
</table>

4.3. Stream flow analysis

The watershed flow is composed of three components that occur separately or simultaneously. As illustrated in the hydrograph which is constituted by the rising limb and recession limb. The components include: (1) surface flow (overland flow), (2) subsurface runoff, or interflow and (3) base flow or groundwater flow (figure 4.9). Quantitatively determining the contribution of the runoff is very important in this study. For example, in the GIUH approach, the model can only simulate the overland flow, so observed hydrograph have to subtract the contribution of base flow; or in the SMA approach, identifying groundwater storage capacity and storage coefficient should be carried out to accomplish its model parameterisation. In this study, the method based on semi-logarithmic plotting (Linsley et al., 1958) is adapted. However, by the related period of the fieldwork campaign, a remark on base flow has to be noted. The fieldwork was conducted during the rainy season hence the lowest stream level cannot be observed.

4.4. Model development

4.4.1. GIUH

1. GIUH development
The channel network of a watershed reflects the relationship of hillslopes and channels. This pattern is represented in a GIUH model in a probabilistic sense. The GIUH is interpreted as the probability density function of the travel times to the outlet of the rain randomly, uniformly distributed over the catchment. The travel times on hillslope or along streams are assumed exponential distributed and the probabilities include the initial probability, transition probability are calculated based on Horton’s mophormotric parameters. The parameters are bifurcation ratio ($R_B$), length ratio ($R_L$) and area ratio ($R_A$).

Using Strahler’s ordering scheme (Strahler, 1969), the ratios can be expressed quantitatively as shown in table 4.2.

Table 4.2: Horton’s ratios

<table>
<thead>
<tr>
<th>Ratios</th>
<th>Formula</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bifurcation</td>
<td>$R_B = \frac{N_i}{N_{i+1}}$</td>
<td>where $N_i$ and $N_{i+1}$ are the number of streams in order $i$ and $i+1$. Let $\Omega$ represent the highest stream order in watershed, $i = 1, 2, \ldots, \Omega$.</td>
</tr>
<tr>
<td>Length</td>
<td>$R_L = \frac{\bar{L}_{i+1}}{\bar{L}_i}$</td>
<td>$\bar{L}<em>i$ is average length of channels of order $i$ is: $\bar{L}<em>i = \frac{1}{N_i} \sum</em>{j=1}^{N_i} L</em>{j,i}$</td>
</tr>
<tr>
<td>Area</td>
<td>$R_A = \frac{\bar{A}_{i+1}}{\bar{A}_i}$</td>
<td>$\bar{A}<em>i$ is the mean area of the contributing subwatershed to streams of order $i$, $\bar{A}<em>i = \frac{1}{N_i} \sum</em>{j=1}^{N_i} A</em>{i,j}$, where $A_{i,j}$ represents the total area that drains into the $j$th stream of order $i$.</td>
</tr>
</tbody>
</table>

The $R_B$, $R_L$ and $R_A$ values vary normally between 3 and 5 for $R_B$, between 1.5 and 3.5 for $R_L$ and between 3 and 6 for $R_A$ (Rodriguez-Iturbe, 1993, p.45).

This concept can be explained through a deterministic concept of routing through linear reservoirs (Chutha and Dooge, 1990) as illustrated by figure 4.10. The $\theta_i$, $p_{ij}$, $\lambda_i$ in this figure are initial probabilities, transition probabilities, mean travel time, respectively.

The initial probability accounts for a drop falling to any hillslope\(^{11}\) areas in the catchment either in 1\(^{st}\), 2\(^{nd}\) or 3\(^{rd}\) catchments (represent by $\theta_1$, $\theta_2$, $\theta_3$).

---

\(^{11}\) Rainfall falls to the channel network is neglected.
The transition probability then accounts for the changing stage of a drop from low order stream to the higher ones. For example at the 1\textsuperscript{st} order stream, the drop can either go to 2\textsuperscript{nd} order or 3\textsuperscript{rd} order (represented by \( p_{12} \) and \( p_{13} \)).

The mean travel time accounts for any stage. It includes travel time from hillslope to stream and along all of streams. The next paragraph will explain how to derive the GIUH as well as how the calculate these parameters.

The GIUH is the \textit{impulse response function} of the system, now denoted as \( u(t) \) is determined as following:

\[
u(t) = \frac{\partial}{\partial t} \Pr(T_B \leq t) \quad \text{or:} \quad u(t) = \frac{\partial}{\partial t} \left( \sum_{S_i} \Pr(\text{ob}(T_{S_i}) \leq t) \Pr(\text{ob}(S_i)) \right)
\]

Where:

- \( \Pr() \) : stands for the probability of the set given in parenthesis;
- \( T_B \) : is the time of travel to the catchment outlet;
- \( T_{S_i} \) : is the travel time in a particular path;
- \( \Pr(S_i) \) : is the probability of a drop which will travel all possible paths \( S_i \) to the outlet;
- \( \text{Pr}(\text{ob}(T_{S_i})) \) : is the probability density function (pdf) of the total path travel time \( T_{S_i} \).

For the 3\textsuperscript{rd} order catchment, the possible paths \( S_i \) of water are:

- Path \( S_1 \) : \( a_1 \rightarrow r_1 \rightarrow r_2 \rightarrow r_3 \rightarrow \text{outlet} \);
- Path \( S_2 \) : \( a_1 \rightarrow r_1 \rightarrow r_3 \rightarrow \text{outlet} \);
- Path \( S_3 \) : \( a_2 \rightarrow r_2 \rightarrow r_3 \rightarrow \text{outlet} \);
- Path \( S_4 \) : \( a_3 \rightarrow r_3 \rightarrow \text{outlet} \).

(\( ai \) is denoted when the drop in hillslope state of order \( i \), and \( ri \) is denoted when the drop in channel state of order \( i \), section 2.5.1)

And the probability of any path is,

\[
\Pr(\text{ob}(S_i)) = \theta_i p_{ij} p_{jk} \cdots p_{j\Omega}
\]

(eq.4.1)

Where \( \theta_i \) are the initial state probabilities and \( p_{ij} \) are the transition probabilities\textsuperscript{12}.

\[
\theta_i = \frac{(\text{total area draining directly into streams of order } i)}{(\text{total catchment area})}
\]

\[
p_{ij} = \frac{(\text{number of streams of order } i \text{ draining into streams of order } j)}{\text{(total number of streams of order } i)}
\]

The travel time \( T_{S_i} \) in a particular path must be equal to the sum of travel times in the elements of that path.

\[
T(S_i) = T_{ai} + T_{ri} + T_{ri+1} + ... + T_{r\Omega}
\]

\textsuperscript{12} Formula to calculate is shown in appendix 3
Where $T_{a}$ is the travel time on the hillslope and the $T_{ri}$ are the travel times in each stream segment of order $i$ ($1 \leq i \leq \Omega$). Assuming that these individual times of travel are independent variables such that $f_{T_{a}}$ is the pdf of $T_{a}$, $f_{T_{ri}}$ is the pdf of $T_{ri}$, and that $f_{Si}$ is pdf path Si, the probability of the sum, $T_{si}$, is a multiple convolution integral of the following form:

$$\text{Pr}_{ob}(T_{si}) = \sum_{s} f_{Si}(t) = \sum_{s} f_{T_{a}}(t) \times f_{T_{ri}}(t) \times f_{T_{ri+1}}(t) \times \ldots \times f_{T_{ri\Omega}}(t)$$ (eq.4.2)

Where:

* : stands for convolution operator.

$$f_{T_{a}}(t) = f_{T_{a}}(t) = \alpha_{i} \exp(-\alpha_{i} t),$$ is a gamma function corresponding to a the travel time of a drop in a given hillslope that obeys the exponential probability density function.

$$f_{T_{ri}}(t) = f_{T_{ri}}(t) = \beta_{i} \exp(-\beta_{i} t),$$ is a gamma function corresponding to a the travel time of a drop in a given channel that obeys the exponential probability density function.

The $\alpha_{i}$, $\beta_{i}$ is mean travel time for hillslope and for stream flow respectively, and $v$ is expressed by $v_{o}$ for hillslope velocity and $v_{s}$ for stream velocity, respectively.

$$\beta_{i} = \frac{v}{L_{i}}, \quad \alpha_{i} = \frac{v}{L_{o}} \frac{1}{2D},$$ is average overland flow and D is drainage density.

The $\alpha_{i}$ is kept constant for any given hillslope ($\alpha_{i} = \alpha_{s} = \alpha_{i}$), while the $\beta_{i}$ is changed according to the average length of each given order stream ($L_{i}$).

Then the GIUH, $u(t)$ is computed as:

$$u(t) = \sum_{s} f_{T_{a}}(t) \times f_{T_{ri}}(t) \times f_{T_{ri+1}}(t) \times \ldots \times f_{T_{ri\Omega}}(t) \times \text{Pr}_{ob}(S)$$ (eq.4.3)

This formula is solved in time step using Excel spread sheet.

Model parameters of the GIUH include the Horton’s ratios, hillslope and stream flow velocity. The estimated flow velocity will be included in the result part (section 5.2.1), hereunder the method to derive the Horton’s morphologic parameter.

The Horton’s statistics including $R_{A}$, $R_{L}$, $R_{B}$ are calculated using a new functionality in ILWIS called “Horton statistics” in module “statistical parameter extraction” (in “DEM – Hydro-processing”).

The process is following:

- Calculating the number of streams, the average stream length (km), and the average area of catchments (km²) for all streams. (Represented by $C_{N}$, $C_{L}$, $C_{A}$ in table 4.3).
- Calculating expected values of the number of streams, the average stream length (km), the average area of catchments (km²) by means of a least squares fit. (Represented by $C_{N}$, $C_{L}$, $C_{A}$ in table 4.3)
- The $R_{A}$, $R_{L}$, $R_{B}$ are the slope of each fitted line connecting the expected values shown in figure 4.12 (result shown in table 4.3);
The obtained values and the least square fit are visualized using a Horton plot to inspect the regularity of the extracted stream network and serve as a quality control indicator for the entire stream network extraction process. It is expected that (Strahler, 1964):

- The number of streams show a decrease for subsequent higher order Strahler numbers;
- The length of streams and the catchment areas show an increase for subsequent higher order Strahler numbers.

From the Horton plot (figure 4.11) and the followed table 4.3, it can be assessed that the drainage network is well extracted and the Horton number are representative and fall within the expected range.

![Figure 4.121: Regression of logarithm of the number of streams, average stream length, average catchment area for the Can Le catchment.](image)

<table>
<thead>
<tr>
<th>Order</th>
<th>C1_N (number)</th>
<th>C1_L (km)</th>
<th>C1_A (km²)</th>
<th>C1_N_LSq (number)</th>
<th>C1_L_LSq (km)</th>
<th>C1_A_LSq (km²)</th>
<th>Horton's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>4.27</td>
<td>6.92</td>
<td>9.826</td>
<td>4.410</td>
<td>7.262</td>
<td>3.16</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>9.58</td>
<td>30.42</td>
<td>3.107</td>
<td>8.981</td>
<td>27.621</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>17.71</td>
<td>100.09</td>
<td>0.983</td>
<td>18.291</td>
<td>105.047</td>
<td></td>
</tr>
</tbody>
</table>

2. Surface discharge calculation based on GIUH

13 See ILWIS’s help for further explanation.
14 The ratio is calculated based on the complete 3rd order catchment. Thus the total area of the area is 105.046 km², which is less than the real catchment (203 km²)
The above section “GIUH development” has shown how to derive the GIUH, the following part will devote to determine how to calculate the surface discharge for each event.

The response function of the GIUH is characterised by its impulse response function as mentioned in the previous part. If a system receives an input of unit amount applied instantaneous (a unit impulse) at time $\tau$, the response of the system at a later time $t$ is described by the unit impulse response function $u(t-\tau)$, $t-\tau$ is the time lag since the impulse is applied (Chow et al., 1988, p.204). The amount of input entering the system between time $\tau$ and $\tau + dr$ is $i(\tau)dr$. If $i(\tau)$ is the effective rainfall, the response of a complete input $i(\tau)$ is the direct runoff $Q(t)$ of the catchment. This runoff can be found by integrating the response to its constituent impulse:

$$Q(t) = \int_{0}^{t} i(\tau)u(t-\tau) \, d\tau.$$  
(eq.4.4)

This expression called *convolution integral*

Where:

- $i(t)$ is effective rainfall intensity, and distributed uniformly over the entire basin.
- $u(t)$ is the GIUH in this case.

The overall discharge calculation steps based on GIUH approach is shown in figure 4.12. In this figure, the GIUH has been explained in the previous part, hereunder is about how to derive the surface discharge.

