GEO-INFORMATICS IN THE CONTEXT OF WATERSHED MODELING A CASE STUDY OF RAINFALL – RUNOFF MODELING

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ABSTRACT

In this study, the role of Geo-informatics in runoff hydrology is discussed and our research is based on integration of 3 Geo-informatic components: Remote sensing (RS) and Geographic information system (GIS) and its utilization in hydrologic modelling, that makes up the third component.

In the paper, a brief discussion on watershed modeling and utilizing of spatial and temporal data is presented. This is followed by a discussion and introduction on the novel approaches in the field of Remote Sensing (RS) and the relevant role of Geographic Information System (GIS) for data processing, preparation and model parameterization. Processed data from various data sources serve as input data for selected rainfall-runoff model approaches known as the HEC-HMS SMA and GIUH. These approached significantly differ with respect to their model structure (eg. where the HEC-HMS SMA approach is a continuous stream flow model and where the GIUH approach is event based storm runoff simulation one). Both serve as clear examples of how modeling and GIS and RS can be combined in the end.

Lastly a case study is executed and, in order to supplement the limited data in the area, satellites imageries from ASTER, SRTM (Shuttle Radar Topography Mission) to TRMM (Tropical Rainfall Measuring Mission) and METEOSAT 5 are used. GIS analyses are performed by applying techniques such as DEM processing to properly extract topographic information, map aggregation to obtain lumped parameters etc.

For this research a field campaign to obtain model input and model calibration data. The data collected included discharge, meteorological data, soil, land use information that all are crucial for validation and calibration of the selected model approaches.

1. WATERSHED MODELING AND ROLES OF REMOTE SENSING (RS) AND GEOGRAPHIC INFORMATION SYSTEM (GIS)

2.1 Watershed modeling

In general, watershed modeling involves with many aspects including natural and manmade activities. To simulate the nature, a number of watershed hydrological cycle components should be accounted for example rainfall, evapotranspiration, runoff, overland flow, groundwater flow. To access the later activities, several important features are considered in the model like land use, water diversions/abstractions, pollution point (non-point) sources.

Therefore, watershed 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 watershed and of how changes in the watershed may affect these behaviors with respects to the water quantity and quality aspects. The second objective 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. (see Wurbs, 1994; Singh, 1995; Xu, 2002 for further discussions)

In terms of spatial domains in watershed modeling, models can be classified as lumped, distributed or semi-distributed ones. The lumped model ignores spatial distributed of the watershed characteristics but there are represented by averaged single values. In contrast, distributed model approaches capture the system by partitioning the watershed into a number of smaller units. Semi-distributed model is something in between the first two that means the watershed 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). (Rientjes, 2005)

Emphasized by Singh (1995) the remotely sensed data are particular useful in watershed modeling clearly in two aspects. Firstly, the land cover and soil information are in principle estimated. Secondly, information obtained from satellite data is over the study area that very much compensates to the point measurement data. Furthermore, proved in advanced applications of remote sensing data in hydrology, a number of main hydrological components of the watershed are nicely observed through remotely sensed instruments. For example, Schultz (1988; 1996) has contributed the introduction of different applications of RS in hydrology, from different satellite sources to various issues like runoff modelling and flood forecasting and in these cases the utilization of spatial and temporal data (remotely sensed data) are clearly evident. 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 of which the land cover information is clearly utilized. De Troch et al (1996) reviewed applications of remote sensing for hydrological modeling such as RS data sources, applications on precipitation, evapotranspiration, soil moisture etc. retrievals, as well a number of RS experiments in hydrology. Although there are many other recent applications of RS in hydrology, it is out of the scope of this paper 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 used in many applications, for example SRTM (Rabus *et al.*, 2003) for DEM generation, TRMM (Rabus *et al.*, 2003), METEOSAT (Barrbera *et al.*, 1995; Levizzani *et al.*, 1999) for rainfall estimation.

GIS processing becomes a critical step in hydrologic modelling since it contributes not only to generating model parameter distribution in spatial manner but also to saving time consumes. 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, aggregate hydrologic parameters from soil, land cover, rainfall maps etc.

With respect to GIS processing products, Digital Elevation Models (DEM) is more important in watershed 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; Hengl *et al.*, 2006; Maathuis, 2006; Maathuis and Wang, 2006) , Tardem (Tarboton, 1997), etc. to extract hydrologic parameters or physical characteristics of a catchment and can serve for model simulation .

2 RAINFALL – RUNOFF MODEL AND USED MODELS

2.1 Rainfall – runoff model

In watershed modeling, 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 modeling is a major part of this job. Therefore, rainfall – runoff modeling is considered as standard tool routinely used today for the investigation and application in watershed hydrology.

