

# AVTOP: a full integration of TOPMODEL into GIS

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## Abstract

The integration of environmental models and Geographical Information Systems (GIS) usually takes two approaches: loose coupling and tight coupling. This paper, however, presents a full coupling approach within a GIS environment that is achieved by developing the existing hydrological models with the macro language of GIS. Such an approach makes it easy to capitalize on the GIS visualization and spatial analysis functions, thereby significantly supporting the dynamic simulation process of hydrological modelling. The full coupling approach is illustrated by AVTOP — a realization of TOPMODEL (TOPography-based hydrological MODEL) with the macro language Avenue of ArcView — within which all stages of model building are undertaken, from the initial parameter input and transformation of datasets, to the visualization of intermediate maps and the final presentation of results in various graphical formats in their geographic context. Furthermore, this approach provides a convenient and single environment for users to visually interact with the model, e.g. by adjusting parameters and observing the corresponding results simultaneously, which significantly facilitates users in exploratory data analysis and decision making in relation to the model applications. © 2002 Published by Elsevier Science Ltd.

*Keywords:* TOPMODEL; Environmental models; Geographical Information System; Integration; AVTOP

## Software availability

Name of software: AVTOP

Developer: B. Huang and B. Jiang

Software required: ArcView/Spatial Analyst/3D Analyst

Program language: Avenue

Availability and cost: Freely available by contacting authors

## 1. Introduction

The development of Geographical Information Systems (GIS) has gone beyond initially data management and thematic mapping, to sophisticated modelling and visualization for both scientific research and decision-

making processes. Attempts have been made to integrate various models into GIS to meet the increasing need of enhancing functionality in environmental modelling (Goodchild et al., 1993, 1996), urban modelling (Longley and Batty, 1996) and analytical tools in a more general sense (Fotheringham and Rogerson, 1994; Fischer et al., 1996; Fotheringham and Wegener, 2000). In these efforts, there are generally two approaches to the integration of environmental models and GIS: loose coupling and tight coupling, as reviewed in the field of environmental and hydrological modelling (Maidment, 1993; Karimi and Houston, 1996; Sui and Maggio, 1999).

Loose coupling [Fig. 1(a)] relies on the transfer of data files between GIS and environmental models. The advantages of this approach lie in the fact that both systems can be developed or be used independently. However, the exchange of data files, usually taking text files (ASCII files) as a link between two systems, is inherently cumbersome and not user-friendly. Tight coupling [Fig. 1(b)], on the other hand, is usually developed within a GIS and is extremely useful for modellers depending on the various functions of a GIS. They

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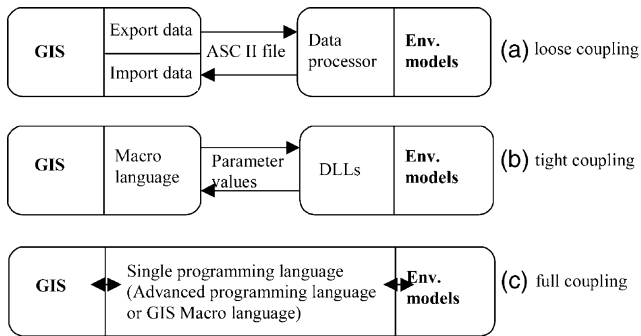


Fig. 1. Different approaches to the coupling of environmental models with GIS.

capitalize on direct access to a spatial database, seamlessly integrating model data with other project data and providing immediate visualization of model results. Generally the models are developed into Dynamic Link Libraries (DLLs) by using advanced programming languages such as Fortran and C/C++, and the DLLs are linked into the macro language of GIS. It should be noted that differences in data models have significant impacts on the computational manipulation of data in the above coupling process.

Compared with loose coupling of the early days, tight coupling is considered to be a more effective integration method and has been widely used in analysis and modelling efforts linking to GIS (e.g. Ding and Fotheringham, 1992; Batty and Xie, 1994). However, it sometimes causes serious problems due to the complicated communication between GIS macro languages and DLLs. This is especially true when models need GIS functions in the middle process of modelling (e.g. in an iterative loop) that makes the organization of DLLs more difficult. In addition, this approach requires a transparent interface to the data structures of GIS, which is, however, rarely provided by GIS vendors.

The availability of large volumes of spatio-temporal data has raised a high demand for dynamic modelling (Burrough, 1998) that requires closer integration of GIS functions and environmental models. We noticed that the PCRaster package (Deursen and Heil, 1995) provides a powerful and flexible modelling language for implementing spatio-temporal dynamics. Visualization, previously employed for mapping analysis results, is nowadays considered an important tool for spatial analysis (DiBiase, 1990; Jiang, 1996); various new terms have been used to reflect this change such as spatial data exploration and exploratory visualization (/simulation). By simulation we mean that spatial phenomena are investigated in an exploratory way, and analytical processes can be simulated for visual interrogation. If we have environmental models fully integrated into GIS, the analytical processes can be simulated thereby making visual exploration more straightforward. With such a highly interactive platform, end users are able to obtain

a comprehensive perception of reality through its counterpart in computer systems. Typical examples in this connection are highly interactive visualization tools for spatio-temporal exploration (e.g. Gahegan, 1998; MacEachren et al., 1999; Claramunt et al., 2000). Within these systems, end users can easily change settings for exploratory purposes to uncover the patterns and structures in space and time dimensions.

