UTILIZATION OF SRTM DATA FOR FLOOD PROTECTION BASED ON GIUH APPROACH

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ABSTRACT

In this paper, a utilization of the Shuttle Radar Topographic Mission (SRTM) data in flood prediction in an ungauged Canle catchment is presented. The SRTM data was obtained and processed in order to create a suitable Digital Elevation Model (DEM). A lumped empirical model, the Geomorphologic Instantaneous Unit Hydrograph (GIUH) rainfall – runoff model, is developed for flood prediction. Model parameters are mainly Horton's morphometric parameters including bifurcation, length and area ratios. A new functionality within the ILWIS GIS-RS package, namely "DEM-hydro processing", is applied to effectively process the DEM and extract these ratios. Results showed that with limited data (e.g from SRTM), the model was successfully applied for the Can Le catchment.

Keywords: Can Le catchment, GIUH, SRTM, DEM, Flood Prediction

1. INTRODUCTION

"Water is essential for life". We are all aware of its necessity, for drinking, for providing food, for washing, etc. 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 society. In addition, "Water is essential for the integrity and sustainability of the Earth's system" (The United Nations - World water development report, 2003). Demand and competition for water resources continue to grow almost everywhere for activities such as agriculture, industry, energy supply, etc. Integrated Water Resources Management[1](IWRM) was introduced as a concept to optimise water resources management and applications are found in publications, such as Global Water Partnership (2005) and Zaag (2005).

Singh (1995) stated that 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 resourcesmanagement linking hydrological functioning and socio-economic behaviour". Therefore, fundamental to integrated water management is catchment modelling. Catchment models are in general designed to meet two primary objectives.

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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.

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, licensing of abstraction or for forecasting. Given catchment heterogeneity, (highly) dynamic and non-linear hydrologic behaviour, it is not easy to quantify the runoff of a system adequately. Appropriate modelling requires a certain level of understanding of its physical characteristics.

Topography plays a very important role in representing a number of characteristics of the catchment (Moore et al., 1992). Topographic maps or field surveys can be used to obtain morphometry information of the catchment such as drainage network, channel/overland flow lenght, and slope that are critical in runoff generation. However, this work is very time consuming and tedious. The Digital Elevation Model (DEM), which can represent surface landscape, has been used in the last few decades. The developments of computer sciences in general and in Geographic Information System (GIS) have made DEM data widely utilizied due to its advantages over maps. Nowaday, DEM data is crucial for any catchment study project.

Although DEM is a critical data source, acquiring a suitable DEM for certain area is not always an easy case. DEM generated from topological map is fairly enough (usually) at large (meso) catchment scale. However, as reported by Maathuis and Sijmons (2005) inadequacy and inaccuracy of these sources are still popular especially in developing countries. Other DEM sources e.g. Synthetic Aperture radar, airbone laser scanning – LIDAR that are quite good quality is still costly to use. The Shuttle Radar Topographic Mission (SRTM) (Rabus et al., 2003) obtained elevation data on the near-global scale to generate the most complete high-resolution digital topographic database of the Earth. The SRTM DEMs released for the United States at 30 meter resolutions and for other countries at 90 meters are essential. Data homogeneity and no-cost availability (possibly) is the most attractive to utilize SRTM data.

In this paper, a procedure of utilizing SRTM data to create a suitable DEM is presented. It is followed by applying a lumped empirical model, the Geomorphologic Instantaneous Unit Hydrograph (GIUH) rainfall – runoff model, which have important parameters extracted from the DEM, developed for flood prediction. Results showed the presenting approach is applicable for limited data area areas.

2. RESEARCH METHODS

2.1. DEM OPTIMIZATION

The development of DEM processing algorithms as well as relevant software tools to extract hydrologic information from DEM is increasing and is currently widely applied. For example, Tarboton et al (1991) introduced criteria to properly extract a drainage network, Moore et al (1992) reviewed many applications of DEM for 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 (Hengl et al., 2006; Maathuis, 2006; Maathuis and Wang, 2006), Tardem (Tarboton, 1997), Rivertools (RIVIX LLC, 2004) etc. to extract hydrologic parameters or physical characteristics of a catchment and can serve for model simulation.

