MODULE 3.7

Extending an Integrated GIS-based Watershed Modelling Approach to Participatory Watershed Management

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Objectives

- To present the state of the art in integrated GIS-based hydrologic modelling.
- To outline how a participatory watershed management dimension could be added to such a model.

Why is watershed modelling important?

- Rainfall-runoff processes affect people, land use, vegetation, channels and geomorphic processes in a complex way in a watershed.
- Developing a model can significantly improve our understanding of the landscape-level response.
- It helps to refocus watershed management towards a systems' approach.
- In view of the shift from traditional watershed management to participatory integrated watershed management, watershed modelling can integrate science and participatory mechanisms.

Many studies in the USA have addressed the interrelationships between timber harvesting and runoff using different modelling and research approaches. Reviewing several modelling and research approaches, Achet (1997) concluded that, in general, the impact of timber harvest on streamflow is blurred and contradictory, and that the appropriate approach to addressing the integrated modelling problem is to use a physically based distributed approach.

What is the approach for hydrologic modelling?

The present know-how on watershed modelling is focused on

- using geographic information systems (GIS), remote sensing (RS), visualisation techniques and computer programming combined with watershed modelling to produce a physically based distributed watershed modelling approach;
- GIS providing spatial reference, programming keeping track of changes in different components of the hydrologic process, and visualisation helping to display and communicate results; and
- borrowing techniques from other relevant disciplines.

What are the models and modelling?

There are no universally ideal models, they have to be developed for specific purposes (Daniels 1992). A model can be used to challenge conventional wisdom, explore complex systems, identify gaps in knowledge (Daniels 1992) and as an aid to resource management decision-making. Hydrologic modelling is also an alternative approach to comparison of treated watersheds with untreated control watersheds. By using a hydrologic model, the cost of data acquisition can be reduced and research can be extended into areas where control watersheds may be impractical (Troendle and King, 1985). Many scenarios can be generated within minutes.

Irrespective of the classification approach, reliable hydrologic models should not only work well, but work well for the right reasons (Kelmes 1986). They must reflect, even in simplified form, the essential features of the system. However, practical considerations can result in a model being accepted as accurate without being a valid representation of the prototype (Beven and Kirkby 1979). Uncertainty or confidence interval of predictions must be an integral part of the modelling (Kelmes 1986). Although models seldom provide unambiguous answers, good models are not only simple but also complete and focus attention on what matters most (Brooks 1992; Daniels 1992). In practice, preference is always given to models with a transparent structure and easy handling, especially if, at the same time, they provide reliable results (Turcan 1990). Since hydrologic models can be used as submodels of complex systems, hydrologists doing simulations need to interact with others to help incorporate new concepts in hydrology into ecosystem-level models (Federer 1982).

How is remote sensing used in modelling?

Remote sensing (RS) provides a means of rapid assessment of various parameters related to a hydrologic model in a convenient, repeatable and objective way. RS as data input to a GIS enhances the possibility of data integration, synthesis and analysis. In the recent past, there have been several applications of RS and GIS in hydrologic modelling. The advantage of using RS is that data with high resolution in space can be obtained for areas for which no measurements exist (Schultz 1986). Increasingly, not only are simulation models and GIS being combined to provide improved means of managing and displaying data, but RS data are also being integrated into GIS as a part of the hydrologic modelling approach. In addition, RS techniques, oriented to aerial rather than point events, have an inherent potential for fertilization of hydrologic thinking (Kelmes 1983). Thus, a GIS-based modelling system with RS data as inputs continue to be the focus of hydrologic modelling.

Expressing hydrologic parameters as a function of current land use makes it possible to predict rationally the impact that future land-use change will have on runoff response (Rango et al. 1983). In any hydrologic model, land cover plays an important role in determining the streamflow response (Duchon et al. 1992). Researchers assert that Landsat-based information gives similar or better results than traditional methods.

Land-use classification techniques commonly integrated in a GIS framework for relating hydrological parameter change are supervised and unsupervised. Supervised classification is used most commonly because it permits greater refinement. Although accuracy associated with the practical use of RS data is variable, applicability of remotely sensed data is not limited by the degree of accuracy.