The effective (excess) rainfall is computed according to the Soil Conservation Service (SCS) runoff method (see Ogrosky and Mockus, 1964 for original) and (Chow et al., 1988, p.147 for latest one). To calculate Curve Number (CN) value, the land use map and soil map are used based on SCS table. The CN values of each map unit are aggregated for the whole catchment by mean of GIS to get an average CN value. Then direct flow or the effective rainfall is calculated using the following formulas:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$

For $P > 0.2 \, S$,  
And $P_e = 0$ if $P < 0.2 \, S$

Where: $P_e$ = effective rainfall expressed as a depth, $P$ = total observed rainfall.

$$S = \frac{1000}{CN} - 10$$  (When water depth are expressed in inches)

$$S = \frac{25.4}{CN} - 154$$  (When water depth are expressed in mm)

Figure 4.12: Surface discharge calculation steps based on GIUH approach.
After having the effective rainfall, Horton’s statistics values to derive GIUH, the surface runoff is calculated based on (eq.4.4) using Excel spreadsheet in a discrete time domain (see Chow et al., 1988, p.211) and the discharge is determined by taking into account the catchment area.

4.4.2. HEC-HMS SMA

1. The HEC-HMS

Data preparation

Rainfall input data, discharge data are prepared in HEC-DSSVue package (Charley, 2003). This package is used to store time series data set because its file can be read in HEC-HMS. Additionally, for hourly discharge data, the linear interpolation within this software was utilized to produce a complete hourly set (estimate missing data).

The base map was prepared in ARCVIEW with additional module namely Geo-HEC-HMS and used as input in the “Basin” module of HEC-HMS (figure 4.13)

![Model setup in Arcview using HEC-GeoHMS extension and imported in HEC-HMS](image)

Figure 4.13: Model setup in Arcview using HEC-GeoHMS extension and imported in HEC-HMS

Although the interest is applying the SMA loss model, the SMA alone could not give the expected result, the discharge at the catchment outlet. It is accompanied with the transform model and base flow method as shown in figure 4.14.

![HEC-HMS components](image)

Figure 4.14: Setup HEC-HMS components

The SCS Unit hydrograph was chosen in order to transform excess precipitation into surface runoff as explained in section 2.5.2. The SCS lag parameter was calculated based on a formulation from the HEC-HMS technical guide (Feldman (ed.), 2000) with information extracted from the DEM using ARCVIEW and some estimated ones like Manning’s roughness coefficient, hydraulic radius, overland-flow roughness coefficient.
The linear reservoir is adapted for base flow calculation methods because this module is suitable with the soil moisture accounting model. (refer to Feldman (ed.), 2000, p. 77)

The next section is devoted to model development of the SMA loss model.

2. The SMA loss model

To run SMA model, 12 parameters are needed, of which some are measurable parameters and some cannot be measured by indirect/direct means. Fleming and Neary (2004) introduced several techniques to acquire these parameters using GIS, streamflow analysis and model calibration. Table 4.4 shows the parameters and suggests sources to acquire those which are adapted from Fleming (2002) and Fleming and Neary (2004). Data requirement for processing includes: soil map and its related information like saturated hydraulic conductivity, porosity, hydraulic conductivity, field capacity, soil depth; land cover map; and also rainfall, monthly average evapotranspiration.

Table 4.4: SMA parameters and suggested sources to acquire

<table>
<thead>
<tr>
<th>Layers</th>
<th>Parameters (unit)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy interception storage</td>
<td>Storage capacity (in);</td>
<td>GIS processing</td>
</tr>
<tr>
<td>Surface depression storages</td>
<td>Storage capacity (in);</td>
<td>GIS processing</td>
</tr>
<tr>
<td></td>
<td>Soil infiltration max. rate (in/hr);</td>
<td>GIS processing</td>
</tr>
<tr>
<td>Soil profile storage</td>
<td>Storage capacity (in);</td>
<td>GIS processing</td>
</tr>
<tr>
<td></td>
<td>Tension zone capacity (in);</td>
<td>GIS processing</td>
</tr>
<tr>
<td></td>
<td>Percolation max. rate (in/hr);</td>
<td>GIS processing</td>
</tr>
<tr>
<td>Groundwater layer-1 storage</td>
<td>Storage capacity (in);</td>
<td>Stream flow analysis</td>
</tr>
<tr>
<td></td>
<td>Percolation max. rate (in/hr);</td>
<td>GIS processing</td>
</tr>
<tr>
<td></td>
<td>Storage coefficient (hr);</td>
<td>Stream flow analysis</td>
</tr>
<tr>
<td>Groundwater layer-2 storage</td>
<td>Storage capacity (in);</td>
<td>Stream flow analysis</td>
</tr>
<tr>
<td></td>
<td>Percolation max. rate (in/hr);</td>
<td>Model calibration</td>
</tr>
<tr>
<td></td>
<td>Storage coefficient (hr);</td>
<td>Stream flow analysis</td>
</tr>
</tbody>
</table>

Model parameterization

GIS processing

For the detailed steps reference is made to the work of Fleming (2002), here only the supplementary information to calculate the above mentioned parameters are listed. Also, because at the Can Le soil information is not as detailed as Fleming found from the STATGO database therefore simple methods are adopted in this study.

The GIS processing is implemented in this study simply as map overlaying. The land use map, soil map with relevant attributes are processed to create attribute maps and then crossed with the sub-catchment map. Aggregation function is used to obtain an average value of each sub-catchment. The whole data processing procedures is done in ILWIS based on raster calculation.

From the soil sheet in Hai and Tu (2003), the soil texture of each soil layer are averaged to identify the soil texture for each soil unit map. Based on this soil texture, using the SPAW software, one is able to derive information on saturated hydraulic conductivity, hydraulic conductivity, porosity, field capacity, infiltration rate.(figure 4.15)
- The saturated hydraulic conductivity of the first soil layer is used as the maximum infiltration rate;
- The porosity and field capacity values were simply multiplied by the depth of soil layer (assume one meter for the whole catchment) to obtain maximum soil profile and tension zone depths respectively;
- The average hydraulic conductivity for whole soil layers was used as percolation rate for soil zone and groundwater 1.

Then all is aggregated by catchment to have average values. Detail steps are shown in figure 4.16 and results are shown in next chapter, table 5.3.

Adopted from Fleming (2002), according to the land use map the interception values for each of land use type are: 1.270 mm for agriculture_mixed; 2.032 mm for agriculture_crop; 2.540 mm for agriculture_trees and agriculture_trees_small; base soil and urban area get 0 mm.

The surface depression storage was calculated based on the surface slope (table 4.5)

Table 4.5: Surface depression storage (Fleming and Neary, 2004)

<table>
<thead>
<tr>
<th>Description</th>
<th>Slope (%)</th>
<th>Surface Storage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paved Impervious Areas</td>
<td>NA</td>
<td>3.18 – 6.35</td>
</tr>
<tr>
<td>Steep, Smooth Slopes</td>
<td>&gt; 30</td>
<td>1.02</td>
</tr>
<tr>
<td>Moderate to Gentle Slopes</td>
<td>5 – 30</td>
<td>6.35 – 12.70</td>
</tr>
<tr>
<td>Flat, Furrowed Land</td>
<td>0 - 5</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Stream analysis

As mentioned in section 4.3, the semi-logarithmic plot method (Linsley et al., 1958) is used for stream analysis. During recession, the discharge will depend upon the storage remaining. If the storage-discharge is assumed to be linear,

\[ S = kQ \]  

(eq.4.5)

Where \( S \) is storage and \( Q \) is discharge and \( k \) is constant having dimension of time.

The recession curve can be described by (eq.4.6), where \( q_0 \) is flow at any time and \( q_r \) is flow \( t \) time units after \( q_0 \), and \( K_r \) is a recession constant. The time unit, \( t \), is in days.
\[ q_t = q_o \times K_r \quad \text{(eq. 4.6)} \]

Integrating (eq. 4.6) with respect to time results in (eq. 4.7) which is similar (eq. 5), where \( S_t \) represents the interflow or groundwater storage volume at time, \( t \) equals the outflow, \( q_o \), multiplied by a storage coefficient. From equation (eq. 4.7), the storage coefficient can be obtained by solving, 
\[ -\frac{1}{\ln(K_r)} \ln(\frac{q_t}{S_t}) \]

For example, analysing the storm of the first event, the \( K_r \) for the interflow is about 0.36 and for the base flow is about 0.92 (figure 4.17)

Figure 4.16: GIS processing for SMA parameterization
4.4.3. REW

Model setup

Before going to detail model setup, a brief description on model working processes is presented, one can refer to the work of Reggiani (2005) and Reggiani and Rientjes (2005) for more detail.

The model operates according to the flow chart shown in figure 4.18. The relationship of different processes in a catchment has partly been discussed in section 2.2. Hereunder, an explanation for each zone with respect to processes applied in the REW approach as following:

- Infiltration excess flow /Horton-type flow (C-zone): Rainfall firstly falls into this zone and infiltrate to the unsaturated zone (U-zone). If the rainfall intensity exceeds the infiltration capacity of the soil layer, it will create overland flow which then joins to the saturation excess flow zone (O-zone)\textsuperscript{15}.

- Unsaturated zone (U-Zone): Having infiltration flux from the C-zone, water in the U-zone is exchanged with saturated zone through percolation and capillary rise.

- Saturated zone (S-Zone): There are various processes involved in this zone that comes from U-zone or exchanged with the O-zone by exfiltration and recharge processes and also with stream flow by either recharge or seepage mechanisms. In the S-zone of a REW itself is linked to its neighbouring REWs.

- Saturation excess flow/Dunne-type flow (O-zone): When water table rises to the surface, the saturation excess flow occurs. At this moment the O-zone is established and then exchanged with the S-zone and contributes directly to the river.

\textsuperscript{15} Due to limitation in implementing the REW code, this process (from C-zone to O-zone) was set in active in the REW model version 8.0. Thus water from C-zone only goes to U-zone.
Subsurface stormflow (P-zone): When the subsurface layer with high conductivity the subsurface stormflow is generated (usually termed perch flow). The P-zone is fed by direct infiltration of precipitation and discharges directly toward the channel.

Channel flow (R-zone): the recharged flows from different zones to the river network are routed along the river network (linked with R-zone of neighbouring REW) and to the catchment outlet.

REW 8.0 operation

An overall flow chart for REW modelling is illustrated by figure 4.19. Detail descriptions are explained by Reggiani (2005). Hereunder, brief descriptions on these processes are presented:

Data preparation is providing for all steps in the REW model.

The Digital Elevation Model is prepared for TARDEM processing. At this stage, 2 typical thresholds were introduced with respect to extracted drainage network, catchments. The first threshold is for extracted channel network. Several attempts were done in order to find a representative network that matched to the existing one.

16 This zone is recently added in this REW model (version 8.0)
Strahler 2 order was chosen as the second threshold. At this step, 35 REWs were extracted and prepared for the next steps. (Figure 4.20)

In REWANALYSIS, provided data includes output from TARDEM and other information on soil, land use\(^{17}\). After this stage, using REWANALYSIS and RECANALYSIS software, the geometry of each REWs and inter-connectivity between REWs were established.

Having the output from REWANALYSIS, provided data including initial condition, boundary condition, meteorological data and model parameters, the PREPROCESSOR software is performed. At the end of this stage, model parameters and materials properties were assigned for each REW.

By running SOLVER software, the final results of the REW model are generated. The outputs include time series discharge, flux exchange, soil moistures for each of REWs. Sequentially, after running POSTPROCESSOR, all the output files are packed into one and can be read/visualised in Matlab software. Data prepared for the SOLVER includes information for computation (time steps), other parameters for Richards Equation Solver, groundwater table interpolation. And for the POSTPROCESSOR, a number of extracted variables should be identified.

### 4.4.3.1. Model parameterization

Due to the high demand of model parameters to run the REW approach and due to the limited data in the Can Le catchment, most of the model parameters were adapted from an application of REW at Keelung catchment (Taiwan)\(^{18}\) for the first run. Few catchment parameters were estimated based on the field knowledge obtained during the fieldwork period and from literature as shown in table 4.6

In the application of REW conducted by Reggiani and Rientjes (2005), the soil texture, structure parameters and Manning coefficients etc. are assumed as homogeneous and uniform in space. In this study, the assumption is also applied.

After the first run, the model parameters were obtained by tuning a number of sensitive parameters in order to get the “Goodness-of-fit”. This work will be reported in section 5.4.

---

\(^{17}\) Due to limitation of time, exploration of soil, land use characteristics was not carried out in this study.

\(^{18}\) The data set for Keelung case was provided by Reggiani (personal communication, 2006)
Table 4.6: Initial values of several model parameter and sources

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Subsurface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>✓ Water table depth (m)</td>
<td>1</td>
<td>Field knowledge</td>
</tr>
<tr>
<td>✓ Bedrock depth (m)</td>
<td>10</td>
<td>Field knowledge</td>
</tr>
<tr>
<td>✓ Soil porosity (%)</td>
<td>0.5</td>
<td>(Dingman, 2002, p.235)</td>
</tr>
<tr>
<td>✓ Saturated hydraulic conductivity (m/day)</td>
<td>0.014</td>
<td>(Dingman, 2002, p.235)</td>
</tr>
</tbody>
</table>

2. Richards Equation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Unsaturated zone cell thickness (m)</td>
<td>1</td>
<td>Field knowledge</td>
</tr>
<tr>
<td>✓ Depth of top soil layer (m)</td>
<td>0.4</td>
<td>Field knowledge</td>
</tr>
</tbody>
</table>

4.5. Model evaluation

Model performance is the most important aspect to evaluate the model approaches. Selected criteria used to evaluate the goodness-of-fit of each model approach are shown in table 4.5.