In this study, DEM processing was done by using Open-source ILWIS RS-GIS package (the Intergrated Land and Water Information System (ILWIS) (ITC, 2001), given a newly-developed routing procedure namely “DEM hydro-processing”. First of all, The DEM was optimised through integration of the existing digitised drainage networks to obtain a final DEM. Consequently, this optimized DEM was processed through several steps such as fill sink, calculate flow direction, flow accumulation to extract the Can Le catchment as well as the topological drainage network. During the whole process, a number of decisions have to be taken so that the extracted information is representative, e.g. defines width, depth of the existing drainage networks when integrate it into the DEM (based on AGREE method (Hellweger, 1997)), selects the multiple variable thresholds for drainage line initialization as described in Maathuis and Wang (2006). Finally, the optimized DEM is used to calculate the Horton’s statistic number which are later used within the GIUH model. The final optimized DEM is shown in figure 1.

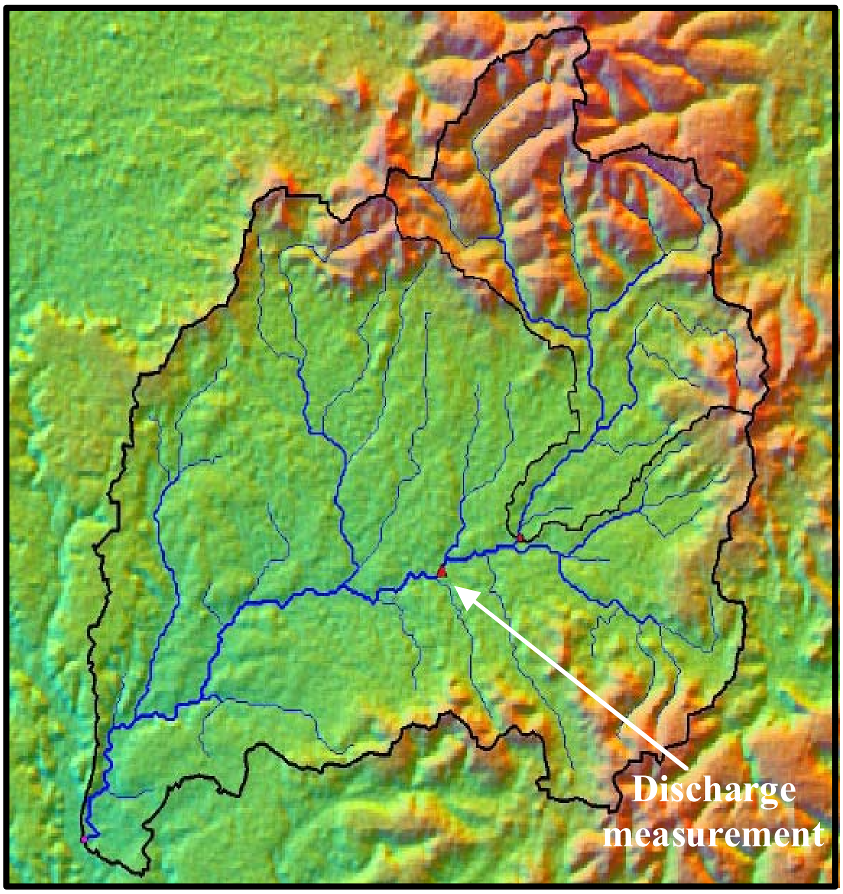

Figure 1 – 3rd and 4th order catchments and drainage extracted from SRTM (discharge station is 3 km below from the beginning of 3rd order river)

2.2. GIUH model

GIUH is an empirical event based model approach that combines easily observable (surface) geomorphologic catchment characteristics with simple regression analysis. The approach is particularly applicable in data scarce areas and model parameterization relies on GIS based DEM processing. Coupling of quantitative geomorphology and hydrology which is at the core of this approach is not a new concept, however, with the advent of new RS systems that operate at high resolutions and new processing capabilities in GIS the use of GIUH has become very attractive for water practitioners and hydrologic modelers. The model is applied to the watershed scale and links geomorphologic catchment characteristics to spatially and temporally distributed rainfall input and simulates runoff at the catchment outlet. In this approach, the Horton's morphometric parameters (Strahler, 1964) that are bifurcation ratio (R_B), area ratio (R_A), length ratio (R_L) are utilized to parameterize the approach.