What are the limitations of GIS and how can they be overcome?

Current GIS represent a static view of the world from a temporal perspective. To analyse spatiotemporal information digitally, current cartographic theory and methods are inadequate (Langran and Chrisman 1988). The GIS have not reached a stage of representing temporal phenomena effectively. Efforts to enhance temporal capabilities of GIS have revealed several problems at the fundamental and conceptual levels (Langran 1989; Peuquet 1994). In cartography, three approaches are used for representing time and depicting change: sequence of discrete displays (snapshots or oscillating colours) at various speeds; dynamic display using interactive control; and a static map with supplemental graphics (Peuquet 1994). However, the primary basis of cartographic approaches to representation is spatial. Temporal representation of time as a way of organizing a database is so complex and challenging that experts have suggested interdisciplinary research involving concepts from perceptual psychology, artificial intelligence, and other fields (Peuquet 1994). The state of the art in modelling the temporal dynamics of a process in a GIS framework comes down to integration with computer-based programming.

What are the model types?

A simulation model can be event-based (storm runoff) or continuous. Some commonly used event-based models are: the flood hydrograph package (HEC-1) of the US Army Corps of Engineers (1981), TR-20 (SCS, 1969), TR-55 (SCS, 1975), SEDIMOT-II (University of Kentucky 1985) and Hydrograph-2. Most of these models are based on unit hydrograph theory implying that the relationship between rainfall and runoff is linear and constant. Commonly used continuous models are: the Stanford Watershed Model, National Weather Service River Forecast System (Curtis and Smith 1976), Sacramento Watershed Model, Precipitation-Runoff Modelling System (Leavesley et al. 1983), SSARR and Simulation of Urban Runoff Process (Australian Water Resources' Council 1977) and the Peatland Hydrologic Model (Guertin et al. 1987).

What are the issues surrounding the accuracy of models and modelling?

Accuracy of any hydrologic model depends on the accuracy of the parameter inputs. Precipitation distribution is an important factor affecting streamflow response. Another factor is evapotranspiration. Since research on evapotranspiration is limited (Nakama and Risley 1993), leaf area index is used as a principal independent variable for ecosystem modelling - including estimation of transpiration (Running and Coughlan 1988). In the absence of evaporation data, water body evaporation rates are taken as close approximations (Nakama and Risley 1993). Representation of the antecedent soil-water condition is one of the most difficult aspects of parameter estimation in hydrologic modelling. A uniform antecedent soil-water content throughout the catchment is often assumed, but this simplification undermines the physical basis of subsequent modelling. Uniform conditions rarely exist under wet conditions. The best approach to defining antecedent conditions is to use the model to establish them.

Model complexity is another issue. A number of studies has compared simple and complex models. Results generally show that simple models are almost as accurate as complex ones. Results of comparative studies as well as development application and evaluation of complex distributed models continue to be areas of active research. Michaud and Sorooshian (1994) concluded that a simple model performed as accurately as a complex distributed model provided that calibration was performed. In another study, comparing four models in South Africa, differences in simulation results could be explained either by differences in complexity of the modelling approach or resolution of input data (Hughes 1994). Many factors affect the accuracy of runoff models: input data, initial conditions, assumptions, parameter values, runoff dynamics and model resolution. These factors are difficult to examine properly (Michaud and Sorooshian 1994). Thus, simple models may be as good as complex ones (Federer 1982 and Dickenson 1982).

In view of the complexity of the model and the practicality of applying it, the use of a compromise approach—in which the model is kept simple but lumping occurs at the land-cover level—emerges as a practical approach to modelling at the watershed level. Process modelling needs to evolve and experimental research needs to develop parameter values. New research should include experimentation on flow representation, expansion and contraction of source areas at the micro- and macro-levels.

How is flow routing important?