Table 4.5: List of criteria used to compare predicted results versus observed measurements

<table>
<thead>
<tr>
<th>ID</th>
<th>Criteria</th>
<th>Equation</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nash_Sutcliffe efficiency, NSE (Coefficient of efficiency)</td>
<td>[ NSE = 1.0 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} ]</td>
<td>(Nash and Sutcliffe, 1970)</td>
</tr>
<tr>
<td>2</td>
<td>Index of agreement, d</td>
<td>[ d = 1.0 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (P_i - \bar{O} + O_i - \bar{O})^2} ]</td>
<td>(Legates and McCabe, 1999; Willmott, 1984)</td>
</tr>
<tr>
<td>3</td>
<td>Coefficient of determination, R² (The square of the Pearson’s product-moment correlation coefficient)</td>
<td>[ R^2 = \left{ \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\left[ \sum_{i=1}^{n} (O_i - \bar{O})^2 \right]^{0.5} \left[ \sum_{i=1}^{n} (P_i - \bar{P})^2 \right]^{0.5}} \right}^2 ]</td>
<td>(Legates and McCabe, 1999)</td>
</tr>
</tbody>
</table>

Where: \( O_i \): Observe, \( P_i \): Predict, \( \bar{O} \): average of the observe value, \( \bar{P} \): average of the predicted value

In order to recommend which model approach is suitable, besides the performance criteria, other interests should be taken into account.

Based on a ranking scheme developed by Cunderlik (2003, p.24 - 25), a set of 14 criteria was adapted and modified to fit into the context of the three selected model approaches. The criteria are used for a particular project. For example, this study is rainfall – runoff modelling project which required prediction of the discharge at the outlet of the Can Le catchment. Since the discharge changes in a short time, at least an hourly scale is required.
RAINFALL-RUNOFF MODELING IN THE UNGAUDED CAN LE CATCHMENT, SAIGON RIVER BASIN

The criteria used are as following:

1. Temporal scale: The time step used in the model, either hourly, daily, monthly or flexible etc. Rank: [0-2]; models with flexible time step receive the highest rank 2, models with limited time step get 1, otherwise 0;

2. Spatial scale: The model is developed for different catchment sizes such as small (urban area), medium (up to 1000km²), large (>1000km²) or flexible in size. Rank: [0-2]; 2 for flexible size, 1 for model with partially applicable spatial scale, and 0 for inapplicable model(s);

3. Processes modelled: The model should be able to capture the dominant processes of the specific catchment (e.g.: event or continuous simulation, interception, infiltration, evapotranspiration, river routing, groundwater flow). Rank: [0-12] (0-2 for each process); get 0 when a given process is not modelled, 1 if partially modelled (such as a process is modelled in a simplified form) and 2 if a process is completely modelled;

4. Model availability: Price of the model. Rank: [0-2]; 0 for expensive model (unacceptable within project budget), 1 for acceptable and 2 for public domain;

5. Set-up time: approximate time needed for the model to be into operational use. Rank: [0-2]; 0 for high time consuming, 1 for medium and 2 for short time;

6. Expertise: Scientific skill required to use the model adequately. Rank: [0-2]; 2-low, 1-medium and 0-high;

7. Technical support: Support available for setting up the model, calibration and use. Rank: [0-2]; 1-low, 2-medium and 0-high;

8. Documentation: Document available about the model such as user’s guide, reference manual, etc. Rank [0-2]; 0-bad, 1-medium, and 2-good;

9. Ease-of-use: the user-friendliness of the model, including Graphic User Interface (GUI), Input-output (I/O) operation, and visualization options [easy, medium, difficult]. Rank [0-2]; 0-difficult, 1-medium, and 2-easy;

10. Operating system (OS): computer OS required for the model [WINDOW, UNIX, DOS, MAC, etc.]. Rank [0-2]; 2 for Windows based application, 1 for DOS application, and 0 for other application;

11. Model performance: The accuracy prediction of the three models when applying in the Can Le catchment. Rank [0-6]19: 6 for very high, 4 for high, 2 for not high and 0 for low.

12. Advantages and disadvantages: pros and cons of a given model; No rank [-];

13. References: list the key reference(s) to the model in literature; No rank [-];

14. Additional comments: any additional information worth mentioning; No rank [-].

The total score gives the sum of all ranked criteria [0-38]

**Summary on chapter 4**

In this chapter, a number of the methods applied in this study have been reported. The applications of GIS through aggregation, map overlaying, DEM processing etc. are used to estimate model parameters; satellite images are utilised to simulate rainfall distributions occurs the catchment. One can make a statement of the indispensable role of Geo-information in a practical issue, the rainfall-runoff modelling. Model development for each model approach also was done, the results will serve as preparation for model simulations that are presented in the next chapter.

---

19 Because the aim of this study is to recommend which model approach is suitable for the Can Le catchment, this performance criterion was set higher than others.
5. Results

5.1. Rainfall analysis

As discussed in chapter 4, the data from the tipping bucket is used as the base data. The rainfall and discharge measurement is plotted in order to analyse which events should be selected. In other words, the relation between rainfall and discharge measurement is first analysed visually. Several “abnormal” events are easily found from figure 5.1, for example the storms on 13 October 2005 or 23 October 2005. For these events, there is no clear relation between rainfall recorded at the location of the tipping bucket and discharge (very small rainfall produces high discharge, or vice versa).

![Figure 5.1: Rainfall measurement by tipping bucket versus discharge measurement](image)

To be consistent for the whole rainy period, numerous events were selected to integrate rainfall from the station with satellite images from: 25/9/2005 (at 9 UTC\(^{20}\)), 4/10/2005 (at 17 UTC), 13/10/2005 (at 12 UTC), 17/10/2005 (at 14 UTC), 23/10/2005 (at 7 UTC), 25/10/2005 (at 9 UTC), 3/11/2005 (at 13 UTC), 9/11/2005 (at 14 UTC).

\(^{20}\) Vietnamese time zone is UTC+7
After processing the Meteosat 5 satellite images, together with data available from Dong Phu station (hourly), Loc Ninh (2 times/day) and the tipping bucket (hourly), a “new” rainfall data set was established. The results are shown in figure 5.2 and the differences with respects to the original storms are shown in table 5.1.

From the table and figure 5.2, it can be concluded that the rainfall from the tipping bucket was not preventative over the catchment. The differences varied from 10 to 30 percent (or within +/- 15 mm) in most cases, except for event (3), (4), (6) although they were not heavy storms. From now on, the interpolated rainfall data is used as input for the three selected models and assumed that it is uniformly distributed over the catchment.

![Figure 5.2: Cumulative original, optimal rainfall and the rainfall differences](image)

Table 5.1: Rainfall changes after interpolation

<table>
<thead>
<tr>
<th>Events</th>
<th>Events number</th>
<th>Time (UTC + 7)</th>
<th>Can Le (mm)</th>
<th>Dong Phu (mm)</th>
<th>Average (mm)</th>
<th>Differences between (b and d) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/25/2005</td>
<td>(1)</td>
<td>16</td>
<td>58.33</td>
<td>0.00</td>
<td>36.31</td>
<td>37.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td>24.66</td>
<td>8.80</td>
<td>15.35</td>
<td>37.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>14.99</td>
<td>6.50</td>
<td>9.34</td>
<td>37.75</td>
</tr>
<tr>
<td>10/4/2005</td>
<td>(2)</td>
<td>17</td>
<td>2.40</td>
<td>68.50</td>
<td>2.69</td>
<td>12.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>22.70</td>
<td>64.50</td>
<td>25.48</td>
<td>12.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19</td>
<td>0.60</td>
<td>5.60</td>
<td>0.67</td>
<td>12.24</td>
</tr>
<tr>
<td>10/12/2005</td>
<td>(3)</td>
<td>20</td>
<td>0.99</td>
<td>0</td>
<td>1.99</td>
<td>101.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21</td>
<td>2.97</td>
<td>0</td>
<td>5.98</td>
<td>101.26</td>
</tr>
<tr>
<td>10/17/2005</td>
<td>(4)</td>
<td>19</td>
<td>19.2</td>
<td>0</td>
<td>6.96</td>
<td>63.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>7.3</td>
<td>0.3</td>
<td>5.11</td>
<td>30.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21</td>
<td>3.7</td>
<td>3.7</td>
<td>2.22</td>
<td>40.00</td>
</tr>
<tr>
<td>10/23/2005</td>
<td>(5)</td>
<td>14</td>
<td>6.30</td>
<td>0</td>
<td>8.80</td>
<td>39.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>1.50</td>
<td>0.8</td>
<td>2.10</td>
<td>39.68</td>
</tr>
<tr>
<td>10/25/2005</td>
<td>(6)</td>
<td>15</td>
<td>3.96</td>
<td>3.9</td>
<td>6.51</td>
<td>64.50</td>
</tr>
</tbody>
</table>
5.2. GIUH

5.2.1. Model development

Since the method to calculate discharges at the outlet was described in chapter 4, this section provides the results of every step. Table 5.2 summarises results of each step.

Table 5.2: Discharge calculation based on GIUH approach: steps and results.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Results</th>
</tr>
</thead>
</table>
| 1. Calculate Horton’s statistics R_A, R_B, R_L by DEM processing and integrating in ILWIS (Chapter 4) | Ratio’s s  
| RB | RL | RA |  
| 3.16 | 2.04 | 3.80 |
| 2. Estimate the hillslope/stream velocity and calculate coefficient of the exponential density function α, β1, β2, β3 |  
| V_0 = 0.06 m/s, (Ramirez, 2005) |  
| V_s = 0.8 (m/s) (Valdes et al., 1979) |  
| α = V_s/L_o (L_o = D/2, where D is drainage density) |  
| β_i = V_i/L_i; α = α_1 = α_2 = α_3 |  
| α | β1 | β2 | β3 |  
| 0.214 | 0.625 | 0.3064 | 0.15 |
| 3. Compute the transition probabilities, the initial state probabilities and then the probability at a given path S_i; |  
|  P_{i2} | P_{i3} | θ1 | θ2 | θ3 |  
| 0.85 | 0.15 | 0.69 | 0.24 | 0.07 |  
| P(S1) | P(S2) | P(S3) | P(S4) |  
| 0.09 | 0.10 | 0.24 | 0.07 |
| 4. Compute the probability density function of travel time at each paths; |  
| f_1(S1), f_1(S2), f_1(S3), f_1(S4) are calculated in time steps^{21}. (solving the non-identical exponential density function, see appendix 3) |  
| 5. Convolute the GIUH; | GIUH = \sum_{n=1}^{n} f_{T_{n1}}(t) \times f_{T_{n2}}(t) \times f_{T_{n3}}(t) \times \ldots \times f_{T_{n4}}(t) \times Pr ob(S) |  
| 6. Calculate the rainfall excess i(t); | The CN value determined was 85 |  
| 7. Convoluting the final discharge, Q. | The convolution of the discharge starts when effective rainfall is larger than 0. (an example is made for the first event on 25 September 2005, figure 5.4) |  

^{21} Using Excel spreadsheet
Figure 5.3. The Geomorphologic instantaneous unit hydrograph of the Can Le Catchment

Figure 5.4: Measured and simulated hydrograph using GIUH at the Can Le catchment (event 25/9/2005) (before calibration, \(v_o=0.06\) m/s, \(v_c=0.8\) m/s)

From figure 5.4 it can be seen that the simulated flow over-estimates the observed discharge and calibration is required.
5.2.2. Sensitivity analysis, model calibration and validation

For the GIUH approach, the initial abstraction was assumed as a correct factor. Therefore, the CN value was kept constant 85.

The most sensitive model parameters identified in literature are the velocity of the hillslope and stream flow (e.g. Al-Wagdany and Rao, 1998; Kirshen and Bras, 1983). Therefore, in this application, the Horton’s ratios were also kept constant during calibration. The hillslope velocity and stream velocity were calibrated manually, simultaneously based on manual calibration. The best “Goodness-of-fit” was obtained at $V_o=0.053$ m/s and $V_s=0.5$ m/s.

![Figure 5.5: Measured and simulated hydrograph using GIUH at the Can Le catchment (event 25/9/2005) (after calibration, $V_o=0.053$ m/s, $V_s=0.5$ m/s)](image)

From figure 5.5, the peak is well simulated after the calibration as well as the shape of the hydrograph. However, the difference in time to peak of about 2 hour is attributed to the shift of the outlet location 3 km further downstream because the simulated runoff is computed for the junction of the 3rd order network location. When the adopted average flow velocity (0.5 m/s) is assumed to be representative for the downstream movement of the peak discharge network, it fully accounts for the time lag observed (1 hrs and 50 minutes).