The GIUH was first proposed by Rodríguez-Iturbe and his colleagues (1979) and restated by Gupta et al (1980) whom defined it 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 rainfall input data is considered as uniform rain drops which are assumed to be randomly distributed over the watershed and over time.

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

Rodríguez-Iturbe and Valdez (1979) defined in a very simple expressions for the time to peak (t_{pg}) and the peak flow discharge (q_{pg}) of the GIUH:

$$q_{pg} = 1.31 R_L^{0.43} \left(\frac{v}{L_\Omega}\right), \text{ (hour}^{-1}\text{)} \tag{1}$$

$$t_{pg} = 0.44 R_L^{-0.38} \left(\frac{R_B}{R_A}\right)^{0.55} \left(\frac{L_\Omega}{v}\right), \text{ (hour)} \tag{2}$$

Where:
L_Ω- is the length in kilometers of the highest order stream;
v – is expected velocity stream flow in meters per second.

In equations (1), (2) the geomorphologic parameters (R_B, R_A, R_L) can easily be extracted based on the topological characteristics of the catchment using GIS e.g. ILWIS. The flow velocity has to be defined by physical reasoning where an average velocity must be related to some average flow length (i.e. travel path) and travel times.

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

$$Q(t) = \int_0^t i(\tau)u(t-\tau) , \tag{3}$$

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

The effective (excess) rainfall is computed according to the Soil Conservation Service (SCS) runoff method (Ogrosky and Mockus, 1964; Chow et al., 1988)

Therefore, in order to implement the GIUH, data needed include:

- ***DEM*** used to deriver the Horton's morphometric parameters
- ***Land cover*** and **soil** data. Used to estimate the curve number (CN) value when applying SCS method.
- ***Rainfall*** used as input of the model
- ***Discharge*** used as references of the output of the model

The DEM data was obtained from SRTM data by freely downloading from internet (see Sijmons et al., 2005). Landcover was extracted from remotely sensed data (see Nguyen, 2006). Soil map was collected from local agency. Rainfall and discharge data was measured and collected during field work period (September 2005 – November 2005). The measurement will be described in the next section.

3. STUDY AREA AND DATA ACQUISITION

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 to the whole 3rd order catchment (figure 1). The study area is also called Can Le Catchment. The Can Le catchment is located in the South of Viet Nam (figure 2). It is a tributary of Sai Gon River, a second biggest river in the South East, which contribute to the Dau Tieng reservoir. The catchment is identified by its corner coordinates of (11^{0}40'10"N, 106^{0}41'25"E), (11^{0}53'52"N, 106^{0}33'15"E). Elevations in the catchment vary from 50 – 220 meter (m) above mean sea level (a.m.s.l). The catchment has the main floodplain about 50-70 m a.m.s.l., next to a transition of about 90 m a.m.s.l. and then bounded by a range of hilly uplands ranging from 120 to 220 m a.m.s.l. In the mountainous areas, the topology is more dissected. The study area locates at the sub-equator, has a tropical, monsoon climate, two distinguished seasons, a rainy and dry ones. Due to the extremely rainfall happening during rainny season, sometime with typhon, together with morphometric charateristics (e.g. high slope), Can Le was consider as a typical flood prone in the region (Binh Phuoc Steering Committee, 1998-2005)