In this study, the rainfall – runoff models used are HEC-HMS SMA and GIUH. These approached significantly differ with respect to their model structure, temporal simulation. For example, where the HEC-HMS SMA approach is a conceptual model toward simulating the continuous stream flow, and where the GIUH approach is an empirical model and focuses on event storms.

2.2 HEC-HMS SMA

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.

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. Especially, when applying the aggregating technique in GIS processing, 7 parameters are easily obtained.

2.3 GIUH

Given the data scarcity the objective here is to implement the Geomorphological Instantaneous Unit Hydrograph (GIUH) concept using a parameterization from GIS based DEM processing. Coupling of quantitative geomorphology and hydrology which is at the core of this approach is not a new concept. The model links geomorphological characteristics of a catchment to its response to rainfall. In this approach, the Horton's morphometric parameters (Strahler, 1964, 1969) including bifurcation ratio (R_B), area ratio (R_A), length ratio (R_L) are mainly used to develop the 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.

The concept so far has been improved and successfully implemented as a hydrological model to simulate rainfall – runoff relation and to forecast floods (Rodríguez-Iturbe, 1993; Jain *et al.*, 1997; Tuong, 1997; Al-Wagdany and Rao, 1998). Simulation results showed that the approach is a very promising tool to estimate event discharges, even for an ungauged catchment (Bhaskar et al., 1997). Rodríguez-Iturbe and Valdez (1979) defined in a very simple form the time to peak (t_{pg}) and the peak flow (q_{pg}) of the GIUH as:

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

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

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), even in the complete procedure to obtain the Instantaneous Unit Hydrograph that explained in detail in Nguyen *et al* (2006a), there is only the velocity is estimated the remaining information (R_B, R_A, R_L) is extracted based on the topological characteristics of the catchment using the well-known academic ILWIS packet.

3 INTEGRATING RS AND GIS IN MODELING

Integrating RS and GIS in modeling in this study is implied as model data preparation and model parameterization through these tools. The data preparation is mainly based on RS data and the later is devoted for the GIS processing techniques. The following sections will briefly describe what kind of RS data are used and for which purposes. Then, 02 typical GIS processing techniques including DEM processing and aggregation are mentioned.

3.1 RS data

To supplement data for model development, the following remotely sensed data are used:

- ASTER image: used to classify land cover, land used map
- SRTM: used to provide the initially Digital Surface Model
- TRMM: provide daily rainfall are not suitable for this application (higher temporal resolution is required)
- METEOSAT 5: provide infrared image every 30 minutes are used to adjust spatial distribution of rainfall due to limited rain gauge distribution. In this study, 8 images corresponding to the moment of 8 significant storm events during rainy season (2005) were processed.

3.2 GIS processing

The most critical model parameters to implement the GIUH are Horton morphometric parameters. There are a number of steps involved to finally derive these parameters that are not given here. Typical stages are: DEM correction/optimization, the routing catchment/drainage extraction, geomorphologic information extraction, and lastly the Horton morphometric. These obtained parameters are plotted in Horton plot in order to qualify whether they are representative for the catchment (figure 1). Here, we see they are nicely located in the straight lines that that means the good information obtained.

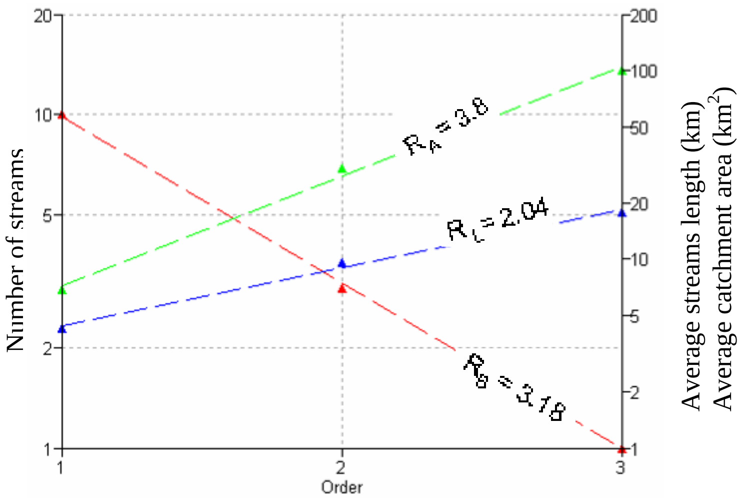

Figure 1: Horton plot showing Strahler order in relation to number of streams, average stream length, average catchment area.