The model parameter values were fixed for model validation. The second event on 4 October was used for this purpose. The result is shown in figure 5.6.
For the second event, the model also can adequately predict the surface runoff. However, the observed peak flow is about 1 hour earlier than the simulated one. The reason might be due to an event that happening in previous day (figure 5.7). It is assumed that the event caused some areas to become saturated and this caused the runoff that is observed.

Figure 5.7: Rainfall and discharge before and after the event on 4 October 2005
5.2.3. Conclusion on GIUH approach

The model was successfully applied for the Can Le catchment. Using the Horton’s morphometric parameters derived from DEM using specific software (ILWIS) and estimated velocities of hillslope and stream, the model is easy-to-use.

The representative velocity suggested by Valdes et al (1979) is the velocity occurring at time of peak flow. However, in this study, the shape increase of the rising limb during the event makes this suggestion not applicable. The reason could be at that time (1979), Valdes et al did not take into account the hillslope velocity (Bras and Rodriguez-Iturbe, 1989) but in this study the hillslope velocity was incorporated. Model calibration on velocities must therefore be accomplished, and both hillslope velocity and stream velocity were calibrated simultaneously.

In this model, the CN value was kept constant (no calibration). It should further investigate what affects this factor has so that the calibrated parameter will be representative.

From the results, it can be confirmed that the application of GIUH approach in runoff estimation is very promising especially in the flooding areas as well as where data availability is limited. However, GIUH is event-based model, it does not take into account the changes in soil, etc (e.g. result from the second event). It is encouraged to incorporate this approach into a hydrologic model where the GIUH plays as a runoff transform module, for example, the work from Karvonen et al (1999).

5.3. HEC-HMS SMA

5.3.1. Model parameters and initial output

The model parameterization methods were described in section 4.3.2. Table 5.3 summaries the values of the 12 model parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy interception storage</td>
<td></td>
</tr>
<tr>
<td>Surface depression storages</td>
<td></td>
</tr>
<tr>
<td>Soil profile storage</td>
<td></td>
</tr>
<tr>
<td>Groundwater layer-1 storage</td>
<td></td>
</tr>
<tr>
<td>Groundwater layer-2 storage</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Initial parameters values of SMA model
After being parameterised, the loss model SMA is incorporated with a method for runoff transform (SCS), base flow model (linear reservoir) in order to run the HEC-HMS. The parameters of SCS module and base flow model are:

- SCS lag: 12 hours;
- Base flow: the storage coefficient is 23 hours and 630 hour for the groundwater storage 1 and groundwater storage 2 respectively.

The first results are shown in figure 5.8. Obviously, the model is not able to simulate the entire hydrograph compared with the observed ones. Especially, almost the simulated peak flows overestimate the observed ones. Similar with the first model (GIUH), sensitivity analysis and model calibration is required also for HEC-HMS SMA.

![Figure 5.8: Measured and simulated hydrograph using SMA for the Can Le catchment (first results)](image)

5.3.2. Sensitivity analysis and model calibration

Sensitivity analysis

Because the objective of this study is to compare the performance of HEC-HMS with respect to the continuous SMA loss model, other parameters relating to runoff transform, base flow estimation were fixed after the initial result.

From the results of Fleming (2002), it proves that the maximum infiltration rate, the maximum soil depth and the tension zone depth are the most sensitive parameters. However, in this study, beside the three parameters, surface parameter like surface capacity and canopy capacity also were taken into account.
The above parameters are analysed within +30% to -30%. Each of the parameter was changed individually. Figure 5.9 shows the effect of these parameters based on the changes of the total volume of water of the first two events.

In the figure 5.10, it can be seen that the most sensitive parameter is the *soil infiltration maximum rate*, and then the *surface storage capacity*, *canopy interception* etc. the least sensitive parameter was tension zone capacity. Therefore, the first three most sensitive parameters were calibrated.

**Model calibration**

To avoid parameter interactions, the parameters are calibrated separately.

Manual and automatic calibrations were used in this model. Manual calibration is used to limit the range of parameters where the output is acceptable. The automatic calibration is used to search for optimised parameters. Calibration for each parameter was according to their sensitivity. The least sensitive parameters were calibrated first and then the more sensitive parameters were calibrated subsequently. These 5 parameters were adjusted; table 5.4 shows the initial parameters and adjusted ones, also followed up by figure 5.10 with the observed and initial/calibrated simulation flows.

It is also noted that the specific stream flow in the catchment is the very sudden/sharp response (high peak flow). Thus, the aim during calibration period is to try to simulate the peak flow so that this model can serve as flood forecasting model in this area.

**Table 5.4: Initial and calibrated parameters for the SMA loss model.**

<table>
<thead>
<tr>
<th>Storages</th>
<th>Parameters</th>
<th>Initial</th>
<th>Calibrated</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy interception</td>
<td>• Storage capacity (mm)</td>
<td>1.5</td>
<td>2.5</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>• Storage capacity (mm);</td>
<td>3.5</td>
<td>4.2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>• Soil infiltration max. rate (mm/hr)</td>
<td>11</td>
<td>17.8</td>
<td>62</td>
</tr>
</tbody>
</table>
The model after calibration yields a better result as compared to the non-calibrated cases. Almost all the peaks were predicted. However, there are still three peaks that were not well simulated as can be seen in figure 5.11. The reason for these mismatches is the contribution of improper rainfall input. For example:

- **Peak (1):** The rainfall was too little to produce effective rainfall\(^{22}\);
- **Peak (2):** In the real world rainfall varies in time. The rainfall observed at the tipping bucket does not reflect this, e.g. rainfall occurred earlier upstream while the rain gauge located downstream;
- **Peak (3):** Seems similar to peak (1) but in this case the higher volume of rainfall produced the peak flow. Moreover, the soil parameters (storage capacity, infiltration) were set a bit high in calibration phase in order to obtain the high peak flow (i.e. in the first event) then such amount of rainfall in the later case can not produce the real peak flow.

![Figure 5.10: Measured and simulated hydrograph using HEC-HMS SMA at the Can Le catchment (before and after calibration)](image)

**5.3.3. Conclusions on HEC- HMS SMA**

- For the HEC-HMS SMA, the model parameterization is based on GIS processing and stream flow analysis. Subsequently model calibration is needed to improve the performance of the model. There are three major conclusions drawn from the simulation results.

- Simple methods to derive model parameters based on GIS processing and stream flow analysis make this model applicable. The adopted method introduced by Fleming (2002) and Fleming and Neary (2004) was also successfully applied in this study.

---

\(^{22}\text{It was checked using satellites images and surrounding station data as mentioned in section 5.1 but very no relation is found (no rainfall observed at rain gauges but the peak flow was recorded)}}
The high peak flow was well simulated. Model calibration with the aim to simulate the peak proves to be efficient. Before calibration, the model mostly overestimates observed peak flows, but after increase the storage capacity of soil zone and surface capacity and infiltration rate the results improved. There are still some mismatches between the observed and predicted flow but it can be explained by the improperly observed rainfall varied in time and space.

However, the base flows were not well predicted. The reason could be that dynamic system characteristics do not obey the linear reservoir algorithms. Also, because the field campaign was in the middle of the rainy season, the lowest water level was not observed can caused to improper estimation of the storage capacity and coefficient of the groundwater system. Moreover, the primary interest of HEC HMS is in simulating flood hydrograph where the base flow is a relatively small contributor. Thus only simple methods were provided in the package itself (Feldman, 1995, p.130).

5.4. REW

5.4.1. Model simulation

The initial result could be improved as can be seen in figure 5.11. The simulated peak flow was very small as compared to the observed one. Due to the fact that in this REW (version 8.0) the link between the C-zone and O-zone was set inactive so there was no contribution of the infiltration excess flow to the channel system.

Figure 5.11: Measured and simulated hydrograph using REW at the Can Le catchment (initial result)
5.4.2. Sensitivity analysis and model calibration

A number of tests were implemented by adjusting the soil porosity and hydraulic conductivity, which reported by Zang et al (2005) are the most sensitive parameters in the REW model, besides some other parameters. Changing these parameters did not significantly affect the results. Given the fact that the infiltration excess overland flow was not simulated in this REW version, an alternative solution was to simulate this zone by forcing the perched system in the area. Therefore, the calibration procedure focused on calibrating the subsurface zone which was designed in the REW model to capture the perched flow. Two main parameters were adjusted including hydraulic conductivity and soil surface depth that account for the perched system. The range for these two parameters is from 0.002 to 0.05 m/s for the $K_p$ and 0.05-0.4 for the depth. Table 5.5 shows the combination of these two parameters with respect to the NSE for every simulation and figure 5.12 shows a number of resulting hydrographs.

Table 5.5: Model calibration by combining the most sensitive parameters including shallow soil depth and hydraulic conductivity with respect to the changes of NSE (Nash-Sutcliffe efficiency)

<table>
<thead>
<tr>
<th>Shallow soil depth (m)</th>
<th>$K_p$ (m/s)</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.002</td>
<td>&lt; 0</td>
<td>0.07</td>
<td>0.06</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.006</td>
<td>&lt; 0</td>
<td>0.19</td>
<td>0.23</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>&lt; 0</td>
<td>0.23</td>
<td>0.24</td>
<td>&lt; 0</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>&lt; 0</td>
<td>0.27</td>
<td>0.06</td>
<td>&lt; 0</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>&lt; 0</td>
<td>0.27</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>&lt; 0</td>
<td>0.07</td>
<td>&lt; 0</td>
<td>&lt; 0</td>
</tr>
</tbody>
</table>

The highest NSE was obtained at 0.27 with the combination of $K_p = 0.02$ and the depth of 0.1m and shown in figure 5.13.

![Figure 5.12: Simulated hydrographs using REW with different combination $K_p$ and shallow soil depth](image)
5.4.3. Final remarks

It is clear that the REW model was sensitive with the forcing data (rainfall) as can be seen by a number of peak flows. By forcing the perched system into the model, the result improved significantly. Moreover, the base flow was better predicted. The pattern of the observed flow was well captured in the model. However, the peak flow is under-predicted.

There are a few reasons that may explain the results as following:

- Due to the missing simulation of the C-zone, the infiltration excess overland flow could not join to the saturated overland flow/channel system that caused less water predicted;

- An important reason is that the simulation period is quite short. To proper simulate the REW model, an “equilibrium” state should be established so that the system characteristics are adapted (internal soil moisture state, water table position, saturated area extension are at equilibrium with the forcing rainfall, evaporation, etc). Thus, longer simulation period is required. For example, in the application of the REW model for the Geer catchment (Reggiani and Rientjes, 2005), 6 years were served to set up the initial state;

- There are a number of parameters to be set in the REW model. REW is a complex model and model calibration can be complicated. Although the result shown could be further improved, given the time constrains and complexity of the approach no more efforts made.
6. Discussions

The main objective of this chapter is to perform a model inter-comparison. However, to compare all three models at the same time (for instance, the GIUH is event-based model and the remaining are continuous simulations) is not applicable. Therefore, in this chapter, a number of aspects with respect to each the approach are discussed. The chapter starts with a discussion of the runoff generation of the Can Le catchment, then a summary of the performance of the three models given and is followed by model inter-comparison which covers not only model performance but also other model aspects such as data requirement, model parameterization, and calibration. “Recommended model” is a followed up part of the comparison section.

Given the fact uncertainty is an issue that can be neglected in modelling. Therefore, in the end of this chapter, a number of discussions on model uncertainty which were concerned in this study are raised.

6.1. Runoff generation at the Can Le catchment

Before discussing the performance of each model approach, one needs to analyse which are the main runoff sources at the Can Le catchment.

As described by Dunne (1978) there are a number of factors which influence the runoff of a catchment. They are, for example, soil, topography, drainage density, climate and land cover of the catchment. These factors vary from catchment to catchment and the Can Le catchment has its own distinguished characteristics. Since they are described in previous section (chapter 3), here only three main aspects are emphasised with regard to runoff generation.

- Clay is the dominant soil in area (figure 3.7) besides a few clay loam areas which is mostly found along the river network. These types of soil have low permeability that causes the overland flow easily occurs.

- The shape of catchment as well as the circular drainage network of the catchment is the factors influencing the travel time of water within the catchment. This phenomenon is observed at the outlet given the high variation of the hydrograph shortly after an event. In another words, the catchment is quite sensitive with a given storm.
The Can Le catchment locates in the humid monsoon climate zone. Rainfall density distribution in time and space is very distinguished. Usually the rainfall occurs in a short time period but at a very high intensity (for example the first storm has about 50mm of rainfall in one hour). As explained by Whipkey and Kirby (1978, p.132) the infiltration-excess overland flow then becomes dominant when this type of rainfall occurs. A sample picture on the overland flow is shown in figure 6.1

Therefore, it can be qualitatively concluded that the infiltration – excess overland flow is the main runoff source in the study area. This fact will be considered when evaluating the performance of each model approach.