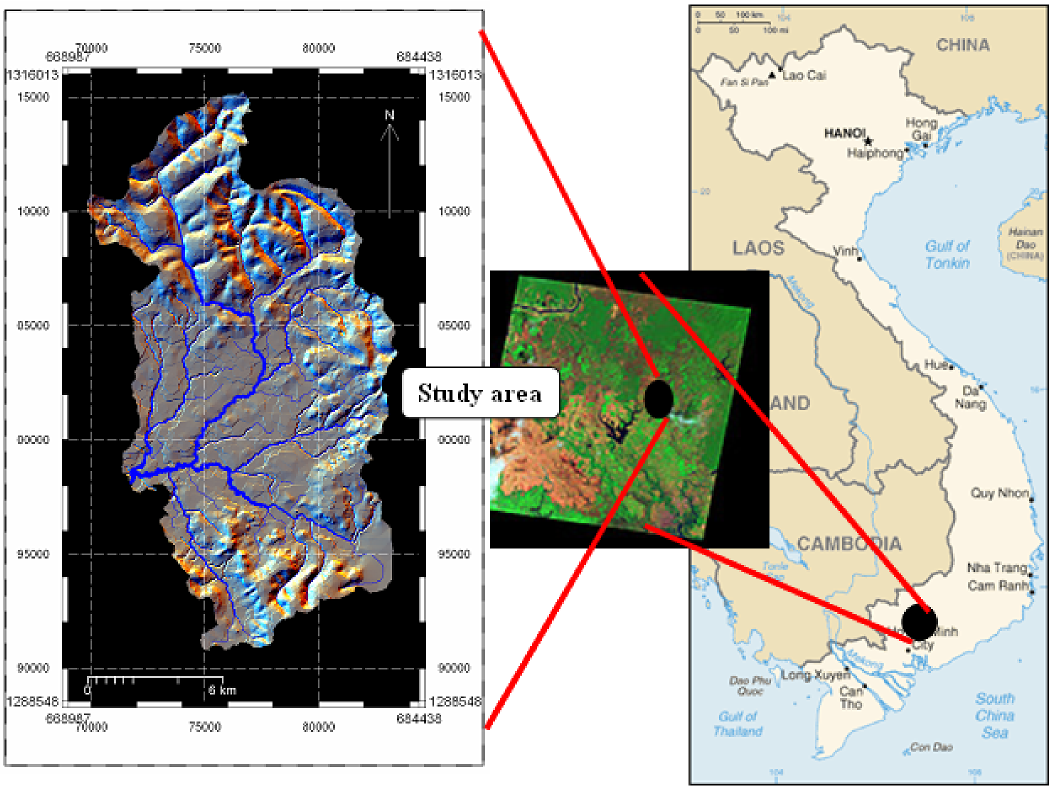

Figure 2 – Study area (on the left) in the context of its region: Upper Dau Tieng resevoir (in the middle), southern Vietnam (on the right)

3.2. DATA ACQUISITION

A temporary rainfall station was set up at an open space 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 provide hourly recording and others are measuring 2 times[1]/ day. By analysing the relation between own rainfall data[2] and discharge a non-uniform distribution of rainfall was observed. Several rainfall data sources were used for correction as a proper rainfall distribution is needed for the GIUH approach. The first source, TRMM (Tropical Rainfall Measuring Mission), providing daily rainfall in the world within the satellite 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). 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[3] are used to interpolate rainfall data from the tipping bucket and the nearest national station based on weight ratios. Detailed description of this procedure is referred to the work by Nguyen (2006).

A discharge station was set up at 3km below from the beginning of the 3rd order river due to its assessibility (figure 1). The method adopted to measure discharge is according to Herschy (1995) and Gioi et al (1990). The flow velocity was measured at a depth of 0.2, 0.6 and 0.8 from the surface if there was sufficient depth; otherwise it was measured at 0.6 alone using a current meter. The velocity was multiplied by a factor of 0.85 to account for the lower flow velocity at the bank / bed of a stream (Gioi et al., 1990). The cross section of the river at the station was determined using a theodolite. The maximum width at the cross section was 25.57 m, the maximum depth observed during the fieldwork period was 4.35 m, and the maximum water level changes were 3.2 m. The discharge data of several storms was calculated until sufficient to set up stage-discharge curve according to the method given by the International Institute for Land Reclamation and Improvement - ILRI (1972). Since then, only water level was recorded.