To determine parameters for the lumped model, aggregation technique in GIS is usually applied. The reason is because this technique is able to estimate an average value of model parameter in spatial manner. As mentioned in the HEC-HMS SMA part, 7 of 12 model parameters are calculated using this method. They are: Storage capacity; Storage capacity; Soil infiltration maximum rate; Storage capacity; Tension zone capacity; Percolation maximum rate. To implement the job, the catchment boundary layer is applied as the block that used to calculate the average values from a number of other layers like canopy, slope, and soil as given in detail in (Nguyen *et al.*, 2006b). Additionally, the same technique was also applied to calculate the Curve Number (CN) based on soil and land cover map that is later used to calculate flow discharge of the catchment from the GIUH concept.

4 MODEL RESULTS

4.1 Event simulation

As resulted from the GIUH model, after calibrated (the velocity parameter), the simulated flow is very closed to the observed for both calibrated event and validated one. Here, it is that 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 2, 3).

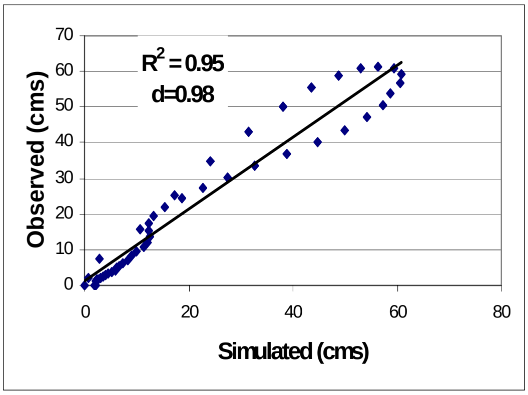

Figure 2: Scatter plot hourly observed versus simulated flow (event 1, 25 September 2005)

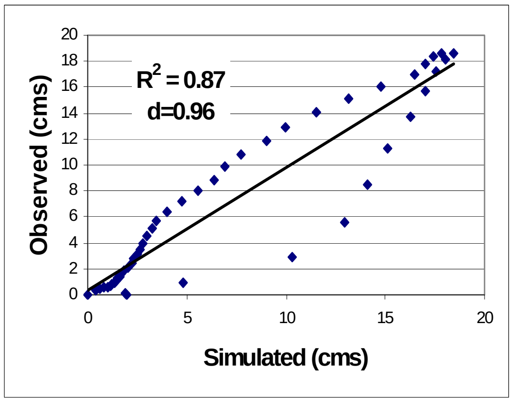

Figure 3: Scatter plot hourly observed versus simulated flow (event 2 , 4 October 2005)

4.2 Continuous simulation

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 4. The reason for these mismatches is the contribution of improper rainfall input. For example:

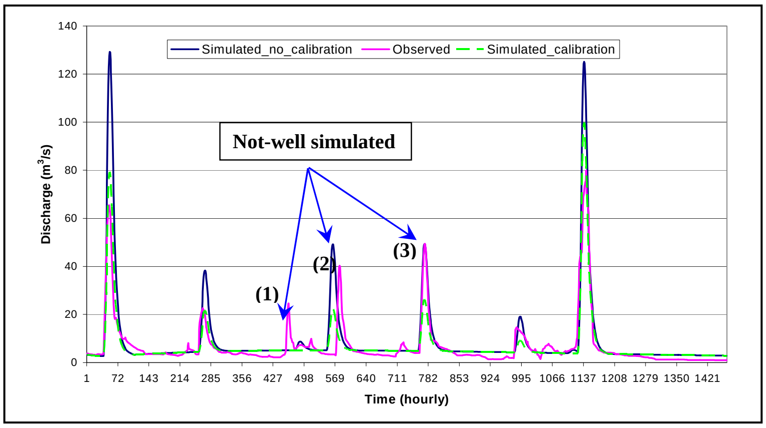

Figure 4: Measured and simulated hydrograph using HEC-HMS SMA at the Can Le catchment (before and after calibration)

- Peak (1): The rainfall was too little to produce effective rainfall[1];
- 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;

[1] It was checked using satellites images and surrounding station data but no relation was found (no rainfall observed at rain gauges but the peak flow was recorded)

- 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.

5 CONCLUSIONS

In this paper, various aspects of utilizing RS data and application of GIS techniques in rainfall – runoff modeling are presented. 02 examples of modeling are evident to prove the usefulness of these tools in natural resources management in general and in watershed management in particular. Given limitation of the description, many further related issues were not addressed in detail, for those interested are highly recommended to the citation list.

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