6.2. Model performance

The GIUH model performed very well, especially the peak was not difficult to capture after calibration. Due to the fact that the dominant runoff sources in the catchment were incorporated into the model. However, the time to peak is under predicted. The main explanation could be the location of the outlet which was not at the end of the highest order stream. Nevertheless, with respect to the performance criteria, the result of the GIUH is very promising. The Nash_Sutcliffe efficiency was calculated and is 0.94 (event 1) and 0.86 (event 2), and the $R^2$ is 0.95 and $d$ is 0.98 for the first event, and $R^2$ was 0.87 and $d$ was 0.96 for the second event, respectively (figure 6.2, 6.3).

As already discussed in chapter 5, in this study the HEC-HMS SMA can only simulate the high peak flow due to model calibration with the aim of matching the high peak flows. The main contributions from the overland flow based on infiltration excess mechanism were completely transformed to runoff as similar to the GIUH. However, the linear reservoir approach is not an approximate solution to capture the base flow variation.

However, the model performance improved after calibration The NSE calculated is 0.76 (after calibration); also the $R^2$ and $d$ improved after calibration (figure 6.4 and figure 6.5). From the results it can be seen that, HEC-HMS SMA performed quite acceptable in continuous mode.
Given a number of reasons explained in section 5.4.3, the performance of the REW model was not high in this study. The main reason identified is due to the fact that the flow simulation between C-zone and O-zone was inactive in this model while the contribution of infiltration excess overland flow was determined as the most dominant runoff source at the Can Le catchment. This limitation is partly solved by forcing calibration on the P-zone. However, the model still hardly predicted the high peak flow as can be seen in figure 6.6. Time constrains and limited data also contribute to the result.

Nonetheless, the performance criteria was calculated and given: the NSE is 0.27, $R^2$ is 0.33, the agreement is slightly better (d=0.53) that are encouraging.

### 6.3. Model comparison

Model comparison is one of the main objectives of this study. The 3 models are different with respect to each other. In this study an intercomparision among these models is made based on several criteria. As summarised in table 6.1, a discussion on each characteristic is as following:

The model structure or designed model concept is the most important aspect of any model approaches. The structure of the GIUH, HEC-HMS SMA, and REW vary from simple to more complexes. They differ not only from model algorithms but also from their ability to capture certain aspects of the catchment hydrology.

- The GIUH only takes into account the surface runoff of the catchment and routes it through the channel network. The rainfall contributes to this model is effective rainfall within the catchment is calculated based on another method (in this study the SCS method is applied). In order to evaluate the model performance, stream flow analysis has to be taken so that the contribution of base/inter flow is eliminated. Because the GIUH is generated from the...
effective rainfall, the GIUH is limited at event scale simulation. The GIUH is simple and objective approach that purely adapts the characteristics of the catchment using Horton’s ratio. However, it depends on other methods which are highly subjective (e.g.: SCS CN method and stream flow analysis\textsuperscript{23}).

- The HEC-HMS SMA model describes the system as a number of interconnected storage layers. Five zones of a profile seem adequately to present the behaviour of the real world as discussed in section 2.1. The simplification of systems based on reservoir mechanisms in this model is a typical characteristic of a conceptual model, by which the model algorithms require relatively low computation time due to uncomplicated interactions. However, similar to the GIUH, the linear assumptions on the base flow may not be able to predict the contribution of the groundwater system adequately.

- The novel REW approach is the most complex one used in this study. Catchment processes are captured in this model in a physical sense. Six zones of the system are linked together and the flux exchanges among them are quantified by a number of mass and momentum balance equations and some particular techniques. Unfortunately, in the version used, the link between the C-zone and O-zone was set inactive which may cause the obtained result. So far, this approach is very encouraged in literature (eg. Beven, 2001; Beven, 2002) although the need of improving model parameterization scheme as referred as “closure problem” is concerned (see Lee et al., 2005; Reggiani and Rientjes, 2005; Reggiani and Schellekens, 2003).

Data requirement and model parameterization is a second topic to be discussed in model comparison. It is obvious that a more complicated the model has higher data requirement, for example it is shown in figure 6.7. The three models have some common input data like rainfall, DEM but also specific data is required for each model approach. Model parameterization techniques for each model approach also differ from each other.

- For the GIUH, out of the DEM data, approximate land use and soil information is needed in order to estimate the effective rainfall. Proper DEM processing is a crucial step for the GIUH model parameterization while stream flow and hillslope flow can be estimated or obtained from literature.

- In the HEC-HMS SMA model, information on soils is a prerequisite so that the model is able to capture the subsurface processes. Other relevant data such as land use, stream flows etc. are also important. Additional monthly evaporation can be utilised in this model approach. To complete model parameterization, GIS processing based on aggregation techniques, and

\textsuperscript{23} More explanations presented in section “model uncertainty”, section 6.5.2
stream flow analysis is required. Although 12 model parameters need to quantify, the model is relaxed by applying these in a lumped manner;

- Assigning of parameters is difficult when applying the REW model. More than 30 parameters are needed to run the model and in addition, other meteorological data such as temperature, potential evaporation, air humidity, daily maximum temperature difference are particularly used data as compared with the previous two models. Adapting model parameters from other applications and calibration is a solution for model parameterization when implementing the REW model.

Calibration requirements and implementation for each model approach is a following topic of discussion. As showing result from chapter 5, all three models require calibration to come up with an improved result. Manual calibration based on Trial and Error was executed for the three models. Only the offered automatic calibration procedure in HEC-HMS SMA was used as automatic calibration in this study.

Last but not least, the performances of each model are compared.

- The GIUH was successfully applied in event mode with very good agreement between predicted and observed flow (section 6.1) in both calibration and validation scheme.

- The HEC-HMS SMA used in continuous simulation also produces good prediction for a period of 2 months. Due to data limitation, model validation could not be carried out.

- Incomplete model implementation, time constrains and large number of parameters needed to be quantified in applying the REW model caused the model performs not well in this study. Lack of experience of the author in working with a complicated model approach also contributed to it. However, the results are encouraging.

### Table 6.1: Main characteristics of the selected models for this study

<table>
<thead>
<tr>
<th>ID</th>
<th>Characteristics</th>
<th>REW</th>
<th>SMA</th>
<th>GIUH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Structure</td>
<td>6 zones</td>
<td>5 zones</td>
<td>2 zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Saturated zone</td>
<td>- Canopy,</td>
<td>- Hillslope</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Unsaturated zone</td>
<td>- Surface,</td>
<td>- Channel reach</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Channel reach</td>
<td>- Soil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Concentrated overland flow zone</td>
<td>- Groundwater 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Saturated overland flow</td>
<td>- Groundwater 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Perched flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temporal scale</td>
<td>- Event;</td>
<td>- Event;</td>
<td>- Event.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Continuous.</td>
<td>- Continuous.</td>
<td></td>
</tr>
</tbody>
</table>

24 Inactive in this version (REW 8.0)
### Climate data requirements

- Hourly rainfall;
- Temperature;
- Potential evaporation;
- Air humidity;
- Daily maximum temperature difference.

### Others data requirement

- Land use
- Soil
- DEM;
- Stream flow characteristics;

### Model parameterisations

- Estimate
- Calibrate
- GIS aggregation;
- Stream flow analysis.

### Calibration requirement

- Yes
- Yes
- Yes

### Calibration implementation

- Manually;
- Manually;
- Automatically.

<table>
<thead>
<tr>
<th>ID</th>
<th>Characteristics</th>
<th>REW</th>
<th>SMA</th>
<th>GIUH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Climate data requirements</td>
<td>Hourly rainfall;</td>
<td>Hourly rainfall;</td>
<td>Hourly rainfall;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature;</td>
<td>Monthly evaporation;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential evaporation;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air humidity;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daily maximum temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>difference.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others data requirement</td>
<td>Land use(^{25})</td>
<td>Land use;</td>
<td>Land use;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soil (^{26})</td>
<td>Soil;</td>
<td>Soil;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DEM;</td>
<td>DEM;</td>
<td>DEM;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stream flow characteristics;</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>velocity.</td>
</tr>
<tr>
<td></td>
<td>Model parameterisations</td>
<td>Estimate</td>
<td>GIS aggregation;</td>
<td>DEM processing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calibrate</td>
<td>Stream flow analysis.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calibration requirement</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Calibration implementation</td>
<td>Manually;</td>
<td>Manually;</td>
<td>Manually;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Automatically.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Model performance</td>
<td>Low</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.27</td>
<td>0.76</td>
<td>0.94 (event 1) and 0.86 (event 2)</td>
</tr>
<tr>
<td></td>
<td>R(^2)</td>
<td>0.33</td>
<td>0.79</td>
<td>0.95 (event 1) and 0.86 (event 2)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>0.53</td>
<td>0.94</td>
<td>0.98 (event 1) and 0.96 (event 2)</td>
</tr>
</tbody>
</table>

### Recommended model

Resulting from the previous section, this tries to recommend which model approach is appropriate to introduce in the study area and (possibly) to the upper stream region\(^{27}\) of the Sai Gon river basin.

To start this part, I would like to quote a few sentences given by Refsgaard et al (1996): “if the sole objective is to model the rainfall – runoff process and predict discharges at the outlet of a catchment, then the simpler model (than distributed model) are adequate, example from (Refsgaard and Knudsen, 1996), where the lumped conceptual code (NAM), semi-distributed conceptual/physically-based model (WATBAL) are just good as more complex model such as MIKE-SHE”

\(^{25}\) Not yet applied in this study

\(^{26}\) Not yet applied in this study

\(^{27}\) Upper parts of Dau Tieng Dam
Based on the ranking scheme was introduced in section 4.5. The results are shown in table 6.2. It must be realised that the ranking doesn’t take into account specific objectives except the performance in this study. It is in general form. Therefore, one can modify this ranking system by giving weigh ratio for each of criteria so that hopefully the recommended model can meet the predefined objective of any project. A number of remarks are drawn with respect to the “recommended model” as following:

- Objectively, from table 6.2, it can be concluded the HEC-HMS SMA is the most preferable. This model responds to all the given criteria. The only disadvantage is that the model simulates the system in a too simplified form with the aim to capture the discharge of a catchment. This issue easily leads to a misunderstanding of the internal behaviour of the system. Therefore, generally if the aim of a defined project is only to know the final discharge of a catchment in continuous mode, this model is highly recommended;

- The REW model although has lower rank as compared to the HEC-HMS SMA, it has some strong elements. To be able to simulate dominant processes of the system in a physical sense is the most appealing characteristics of the REW model. It can serve as a research tool in order to investigate the interactions within catchment. However, the REW is still in developing phase, not all the algorithms are incorporated into the model. This may be the main reason which caused the performance was not high in this study;

- Although GIUH has the best performance in this study, it gets the same rank as the REW. It is clearly because the GIUH only pay attention to the routing procedures which involve the hillslope and river network. However, the result of applying GIUH in this study for 2 events has confirmed the potential of using this model for extreme flow prediction. Using very limited data makes this model very useful for ungauged catchment with the aim at event prediction.