4. RESULTS

4.1. HORTON'S NUMBER EXTRATION

Model parameters of the GIUH include the Horton's ratios, hill slope and stream flow velocity. The velocity can be referred to literature and is a subject for calibration. The Horton ratio's (RA, RL, RB) are calculated using a newly–developed functionality in ILWIS called "*Horton statistics*" within the "DEM-Hydro processing" module. The process is as 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 1).
- 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_LSq, C_L_LSq, C_A_LSq in table 1)

The RA, RL, RB are the slope of each fitted line connecting the expected values shown in figure 3 (result shown in table 1). 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 3) and table 1, it can be assessed that the drainage network is well extracted and the Horton ratio values are representative and fall within the expected range.

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[1] 2 times/day: at 7AM and 7PM.

[2] Rainfall data from temporary installed tipping bucket station.

[3] Due to limitation in retrieving the radiometry of the images, only DN values of the IR band was used.

Table 1 – Values of number of streams, the average stream length, the average area, their expected values and the Horton's ratios

Order	C_N (number)	C_L (km)	C_A (km^2)	C_N_LSq (number)	C_L_LSq (km)	C_A_LSq (km^2)	Horton's Ratio R_B	R_L	R_A
1	10	4.27	6.92	9.826	4.410	7.262	3.18	2.04	3.8
2	3	9.58	30.42	3.107	8.981	27.621			
3	1	17.71	100.09	0.983	18.291	105.047			

105.047 = The ratio is calculated based on the complete 3rd order catchment. Thus the total area of the area is 105.046 km^2, which is less than the study catchment (203 km^2)

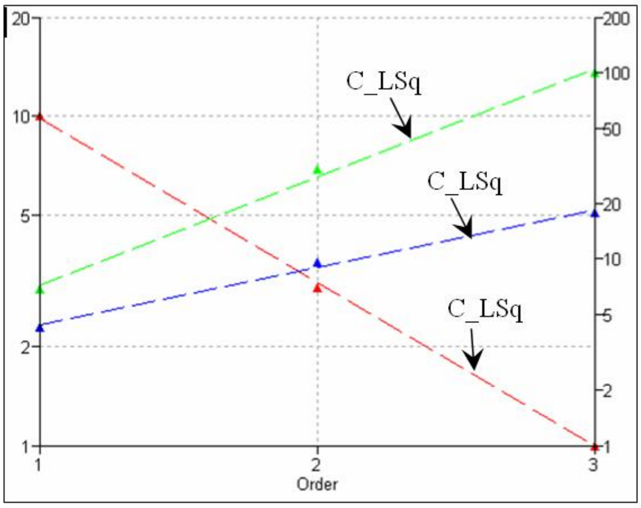

Figure 3 – Horton plot showing Strahler order in relation to number of streams, average stream length, average catchment area for the 3rd order Can Le catchment.

4.2. MODEL RESULTS

Having obtained the effective rainfall and the Horton ratios and estimated hillslope and stream velocity (V_o, V_s) to derive the GIUH (figure 4), the surface runoff is calculated based on equation (3) using an Excel spreadsheet in a discrete time domain (see Chow et al., 1988, p.211) taking into account the catchment area. From figure 5 it can be concluded that the simulated flow over-estimates the actual discharge measured for the event and calibration is therefore required.

For the GIUH approach, the initial abstraction was assumed correctly, therefore the CN value was kept constant as 85. The most sensitive model parameters identified in literature are the hill slope flow velocity and stream flow velocity (e.g. Kirshen and Bras, 1983; Al-Wagdany and Rao, 1998). Therefore the Horton's ratios were also kept constant during calibration. The hill slope velocity and stream velocity were calibrated manually. The best "Goodness-of-fit" was obtained at V_o= 0.053 m/s and V_s = 0.5 m/s. From figure 6, the peak is well simulated after the calibration as well as the shape of the hydrograph. However, the difference in time to peak of nearly 2 hours 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 (see figure 1). 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).