Flow routing is another important factor in determining streamflow response. Usually, prior to flow routing, hydrologic analysis is performed by subdividing the catchment into subwatersheds. Runoff hydrographs are obtained for each subwatershed, routed through interconnected channels and combined to develop a design flood hydrograph at approximate locations. Flow routing may be done by using kinematic wave approximation, Muskigum method or dynamic wave formation (Prakash 1986). In recent years, digital elevation models (DEM) have been used in hydrologic modelling for representing terrain and its attributes. Approaches to terrain representations can be grouped as continuous and discrete. Continuous approaches include surface elevation contours, triangulated irregular networks (TIN) and grids. The grid-based approach is applied most widely because of the low cost of computer memory. In the gridded approach, the steepest downslope gradient between the cell and its adjacent neighbour is used to determine the flow path; the drainage network is identified based on a channel threshold value. There are basically two variations of this approach: treating sinks as artifacts and accepting DEMs as accurate.

The approach of flow representation in only one direction fails to represent divergent flows on convex slopes and can lead to bias in flow path orientation. So, approaches for divergent flow have been proposed. The divergent flow approach requires six to seven times more computer execution time than the one-dimensional steepest gradient representation. The quality of information that can be automatically derived from DEM as well as the quality of slope information are functions of both horizontal and vertical resolution of the DEM (Jenson 1991). In fact, the one-dimensional steepest gradient approach is sufficient for channel representation and overland flow routing in a large mountain watershed. More recently, multiple flow direction approaches have also been proposed. The application of current physically based models might be carried out in conjunction with a programme of field measurements to ensure consistency between model predictions and real-world processes (Beven 1992; Grayson et al. 1992).

How are results displayed and communicated?

Display and communication of model results are receiving attention in watershed modelling research. Several three-dimensional visualisation models (e.g., Utools, Vantage Point, Grass) and computer graphic techniques are used to display and communicate results. Combining watershed modelling, computer programming, GIS, RS and visualisation is the present state of the art in integrated watershed process modelling.

An example of an integrated approach to GIS-based watershed modelling

The approach is illustrated by using a study developed for the US Man and the Biosphere Programme. The main features of the approach are presented in Figure 1.

- Use of RS for land-use/land-cover information for generating different management scenarios
- Use of existing model for precipitation distribution in mountain areas
- Use of C programming to generate initial conditions and characterise hydrologic conditions based on antecedent conditions and event magnitude