From the above discussions, the following conclusions are drawn:

- To predict the discharge of the Can Le catchment in event mode, the GIUH is recommended;

- To predict the discharge of the Can Le catchment in continuous mode, the HEC-HMS SMA is recommended;

- To understand different processes within the Can Le catchment, the REW is preferred since all the REW algorithms are incorporated into the model.
Table 6.2: Ranking scheme for the three selected models

<table>
<thead>
<tr>
<th>Criteria</th>
<th>GIUH</th>
<th>HEC-HMS SMA</th>
<th>REW (Ver. 8.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Temporal scale</td>
<td>Flexible</td>
<td>Flexible</td>
<td>Flexible</td>
</tr>
<tr>
<td>2. Spatial scale</td>
<td>Medium</td>
<td>Flexible</td>
<td>Flexible</td>
</tr>
<tr>
<td>3. Processes modelled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event simulation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Continuous simulation</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Interception</td>
<td>yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Infiltration</td>
<td>yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>River routing</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Groundwater flow</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4. Cost</td>
<td>Unknown</td>
<td>Public Domain</td>
<td>Unknown</td>
</tr>
<tr>
<td>5. Set-up time</td>
<td>Medium</td>
<td>Fast</td>
<td>Medium</td>
</tr>
<tr>
<td>6. Expertise</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>7. Technical support</td>
<td>No need</td>
<td>US-Corp</td>
<td>Possibly from the author</td>
</tr>
<tr>
<td>8. Documentation</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>Criteria</td>
<td>GIUH</td>
<td>HEC-HMS SMA</td>
<td>REW (Ver. 8.0)</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>----------</td>
<td>-------------</td>
<td>----------------</td>
</tr>
<tr>
<td>9. Ease-of-use</td>
<td>Medium</td>
<td>Medium</td>
<td>Difficult</td>
</tr>
<tr>
<td>10. Operating system (OS)</td>
<td>Window-based</td>
<td>Window-based</td>
<td>DOS</td>
</tr>
<tr>
<td>11. Model performance</td>
<td>Very High</td>
<td>High</td>
<td>Not high</td>
</tr>
<tr>
<td>12. Advantages</td>
<td>• Low data requirement;</td>
<td>• Public domain;</td>
<td>• Almost the processes modelled in physical sense;</td>
</tr>
<tr>
<td></td>
<td>• Good performance for extreme events</td>
<td>• Compactable with HEC-GEOHMS, HEC-DSS for data preparation</td>
<td>• Meaningful in research work</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Event simulation only; Few processes modeled</td>
<td>Low applicable research tool</td>
<td>Data requirement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Data preparation</td>
</tr>
<tr>
<td>14. Additional comments</td>
<td>The GIUH calculation EXCEL spreadsheet have developed for 3rd and 4th in this study, for higher order network, a similar work should be done that seems high time consuming.</td>
<td>There are more functionalities/options available within HEC-HMS which still can be explored</td>
<td>REW is currently a research tool owned by the author. It is expected to integrate or become released software.</td>
</tr>
<tr>
<td>Total score</td>
<td>23</td>
<td>30</td>
<td>23</td>
</tr>
</tbody>
</table>
6.5. Model uncertainties

Model uncertainty is a very important topic for every hydrologic modeller. Various steps involved during modelling processes lead to a number of uncertainties that need to be quantified. As described by Melching (1995) the uncertainties sources include: (1) natural randomness, (2) data, (3) model parameters, (4) model structure. Other authors (Rosbjerg and Madsen, 2005) stated that the main uncertainty sources related to (i) errors in model forcing, (ii) use of an incomplete model structure, (iii) use of non-optimal model parameters, and (iv) error in the measurement used for model calibration. Although there is somehow a similarity between the two schemes, the following paragraph will adapt the second scheme as a frame to discuss how it relates to this study.

6.5.1. Uncertainties in input data

In chapter 4, two main input data sets which were processed in detail are rainfall and DEM. In this part, the uncertainty from these two sources is discussed.

Several input data are required for each model approach. They vary from one to another model as already listed in section 6.3. However, obviously, rainfall data is the most important data source to be considered. However, rainfall variation is so dynamic in time and space that quite a few hydrologists devoted in finding the “proper” rainfall. Review on this issue can be found in the work of Melching (1995), Singh and Woolhiser (2002) and Gupta et al (2005).

For example, Singh (1997) reported that the shape, timing and peak flow of a stream flow hydrograph is significantly influenced by spatial and temporal variability in rainfall and watershed characteristics. Dunne and Leopold (1978) reported that errors for rainfall point measurements can range from several percentage points to 30 percent. The results from rainfall analysis in chapter 5 are acceptable with regards to the range. However, one can not deny the uncertainty in the rainfall interpolation method proposed in this thesis. The uncertainties could come from different sources, for example:

- The assumption of the uniformly distribution of rainfall made is not valid for several events;
- Linear correlation between DN value and rainfall intensity may not be reliable;
- Unreliability of the tipping bucket itself due to human interaction.\(^{28}\)

Although there are still many issues related to uncertainties in rainfall input data, they seem out of the scope of this thesis. To conclude this part, it is highly recommended that before trying to operate the model, the modeller must analyse the reliability of the available rainfall data.

Another source of data input uncertainty is the DEM. Much research has been devoted assessing the accuracy of the DEM and quantify its effects for hydrologic or flood modelling. For example, based on the TOPMODEL approach Kenward et al (2000) showed the effect of different DEM solution and sources on the total annual discharge which range from 0.3 to 7%. Haile and Rientjes (2005) also showed the uncertainty of using different DEM resolution based on flooding model approach. In this study, the used DEM is based on the SRTM data a combined with topographic maps. The final 30 m pixel resolution was used as the base for all the model approaches. For the GIUH and HEC-HMS

\(^{28}\) The tipping bucket placed inside a compound. It is sometime uncontrolled.
6.5.2. Uncertainty in model structure

Model-structure uncertainty comes from the inability to truly represent the physical characteristics of the catchment in model simulation (Melching, 1995, p.84). Therefore in this section, the aim is to point out for each selected model approach which processes were neglected and whether these uncertainties affect the final results.

For the GIUH, an event based model, only 2 processes are included although the hillslope process seems not realistic. However, the probability theory makes this issue more relaxed to apply. Other processes in the catchment were not accounted for in the model itself but through other methods like the SCS-CN, and stream flow analysis. Thus the model is having high uncertainties. Nevertheless, the model operates in event mode when the contributions of other processes in the catchment are of much less importance as compared to the two processes. Therefore, for event simulation the uncertainty in this model structure is accepted with respect to other related methods.

The HEC-HMS SMA model approach simulates the complex interactions of hydrologic processes using a linearized structure, such as a cascade of linear reservoirs (Fleming, 2002, p.35). But they do not often happen in the real world which is usually nonlinear due to the heterogeneity and dynamics of the catchment (see discussion about "the problem of nonlinearity" in Beven, 2001). Nevertheless, by averaging the system variables this approach usually gives reasonable results in predicting discharge at the outlet.

For continuous time base, simulation of evaporation and interception is required but for event based model this is less restrictive because they have a small effect on runoff volume (Rientjes, 2004, p.92). It’s a limitation in the REW model because the interception was not incorporated. However, the model was running for the rainy season so that the assumption of “small effect” could be still valid. Another issue in applying the REW ver.8.0 is that the C-zone was set inactive. This may not be considered as uncertainty in the model structure but it is clear that the process was not simulated in the model.

It is concluded that each model approach has certain uncertainties which vary in different aspects. Nonetheless, as stated above, given the specific characteristics of the Can Le catchment, the structure uncertainty of the three applied model may not to be concerned the need on completing simulation of the C-zone in the REW model.

6.5.3. Uncertainties in model parameterizations

Parameter uncertainties can not be neglected in any model development. The reason is because it is still very difficult to determine the “representative model parameters”. Numerous authors have contributed to solve the problem of the uncertainty in model parameters. For example in the GLUE method (Beven, 2000), which rejects the idea of an optimum parameter set and produce a wider range
of final output based on wider parameter sets. By doing this, people will be aware of using the results for other applications such as water abstraction, flood forecasting etc. Thus, quantifying the uncertainty in model parameterization is a very important task. However, to do this work in the scope of this thesis is impossible. The following paragraphs address where the uncertainty could come from during model parameterization. In this study, three main points were identified:

1. Estimating initial parameters;
2. Setting up initial and boundary condition;
3. Reliability of the calibrated model parameters.

To estimate the initial parameters, referring from literature is the most convenient way for an ungauged catchment. For a particular model approach, additional information such as field knowledge and GIS data based on aggregation technique is also very helpful. Uncertainty which comes from these sources is not discussed herein. Only uncertainties from the applied methods for model parameterization are analysed. In this topic, the uncertainties are made based on 3 examples for each model approaches. They are: the SCS-CN method and velocity estimation in GIUH, base flow analysis in HEC-HMS SMA (and GIUH), and geometry parameterization for channel network in REW.

- Beven (2000, p.p.207-208) summarised a number of limitations when applying SCS-CN method, for example the loose relation between the CN value and antecedent condition. In the GIUH approach in this study, the effective rainfall was calculated using the SCS CN and assumed to be valid for every storm is a major source of uncertainty.

The estimated velocity for GIUH is very important when applying this model. For example, Rodriguez-Iturbe et al (1979) proposed the peak flow velocity as the representative velocity; Rodriguez-Iturbe et al (1982) and Bhaskar et al (1997) suggested a method to estimate the velocity taking into account the rainfall intensity. In this study, the stream velocity was defined after calibration and it was much less than the peak flow velocity. It is concluded that this parameter is very much dependent on the catchment characteristics (see discussion in section 6.1). Therefore, this parameter induces a fair amount of uncertainty.

- Base flow analysis is also a common uncertainty issue. The reason is because it is extremely difficult to quantify how much water recharges to the river from different sources. Beven (2000, p.32), Dingman (2002, p.396) warned that hydrograph analysis based on graphical separation is not always accurate. In applying this method, it is the most important to be consistent for all the events. However, highly subjective behaviour in using this method can not be neglected. Although the contribution of base flow in the Can Le catchment is relatively small, other applications of using HEC HMS SMA (and GIUH) should be aware of this issue since this method is applied.

- In the REW model, the geometry of the channel network was obtained by a combination of the at-a-station\textsuperscript{29} and downstream\textsuperscript{30} hydraulic geometry (Reggiani and Rientjes, 2005).

\textsuperscript{29} At a station: at a given cross section.
\textsuperscript{30} Downstream: cross section situated along the length of a stream.
developed by Leopold and Maddock (1953). By applying the method, in this study 3 unsolved difficult issues were found:

(1) The method of Leopold and Maddock was based on the use of the mean annual discharge at each point along the stream (Leopold and Maddock, 1953, p.16). In this study, the simulation period was during in the rainy season and therefore the model parameters derived for the stream network may not be relevant;

(2) To derive model parameters based on this method, numerous measurements of discharge should be taken along the river (at least at two points, one at the head of the catchment, another at the outlet). However, these were not feasible in this study due to time constrains during the fieldwork period;

(3) Quantifying 9 parameters in the model is a difficult job. For example, as recommended by Perrin et al (2001), model calibration is effective if the calibrated parameters are about three – five (referred as over-parameterization, see Rientjes, 2004, page 102). In the REW calibration phase, quite a few Trial and Error tests were done but it did not resemble the ideal geometry which was measured at the outlet.

Initial condition and boundary condition are not often reported in rainfall – runoff modelling although they are very important. For example, we need to know which state of the system in the beginning of simulation or we want to know whether water is either transferred to or received from connected systems. The boundary condition is usually not incorporated into a rainfall - runoff model especially for the simple approaches. Fortunately, the natural catchment boundary is a no-flow by default applied all model approaches. These two aspects are discussed for the three model approaches.

- In the GIUH approach, the initial and boundary condition are completely neglected. The reason is because it is based on an empirical approach. In this approach the model outcome do not rely on updating of internal state variables (Rientjes, 2005). The GIUH is calculated based on the catchment boundary only;

- In the HEC-HMS SMA, the initial condition is established by extending the simulation period in advance (“warm-up” period) so that the flow hydrograph can be captured the beginning of the simulation period. The boundary condition applied is the same as in the GIUH;

- In the REW model approach, both initial condition and boundary condition are applied. The initial condition is determined by running the model several times until the simulated base flow is stable compared to the observed hydrograph. However, this may be not enough because the REW not only requires the base flow but also other variables (discussed in section 5.4.3). Besides the catchment boundary, a boundary condition is imposed at the outlet of the catchment.

As a result, the initial condition seems not to be an uncertainty source for the model approaches except the REW model. However, uncertainty from applied boundary condition is not well defined because its effects are not clear for a short term period of simulation.
Last but not least, the uncertainty of calibrated model parameters is the issue of the calibrated parameters. The reason is that the calibrated parameter may not be representative. Different model structures with different parameters may yield acceptable results. The problem is referred to equifinality (see Beven, 2001; Beven and Freer, 2001). However, this problem is not discussed in here because it is out of the scope. Herein, only a discussion on the applied calibration method is presented.

In this study, most of the calibration procedures were done manually by Trial and Error. This procedure actually is not a good solution. For example, Gupta et al. (2005, p.2017) stated “while the manual approach to model calibration is based on subjective judgement and expertise, a trained and experienced hydrologist can often obtain excellent results, so that the model response generates a realistic simulation of the response of the catchment. However, the process can be very time consuming, and because it involves subjective decisions by the modeller, requires considerable training and practice. Further, the knowledge and skills obtained are not easy transferred from one person to another. These limitations have led to interest in methods for model calibration that can be carried out automatically using the speed and power of a digital system”. The manual calibration is also rejected by Rientjes (2004, p.187) because “for any Trial and Error calibration it is uncertain whether the most optimum dataset is found and whether the calibration can be improved further”.

Therefore, the model performance of each model approach could be improved by calibration whether manually or automatically. Unfortunately, time constrains make this statement unproved. Therefore, this aspect needs further attention.

6.5.4. Uncertainty in discharge measurement

With respects to the discharge measurement, two possible sources should be considered: (1) Reliability of the stage-discharge curve and (2) mistakes in recording data. The first was overcome by obtaining more than required stage-discharge pair points (chapter 3). The later can be explained as follows:

The discharge was measured at the outlet of the catchment. Due to the location of the chosen outlet, the water from different tributaries was coming very fast after every event. This resulted in an aggressive flow. Flow raised and receded very quick, usually within a day. Therefore, it is very important to measure the discharge continuously (In this study, it is recorded hourly during the event or 4 times/day if no special observation). The first two events were measured directly by the author in a very careful manner (from 24/9/2005 to 15/10/2005). However, the observation was extended by asking local people trained outside to record the water level changes. A small mistake in reading out the numbers at the staff gauge or missing recording data for a few hours could cause significant errors (for example, reading 91 cm instead of 191cm the discharge already change significantly from 9.28 m$^3$/s to 24.47 m$^3$/s). Thus, the discharge data after the first two events may include uncertainties.