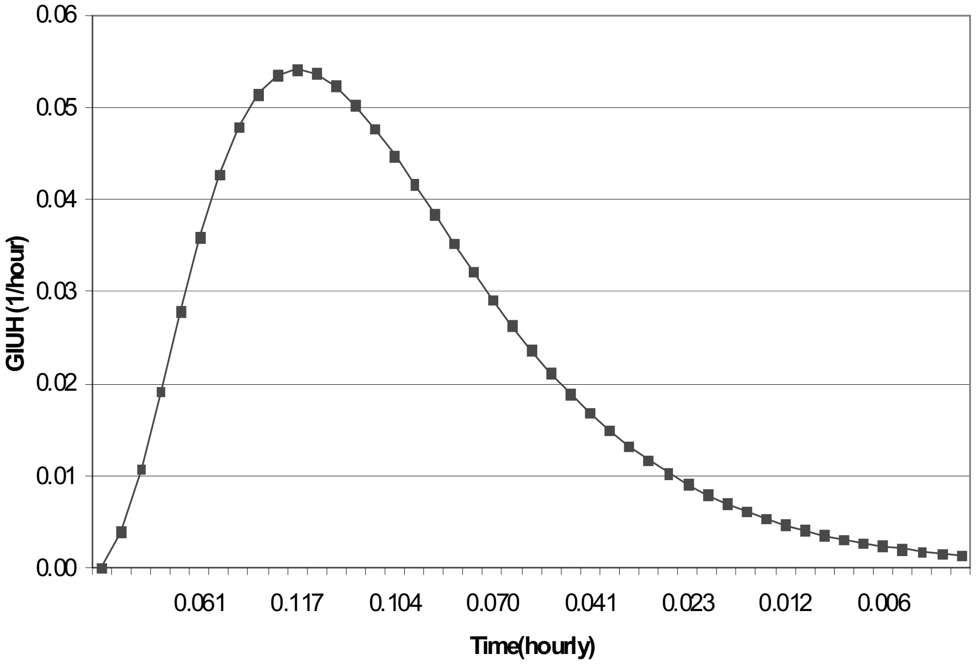

Figure 4 – The GIUH of the Can L tchment.