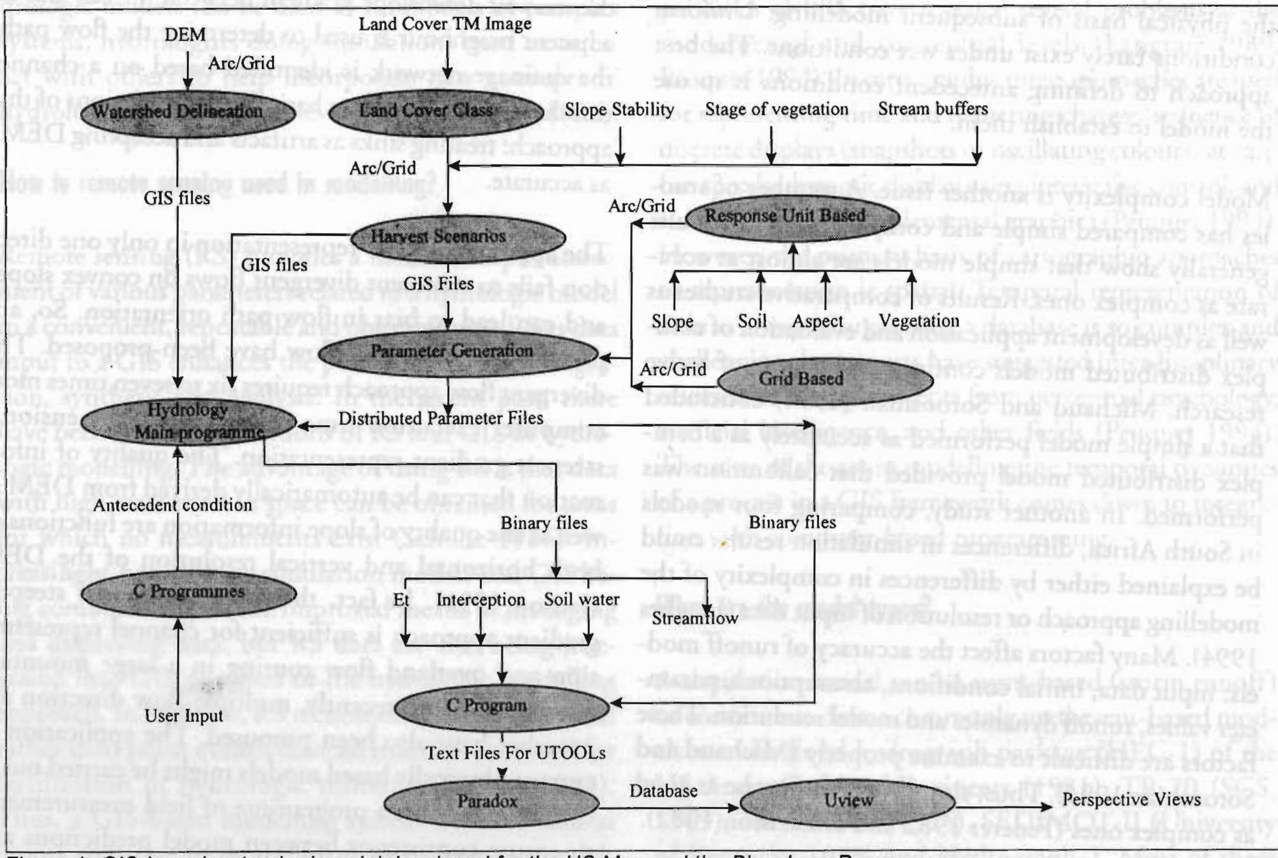

Figure 1: *GIS-based watershed model developed for the US Man and the Biosphere Programme*

- Use of C programming to keep complex accounting of each component of the hydrologic process
- Use of watershed, sub-basin and basin scales for modelling
- Use of an event-based approach to assess impact on streamflow peak, timing to peak and mean daily flow
- Hypothesis testing using 4 management scenarios, 2 modelling approaches, and 3 hydrologic conditions for three watershed scales to confirm model predictions
- Use of two modelling approaches: distributed and response-unit-based to predict hydrologic response
- Use of readily available meteorological information
- Use of GIS-based parameterisation techniques
- Use of ASCE standards for model calibration and validation
- Use of model to arrive at new management criteria
- Outlining of ways to link hydrologic science and natural resource management
- Use of user 3-D perspective views to communicate model results

What are the main activities in formulating and testing hypotheses?

The main activities in formulating and testing hypotheses are

- reviewing and drawing inferences from previous work,
- linking hypotheses to public issues and management concerns,
- formulating clear-cut research questions, and
- designing experiments or approaches to address the question(s) or hypothesis or hypotheses.

How can GIS-based hydrologic modelling be extended to participatory watershed management?

The entry points in embracing participatory watershed management could be as follow.

- Public consensus building before setting objectives.

- Involving the public in accuracy, details and error concerns
- People's participation in defining scenarios, modelling approaches and sizes of watershed scales
- Specifying and changing of model input and output
- Ascertaining 3-D perspective views
- Using the model to evaluate post-development environmental impacts

Conclusions

Adapting an integrated GIS-based hydrologic model to the Asian context involves the following.

- Defining a working hypothesis embracing participatory issues
- Using participation analysis before model building
- Developing management scenarios that reflect people's actions
- Using readily available information
- Providing refresher training in hydrologic modelling
- Using remotely sensed data and data from secondary sources
- Building a modelling database and sharing digital data
- Using PC-based modelling
- Focussing on priority issues needing quantitative predictions
- Making models flexible in order to address gender and equity concerns.

The future of an integrated approach to watershed modelling that encompasses participatory watershed management can be briefly outlined as follows.

- Integration of socioeconomic and ecological processes as a one-step procedure
- Use of models to address sustainability of human-dominated landscapes
- Use of interdisciplinary planning and model building
- Use of transdisciplinary techniques
- Use of a comparative modelling approach

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