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$^{31}$ 6 are for the at-a-station and downstream exponents; and 3 are for downstream coefficients.
7. Conclusions and recommendations

7.1. Conclusions

The main objective is to develop a suitable rainfall – runoff model for the ungauged Can Le catchment. This study is conducted by with respect to the 3 specific objectives raised in section 1.2.1.

Data, an essential aspect of rainfall – runoff modeling, is the first focal point in this study. Various sources were explored in order to obtain the real world data. First, satellite images were used to prepare the land cover map and a DEM for the Can Le catchment during the pre-fieldwork period. Secondly, a field campaign of one and a half month was carried out at the Can Le catchment. During this period, discharge measurements, which were identified as the most important data for model calibration, were successfully obtained for a two month period. In this period, other relevant data about characteristics of the catchment were obtained. Archived data was also explored to have information on the meteorological conditions of the catchment. Moreover, in the processing phase, after analyzing that the rainfall data were not properly collected (due to the high variation as well as limited rain gauge representation), rainfall interpolation by integrating rainfall from the station and satellite images was implemented to correct it. Although a number of efforts are made in data collection, the “real world data” might not be adequately defined yet in this study.

Three different selected model approaches were tested in this study. A number of issues on these model approaches have been reviewed. Literature background on these models was presented in chapter 2, model development in chapter 4 and result, discussion on model performance, model structure, model uncertainties, etc. in chapter 5 and 6 respectively. Hereunder, a few comments on each model based on the results from this study are followed:

- The GIUH uses very limited data. Model parameterization is mostly based on DEM processing to extract the Horton’s morphometric parameters. An Excel spreadsheet developed for the 3rd stream network was used and simulated the peak flow adequately for 2 typical events.

- Model parameterization based on GIS processing and stream flow analysis was successfully applied in the HEC-HMS SMA. The model works in a lumped manner but results were very encouraging. However, model validation for long term modeling is recommended for more detail investigation;

- REW model, the most complex model approach, had difficulty in producing the runoff of the Can Le catchment since the efficiency was not high. Most likely an incomplete and too complex model structure caused that the observed hydrograph was not well simulated. Furthermore, time constrains, limited experience of the author in model calibration contributed to the final result as well.
Based on model performances and a number of criteria introduced in chapter 6, a suitable model is recommended for each of specific objectives for future application. In case of predicting the runoff of the catchment for events only, the GIUH is recommended. For continuous simulation of discharge of the catchment the conceptual HEC-HMS SMA model is preferred. For in-depth research on the internal hydrologic behavior of the catchment, the REW is the only tool provided when the model concept is fully implemented.

A complete rainfall – runoff modelling for the ungauged Can Le catchment has been done in this study. Various important steps including data acquisition either from satellite images or field measurements, model parameterization using various techniques, model development for different model approaches and model calibration were systematically carried out in this study (approximately 8 months). Although the results did not meet all expectations, this exercise has brought to the author a number of interests in the field of hydrology in general and rainfall – runoff modelling in particular.

7.2. Recommendations

Regarding the research methods and the ability to improve model results, further research can be considered as follows:

- Improve rainfall retrieval either by increasing rainfall stations in the area or by integrating satellite images and rain-gauge observation relation. Advanced techniques to integrate satellite image and rain gauge for rainfall retrieval are needed as one can refer to the work of La Barrera et al. (1995), Grimes et al. (1999);

- The GIUH was successfully adapted in Can Le 3rd order catchment. In this study, an attempt to producing an Excel spreadsheet for the 4th order drainage network was developed, by which up scaling of this approach for the Can Le 4th order catchment based on the result from this study should be considered (see Maathuis, 2006, p.58). The result is shown in appendix 4. Additionally, this model may serve for other ungauged catchments in the region which have similar characteristics as those of the Can Le catchment.

- For the HEC-HMS SMA, the whole catchment was simulated in a lumped manner. Thus, the variation of the catchment characteristics was not explicitly taken into account. Therefore, simulating the catchment at a finer lumped manner by partitioning the catchment into smaller sub-catchment is recommended;

- It is assumed that if applying a complete REW model, the efficiency will be much improved. If so, the results will essentially serve for water resources planning in the area (eg. Flood forecasting, groundwater abstraction);

- Longer time of observation for model simulation and validation is needed for the three selected models, especially for the HMS-SMA and REW;

- There are several small reservoirs in the upstream area which has not been mentioned in this thesis. This would be a reason why some parts of the hydrograph can not be predicted. Therefore, in future work, more detailed data on these reservoirs should be obtained and incorporated in the model before doing simulations;
➢ The contribution of groundwater to the flow was just simply estimated for this study area; therefore, further study is needed;

➢ There are still a number of the model uncertainties discussed in chapter 6 that requires a better understanding on the hydrological processes in the Can Le catchment;

Last but not least, a final recommendation is made for this particular Can Le catchment. Having observed the sudden water level changes at the outlet, the hourly time steps seems still a bit coarse to capture the channel behaviours. Therefore, finer time steps i.e. quarter-hourly recording for model simulation is highly recommended.
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RAINFALL-RUNOFF MODELING IN THE UNGAUGED CAN LE CATCHMENT, SAIGON RIVER BASIN

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Appendix 1: Determination of number of observations necessary for establishing a reliable stage – discharge station\(^\text{32}\)

The reliability of the mean relation is measured by the standard error of the percentage deviation, which is given by:

\[
S_E = \frac{S_D}{\sqrt{m}}
\]

Where:
- \(S_D\) is standard deviation
- \(m\) is number of observations

If the acceptable shift at a confidence level of 95% is set at \(P=5\%\) then \(2SE\) should not exceed \(P\)

But \(S_E = \frac{S_D}{\sqrt{m}}\); therefore \(S_E = \frac{2S_D}{\sqrt{m}}\) should not exceed \(P\), from which it follows that \(m\) should not be less than \(\left(\frac{2S_D}{P}\right)^2\)

Given discharge measured at the Can Le station, the \(S_D\) is 16.4, apply the acceptable shift at confident 95%, so \(P\) is taken as 5%. The minimum observation (\(m\)) is:

\[
m = \left(\frac{2S_D}{P}\right)^2 = \left(\frac{2 \times 16.4}{5}\right)^2 = 43
\]

But \(m=59\), therefore the number of stage – discharge observation is **sufficient**.

\(^{32}\) Based on materials prepared by the International Institute for Land Reclamation and Improvement (p.172-190)
# Appendix 2: Surveyed points and corresponding information during field campaign

<table>
<thead>
<tr>
<th>ID</th>
<th>Code</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Date</th>
<th>Land cover</th>
<th>Water table</th>
<th>Groundwater base</th>
<th>Local people</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P1</td>
<td>671,988.25</td>
<td>1,301,232.15</td>
<td>69.90</td>
<td>19/9/2005</td>
<td>Rice field</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Shallow water level, flooding areas, etc.</td>
</tr>
<tr>
<td>2</td>
<td>P2</td>
<td>672,325.13</td>
<td>1,303,666.77</td>
<td>74.80</td>
<td></td>
<td>Coconut-tree</td>
<td>2m</td>
<td>&gt;5m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>P3</td>
<td>673,426.63</td>
<td>1,305,357.21</td>
<td>87.40</td>
<td></td>
<td>Resident house</td>
<td>0.5m</td>
<td>4m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>P4</td>
<td>674,334.73</td>
<td>1,307,602.15</td>
<td>94.90</td>
<td></td>
<td>Fruit garden</td>
<td>4m</td>
<td>6m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P5</td>
<td>673,620.98</td>
<td>1,309,832.01</td>
<td>109.90</td>
<td></td>
<td>Rubber trees</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>P6</td>
<td>673,025.40</td>
<td>1,311,144.41</td>
<td>114.40</td>
<td></td>
<td>Streams, resident areas</td>
<td>2m</td>
<td>15m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>P7</td>
<td>672,872.67</td>
<td>1,311,886.23</td>
<td>121.70</td>
<td></td>
<td>Road</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>P8</td>
<td>673,867.14</td>
<td>1,312,494.25</td>
<td>115.40</td>
<td></td>
<td>Rung Cam lake</td>
<td>4-5m</td>
<td>15m</td>
<td>NA</td>
<td>Cam Dam forest</td>
</tr>
<tr>
<td>9</td>
<td>PA1</td>
<td>674,692.21</td>
<td>1,306,387.82</td>
<td>95.80</td>
<td>21/9/2005</td>
<td>Resident house</td>
<td>1-2m</td>
<td>3m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>PA2</td>
<td>674,847.75</td>
<td>1,306,201.57</td>
<td>88.40</td>
<td></td>
<td>Loc Dien Bridge</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>PA3</td>
<td>675,020.14</td>
<td>1,306,185.02</td>
<td>101.00</td>
<td></td>
<td>Bamboo</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>PA4</td>
<td>675,460.39</td>
<td>1,306,082.29</td>
<td>92.40</td>
<td></td>
<td>Resident house</td>
<td>12m</td>
<td>15m</td>
<td>NA</td>
<td>No well water in dry season</td>
</tr>
<tr>
<td>13</td>
<td>PA5</td>
<td>676,202.39</td>
<td>1,306,197.67</td>
<td>110.00</td>
<td></td>
<td>Rubber trees</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>PA6</td>
<td>677,016.80</td>
<td>1,306,120.51</td>
<td>83.50</td>
<td></td>
<td>Resident house</td>
<td>1.5m</td>
<td>5m</td>
<td>NA</td>
<td>0.5m water in dry season</td>
</tr>
<tr>
<td>15</td>
<td>PA7</td>
<td>677,141.81</td>
<td>1,306,080.30</td>
<td>78.10</td>
<td></td>
<td>Loc Dien Bridge II (house near by)</td>
<td>2m</td>
<td>5m</td>
<td>NA</td>
<td>Water supply from stream</td>
</tr>
<tr>
<td>16</td>
<td>PA8</td>
<td>677,117.08</td>
<td>1,305,220.49</td>
<td>82.70</td>
<td></td>
<td>Small Dam (house near by)</td>
<td>1m</td>
<td>&gt;5m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>PA9</td>
<td>677,192.59</td>
<td>1,305,519.18</td>
<td>83.00</td>
<td></td>
<td>Resident house</td>
<td>4m</td>
<td>10m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>PA10</td>
<td>677,207.82</td>
<td>1,303,916.90</td>
<td>66.90</td>
<td></td>
<td>Soc Lon Bridge (house near by)</td>
<td>3m</td>
<td>5-7m</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>PA11</td>
<td>677,049.30</td>
<td>1,303,588.49</td>
<td>75.80</td>
<td></td>
<td>Rice field, other agriculture activities</td>
<td></td>
<td></td>
<td>NA</td>
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</tr>
<tr>
<td>20</td>
<td>PA12</td>
<td>676,240.92</td>
<td>1,302,607.21</td>
<td>74.30</td>
<td></td>
<td>Field and bare soil, rocky road</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>PA13</td>
<td>676,118.16</td>
<td>1,302,255.62</td>
<td>71.90</td>
<td></td>
<td>Resident house</td>
<td>3m</td>
<td>30m</td>
<td>NA</td>
<td>No pictures taken</td>
</tr>
<tr>
<td>22</td>
<td>PA14</td>
<td>675,627.40</td>
<td>1,301,831.75</td>
<td>71.50</td>
<td></td>
<td>Agriculture activities</td>
<td></td>
<td></td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Code</td>
<td>X</td>
<td>Y</td>
<td>Rainfall</td>
<td>Runoff</td>
<td>Land Use</td>
<td>Depth</td>
<td>Interceptor</td>
<td>Owner</td>
<td></td>
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<td>-----</td>
<td>------</td>
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<td>----------</td>
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<td>-------</td>
<td>-------------</td>
<td>-------</td>
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</tr>
<tr>
<td>23</td>
<td>PA15</td>
<td>672,572.05</td>
<td>1,297,802.71</td>
<td>56.50</td>
<td>Loc Khanh stream</td>
<td>1.5m</td>
<td>20-30m</td>
<td>Mr. Vu Xuan Thang</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>PB1</td>
<td>672,934.72</td>
<td>1,297,775.51</td>
<td>57.40</td>
<td>Cashew</td>
<td>4m</td>
<td>&gt;11m</td>
<td>Mr. Thanh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>PB2</td>
<td>673,672.21</td>
<td>1,297,674.41</td>
<td>50.80</td>
<td>Bare soil, agriculture activities</td>
<td>0.5m</td>
<td>6m</td>
<td>Mr. Dao</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>PB3</td>
<td>673,826.75</td>
<td>1,297,669.43</td>
<td>63.20</td>
<td>Small stream, shallow water level</td>
<td>1m</td>
<td>&gt;10m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>PB4</td>
<td>674,593.03</td>
<td>1,297,732.26</td>
<td>69.50</td>
<td>Cashew garden</td>
<td>8m</td>
<td>&gt;12m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>PB5</td>
<td>674,901.85</td>
<td>1,297,769.10</td>
<td>69.60</td>
<td>Bare soil</td>
<td>0.5m</td>
<td>6m</td>
<td>Mr. Dao</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>PB6</td>
<td>676,154.40</td>
<td>1,298,016.03</td>
<td>56.60</td>
<td>Cashew, bare soil</td>
<td>1m</td>
<td>&gt;7m</td>
<td></td>
<td></td>
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<tr>
<td>30</td>
<td>PB7</td>
<td>677,181.55</td>
<td>1,297,185.68</td>
<td>70.70</td>
<td>Ba Nung stream</td>
<td>1m</td>
<td>&gt;10m</td>
<td>Mr. Nguyen Van Hong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>PB8</td>
<td>678,577.31</td>
<td>1,297,328.27</td>
<td>75.90</td>
<td>Eucalyptus, bare soil, rubber</td>
<td>8m</td>
<td>9m</td>
<td>Mr. Chuong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>PB9</td>
<td>678,125.60</td>
<td>1,297,337.34</td>
<td>70.20</td>
<td>Resident house</td>
<td>8m</td>
<td>9m</td>
<td>Mr. Chuong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>PB*</td>
<td>673,660.29</td>
<td>1,295,574.93</td>
<td>72.60</td>
<td>Small Lake</td>
<td>1-3m</td>
<td>&gt;11m</td>
<td>Swamp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>PC1</td>
<td>674,390.93</td>
<td>1,295,643.39</td>
<td>64.70</td>
<td>Resident house, agriculture (rice, pepper, Eucalyptus)</td>
<td>1.5m</td>
<td>5m</td>
<td>Top of the hill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>PC2</td>
<td>674,872.49</td>
<td>1,295,616.89</td>
<td>82.90</td>
<td>Lai stream (house near by)</td>
<td>2m</td>
<td>&gt;7m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>PC3</td>
<td>675,305.38</td>
<td>1,295,788.95</td>
<td>89.60</td>
<td>Cashew garden</td>
<td>8m</td>
<td>&gt;12m</td>
<td>Mr. Duong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>PC4</td>
<td>675,592.59</td>
<td>1,295,451.39</td>
<td>92.70</td>
<td>Cashew garden</td>
<td>1m</td>
<td>2m</td>
<td>Mr. Duong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>PC5</td>
<td>675,540.50</td>
<td>1,295,205.48</td>
<td>87.20</td>
<td>Pepper, cashew garden</td>
<td>1.5m</td>
<td>15m</td>
<td>Mr. Duong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>PC6</td>
<td>675,717.69</td>
<td>1,294,358.54</td>
<td>77.90</td>
<td>Resident house</td>
<td>8m</td>
<td>13m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>PC7</td>
<td>676,225.60</td>
<td>1,292,846.82</td>
<td>77.50</td>
<td>Lake, rice</td>
<td>1.5m</td>
<td>&gt;11m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>PC8</td>
<td>675,723.26</td>
<td>1,293,381.96</td>
<td>90.70</td>
<td>Rail bridge (house near by)</td>
<td>5m</td>
<td>12m</td>
<td>Bottom of the hill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>PC9</td>
<td>674,907.45</td>
<td>1,292,599.54</td>
<td>100.00</td>
<td>Resident house</td>
<td>2m</td>
<td>5m</td>
<td>Mr. Doan Van Ty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>PC10</td>
<td>673,772.48</td>
<td>1,293,598.97</td>
<td>91.60</td>
<td>Road</td>
<td>12m</td>
<td>&gt;17m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>PC11</td>
<td>671,519.57</td>
<td>1,298,972.24</td>
<td>58.60</td>
<td>Rubber</td>
<td>1.5m</td>
<td>5m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>PD1</td>
<td>676,213.80</td>
<td>1,302,156.76</td>
<td>71.50</td>
<td>Resident house</td>
<td>2m</td>
<td>5.5m</td>
<td>Mr. Nguyen Van Dong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>PD2</td>
<td>676,714.44</td>
<td>1,301,896.48</td>
<td>64.00</td>
<td>Resident house</td>
<td>4m</td>
<td>9m</td>
<td>Mr. Pham Van Sang</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>PD3</td>
<td>677,228.88</td>
<td>1,301,308.81</td>
<td>72.40</td>
<td>Paven bridge (house near by)</td>
<td>1m</td>
<td>10m-12m</td>
<td>Mr. Tran Dinh Long</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>PD4</td>
<td>677,985.59</td>
<td>1,301,979.87</td>
<td>71.60</td>
<td>Rice field, small trees</td>
<td>1.5m</td>
<td>&gt;11m</td>
<td>See rock of the river bed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>PD5</td>
<td>678,112.37</td>
<td>1,302,638.98</td>
<td>71.70</td>
<td>Rice field</td>
<td>1.5m</td>
<td>&gt;11m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>PD6</td>
<td>678,158.50</td>
<td>1,302,899.01</td>
<td>69.10</td>
<td>Resident house (agriculture activities)</td>
<td>0.2m</td>
<td>4m</td>
<td>Mrs. Tui (ethnic minority) in middle of a hill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>PD7</td>
<td>679,554.99</td>
<td>1,300,854.51</td>
<td>79.50</td>
<td>12 houses zone</td>
<td>1m</td>
<td>7m</td>
<td>Mr. Tran Van Liem in the bottom of a valley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>PD8</td>
<td>679,884.49</td>
<td>1,300,400.28</td>
<td>67.90</td>
<td>Resident house</td>
<td>1m</td>
<td>7m</td>
<td>Mr. Pham Van Huyen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>PD9</td>
<td>672,615.18</td>
<td>1,300,404.08</td>
<td>50.20</td>
<td>Small stream, shallow water level</td>
<td>1m</td>
<td>&gt;11m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 3: Detailed expression of the probability functions applied in the GIUH approach