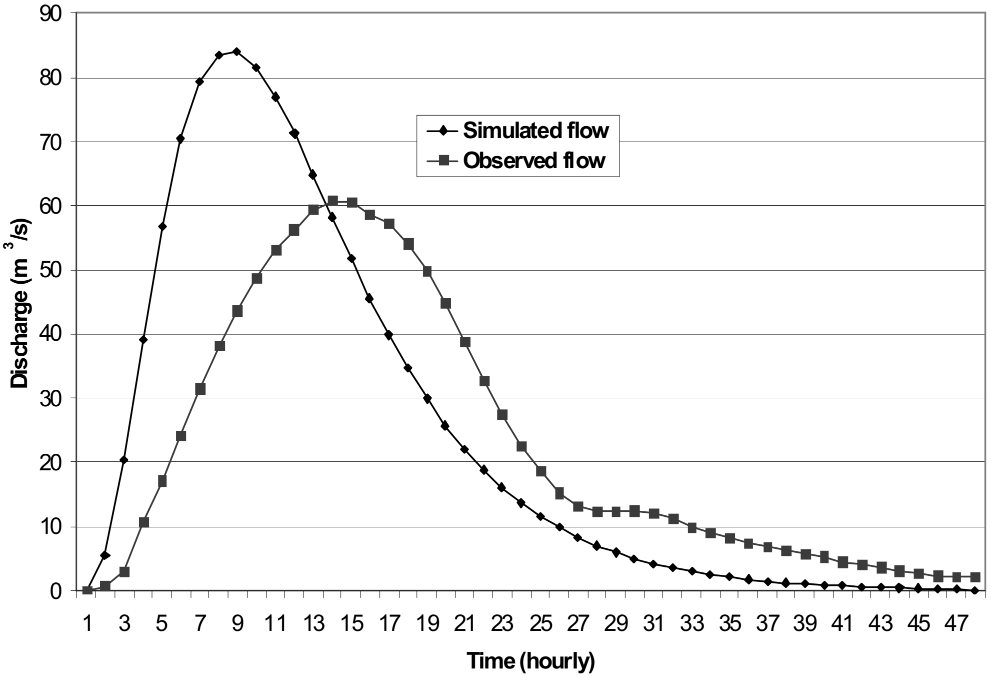

Figure 5 – Measured and simulated hydrograph using GIUH at the Can Le catchment (event 25/9/2005) (before calibration).

The model parameter values were fixed for model validation. Another event, on 4 October, was used for this purpose. The result is shown in figure 7. For this 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 a rainfall event that occurred the previous day. It is assumed that that event caused some areas to become saturated and this caused the quick runoff response observed.

The Nash-Sutcliffe efficiency was calculated and is 0.94 (event 1) and 0.86 (event 2) respectively.

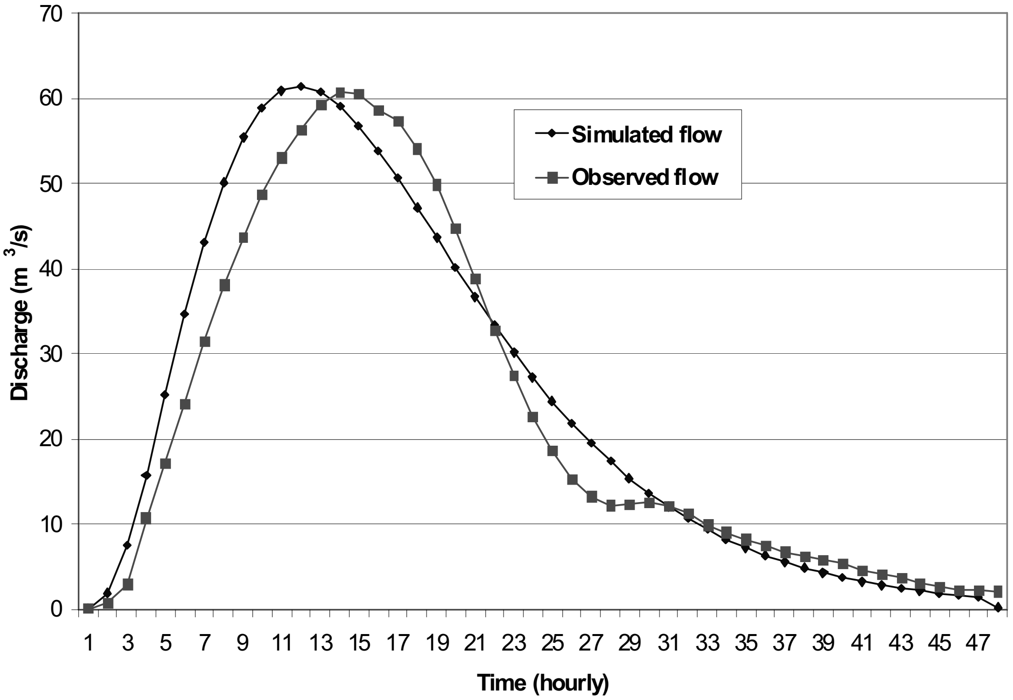

Figure 6 – Measured and simulated hydrograph using GIUH at the Can Le catchment (event 25/9/2005, after calibration).

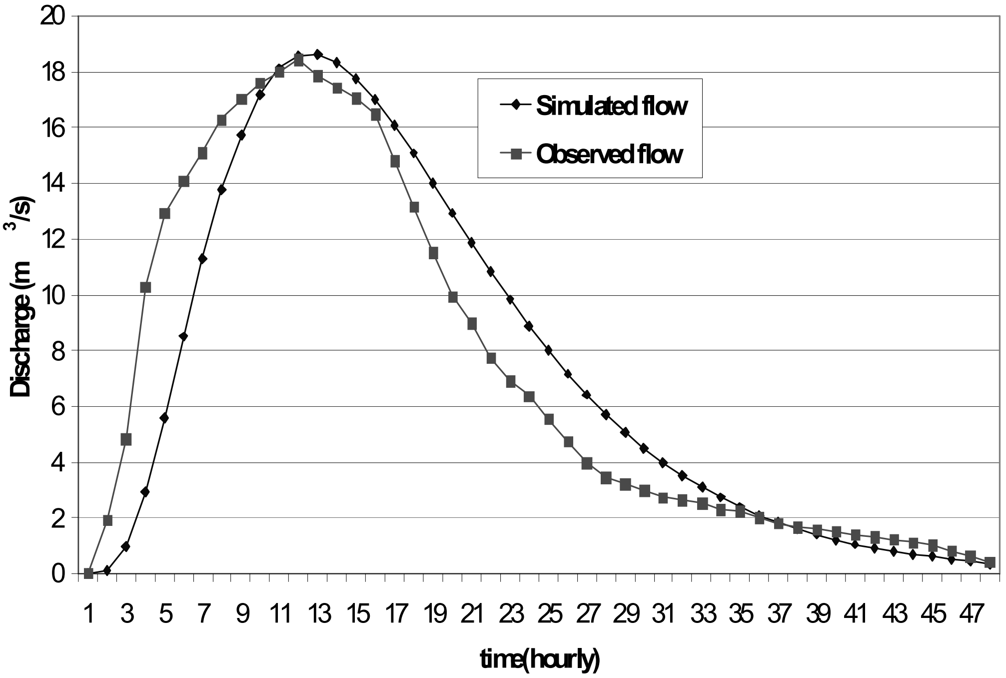

Figure 7 – Measured and simulated hydrograph using GIUH at the Can Le catchment (event 4/10/2005)

5. CONCLUSIONS AND RECOMMENDATIONS

It was shown in this paper that the utilization of SRTM data for flood prediction. DEM processing is a critical step for next stages. Given a routing procedure in ILWIS, an optimized DEM as well as most important Horton's morphometric parameters for model development were easily obtained from SRTM data. Other parameters like flow velocities can be estimated/obtained from literature, or in case of the Curve Number, derived from satellite images. Therefore, it can be confirmed the GIUH model approach can be successfully implemented to data scarce catchments as was the case here, the ungauged Can Le catchment.

The GIUH is an event-based model, it does not take into account the changes in soil moisture, etc (e.g. result from the second event). It is encouraged to incorporate this approach into a hydrologic model where the GIUH acts as a runoff transform module. An example is given in the work of Karvonen et al (1999). The GIUH model performed 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 modelled.

Although the the Horton parameters were well extracted, other parameters like velocity, CN value are objectively uncertain. 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 less applicable. The reason could be at that time (1979), Valdes et al did not take into account the hill slope velocity (Bras and Rodriguez-Iturbe, 1989) but in this study it was incorporated. The CN value was kept constant (no calibration) during model simulation. It should be further investigated what effect this factor has to ensure that the calibrated parameter is representative.

The model structure or model concept is an important aspect of any model approach. The GIUH only takes into account the surface runoff of the catchment and routes it through the channel network. The rainfall that contributes to this model is the effective rainfall within the catchment and here the SCS method is adopted. In order to evaluate the model performance for stream flow analysis the contribution of base – or interflow has to be excluded. Because the GIUH is generated from effective rainfall, the GIUH is limited to event scale simulation.

The GIUH was successfully applied in event mode with very good agreement between predicted and observed flow in both calibration and validation scheme. An Excel spreadsheet developed for the 3rd stream network was used and simulated the peak flow adequately for 2 typical events. Due to the fact that the Horton statistics were substantially different when comparing the 3rd and 4th order catchment an up-scaling of the findings from the 3rd order network to a higher order was not attempted.

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