1. The initial state probability $\theta_j$

$$\theta_j = \frac{N_i \cdot A_i}{A_\Omega}$$

$$\theta_{\omega} = \frac{N_i}{A_\Omega} \left[ \hat{A}_\omega - \sum_{j=1}^{\omega-1} \hat{A}_j \left( \frac{N_j P_{j\omega}}{N_\omega} \right) \right]$$

2. The transition probabilities $p_{ij}$

The transition probabilities can be approximated as a function of the number of Strahler streams of each order $N_i$: 

$$p_{ij} = \frac{(N_j - 2N_{i+1})E(j, \Omega)}{\sum_{k=i+1}^{\Omega} E(k, \Omega)N_i} + 2 \frac{N_{i+1}}{N_i} \delta_{i+1,j} \quad 1 \leq i \leq j \leq \Omega$$

$\delta_{i+1,j} = 1$ if $j=i+1$ and 0 otherwise. $E(j, \Omega)$ denotes the mean number of interior links of order $i$ in a finite network of order $\Omega$.

$$E(j, \Omega) = N_i \prod_{j=2}^{i} \left( \frac{N_{j-1} - 1}{2N_{j-1}} \right), \quad i=2, \ldots, \Omega$$

An interior link is a segment of channel network between two successive junctions or between the outlet and the first junction upstreams.

For a $3^{rd}$ order catchment the initial and transition probability can be expressed as:

$$\theta_1 = \frac{R_B^2}{R_A}$$

$$\theta_2 = \frac{R_B}{R_A} \frac{R_B^3 + 2R_B^2 - 2R_B}{R_A^2 (2R_B - 1)}$$

$$\theta_3 = 1 - \frac{R_B}{R_A} \frac{R_B^3 - 3R_B^2 + 2R_B}{R_A^2 (2R_B - 1)}$$
\[ p_{12} = \frac{R_B^2 + 2R_B^2 - 2}{2R_B^2 - R_B} \]
\[ p_{13} = \frac{R_B^3 - 3R_B + 2}{2R_B^2 - R_B} \]
\[ P_{23} = 1 \]

For a 4\textsuperscript{th} order catchment the initial and transition probability and the possible paths can be expressed as:

\[ \theta_1 = \frac{R_B^3}{R_A^3} \]
\[ \theta_2 = \frac{R_B^2}{R_A^2} \left( 1 - \frac{R_B}{R_A} \left( \frac{2}{R_B} + \frac{(2R_B - 1)(R_B^2 - 2R_B)}{R_B(2R_B - 1) + R_B(R_B^2 - 1) + (R_B^2 - 1)(R_B - 1)} \right) \right) = \frac{R_B^2}{R_A^2} \left( 1 - \frac{R_B}{R_A} \times p_{12} \right) \]
\[ \theta_3 = \frac{R_B}{R_A} \left( 1 - \frac{R_B^2}{R_A^2} \times p_{13} - \frac{R_B}{R_A} \times p_{23} \right) \]
\[ \theta_4 = 1 - \left( \frac{R_B}{R_A} \right)^3 \times p_{14} - \left( \frac{R_B}{R_A} \right)^2 \times p_{24} - \left( \frac{R_B}{R_A} \right) \times p_{34} \]
\[ p_{12} = \frac{2}{R_B} + \frac{(2R_B - 1)(R_B^2 - 2R_B)}{R_B(2R_B - 1) + R_B(R_B^2 - 1) + (R_B^2 - 1)(R_B - 1)} \]
\[ p_{13} = \frac{(R_B - 1)(R_B - 2)}{R_B(2R_B - 1) + R_B(R_B^2 - 1) + (R_B^2 - 1)(R_B - 1)} \]
\[ p_{14} = \frac{(R_B - 1)(R_B - 2)}{R_B(2R_B - 1) + R_B^2(R_B^2 - 1) + R_B(R_B^2 - 1)(R_B - 1)} \]
\[ p_{23} = \frac{R_B - 2}{2R_B - 1} \]
\[ p_{24} = \frac{R_B - 1}{R_B(2R_B - 1)} \times (R_B - 2) \]
\[ P_{34} = 1 \]

And the possible paths \( S_i \) of water for the 4\textsuperscript{th} order catchment are:

- Path \( S_1 \): a1 -> r1 -> r2 -> r3 -> r4 -> outlet;
- Path \( S_2 \): a3 -> r1 -> r3 -> r4 -> outlet;
- Path \( S_3 \): a1 -> r1-> r4 -> outlet;
- Path \( S_4 \): a2 -> r2 -> r3 -> r4 -> outlet;
- Path \( S_5 \): a2 -> r2 -> r4 -> outlet;
- Path \( S_6 \): a3 -> r3 -> r4 -> outlet;
- Path \( S_7 \): a4 -> r4 -> outlet.
3. Convolution of nonidentical exponential probability density function of a given path $S_i$ can be obtained as:

$$f_{S_i} = f_{T_1}(t) \times f_{T_2}(t) \times f_{T_3}(t) \times \ldots \times f_{T_\Omega}(t) = \sum_{j=1}^{\Omega} \frac{\lambda_i \ldots \lambda_{j-1} \exp(-\lambda_j t)}{[(\lambda_j - \lambda_j) \ldots (\lambda_{j-1} - \lambda_j) \ldots (\lambda_{j+1} - \lambda_j) \ldots (\lambda_\Omega - \lambda_j)\ldots]}$$

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33 See Bras (1990, p.616)
Appendix 4: Surface discharge derivation for the Can Le 4th order catchment based on GIUH approach

It was difficult to obtain discharge at the outlet of the 4th order catchment due to the outlet of the 4th order catchment located inside the forest. An attempt to determine the discharge at this location based on model parameter derived at the 3rd catchment. Figure A1 shows the extracted catchment and drainage and the red dots represent the locations of the 3rd outlet, 4th outlet and discharge measurement in between.

![Discharge measurement](image)

Figure A1: 3rd order and 4th order catchment areas and drainage extracted from SRTM (after Maathuis, 2006, p.56)

To be able to up scale the result from 3th order catchment to 4th order catchment. It is assumed that there is a geometrical similarity of the Horton’s ratios between 3rd catchment and 4th catchment. This similarity can be examined through the Horton plot. Figure A2 shows the Horton plot and the 3rd order is presented in dash line and 4th order in solid line.
However, in this case, from the above figure presented is can be noted that the catchments are not having a similar morphological structure and therefore the peak flow observations conducted at the outlet of the 3rd order stream network has to be used with caution for up scaling to obtain an idea of the peak discharge of the 4th order stream network for the observed rainfall event.

Keeping the same model parameters (hillslope and stream velocity) applied for the 3rd order and used for 4th order catchment. The surface discharge at the outlet of the catchment can be obtained as shown in figure A3.

Figure A2: Horton Plot of the Stream Network Extracted (Maathuis, 2006, p.57)

Figure A3: Discharge derivation for 3rd and 4th order catchment