A full integration of environmental models with GIS [Fig. 1(c)] is, therefore, advocated for both modelling and visualization purposes. Such an integration can be achieved by using a single programming environment, either advanced programming languages like C++ or GIS macro languages. Here we use the latter option for the sake of ensuring longevity, stability or compatibility of the software as well as avoiding reprogramming GIS functionality.

We take the implementation of TOPMODEL (TOPography-based hydrological MODEL) with Avenue, an object-oriented macro language of the ArcView GIS, as an example to illustrate the advantages of such a full integration manner for modelling and visualization. It is noted that the improvement of TOPMODEL itself is not the focus of this paper.

The remainder of the paper is organized as follows. Section 2 introduces TOPMODEL concepts and current practice of TOPMODEL implementation as both a standalone package and loose/tight coupling to existing GIS. Section 3 presents a new implementation: namely AVTOP, a full integration of TOPMODEL into GIS for environmental modelling and visualization. Section 4 illustrates various results of the full integration approach with some sample data. Finally, Section 5 draws the conclusion.

## 2. TOPMODEL concepts

TOPMODEL, proposed by Beven and Kirby (1979), is a physically based watershed model that simulates the variable-source-area concept of streamflow generation. This model requires Digital Elevation Model (DEM) data and a sequence of rainfall and potential evapotranspiration data, and it predicates the resulting stream discharges. TOPMODEL has become increasingly popular and widely used in various applications in recent years, as it provides computationally efficient prediction of distributed hydrological responses with a relatively simple framework for the use of DEM data (Beven, 1997).

Since the theoretical basis of TOPMODEL has been clearly reported elsewhere (Beven and Kirby, 1979; Beven, 1997), we provide here only a brief description of the model. TOPMODEL makes use of a topographic index of hydrological similarity based on an analysis of the topographic data (Quinn et al., 1997), which can be described as follows:

$\ln(\alpha/\tan \beta)$ ,

where  $\alpha$  is the cumulative area drained through a unit length of contour line, and  $\tan \beta$  is the slope.

The subsurface flow rate per unit width of contour length,  $q_i$ , at any point on the hillslope is approximated by:

$$q_i = T_0 \tan \beta_i e^{-S_i/m}, \quad (1)$$

where  $T_0$  is the average soil transmissivity (a homogeneous soil throughout the catchment is assumed),  $\beta_i$  is the slope angle,  $S_i$  is the local storage deficit and  $m$  describes the change in transmissivity with depth.

Based on this exponential approximation, the local deficit is derived as:

$$S_i = \bar{S} + m[\Lambda - \ln(\alpha/\tan \beta)_i], \quad (2)$$

where  $\bar{S}$  is the average storage deficit and  $\Lambda$  is the areal average of  $\ln(\alpha/\tan \beta)$ . Eq. (2) is used to predict the saturated contributing areas at each time step. A negative value of  $S_i$  indicates that the area is saturated and saturation overland flow is generated, while a positive value of  $S_i$  indicates that the area is unsaturated. Unsaturated zone calculations are made for each  $\ln(\alpha/\tan \beta)$  increment.

The calculations use two storage elements, SUZ and SRZ. SRZ represents a root zone storage, the deficit of which is 0 at 'field capacity' and becomes more positive as the soil dries out; and SUZ represents an unsaturated zone storage which is 0 at field capacity and becomes more positive as storage increases. Storage subject to drainage is represented by  $SUZ_i$  for the  $i$ th increment of  $\ln(\alpha/\tan \beta)$ . When  $SUZ_i > 0$ , vertical flow to the zone is calculated as

$$Q_v = \frac{SUZ_i}{S_i t_d}, \quad (3)$$

where the parameter  $t_d$  is a time constant.

Evapotranspiration is taken from the  $SRZ_i$  store. The maximum value of storage in this zone is SRMAX. The rate of evapotranspiration loss  $E$  is assumed be proportional to a specified potential rate  $E_p$  and the root zone storage SRZ as

$$E = E_p \times SRZ/SRMAX. \quad (4)$$

The sum of vertical flows weighted by the area associated with each  $\ln(\alpha/\tan \beta)$  increment is added to reduce the average saturated deficit  $\bar{S}$ . An outflow from the saturated zone,  $Q_b$ , is calculated as

$$Q_b = e^{-\Lambda} e^{S_i/m}. \quad (5)$$

A water balance calculation for  $\bar{S}$  produces a new end-of-time-step value that is used to calculate the new value of  $S_i$  at the start of the next time step. There should be

no water balance error involved since the incremental change in  $\bar{S}$  is equal to the areally weighted sum of changes in the  $S_i$ .

The model is applied to each of the subcatchments, obtained by dividing the catchment into smaller areas based on the channel network. The flow is then routed to the outlet based on the assumption of constant kinematic wave velocity. Over the past two decades, TOPMODEL concepts have been implemented with various computer languages upon different computer platforms (see, for example, Beven, 1997). The tools developed have been used widely in the application of hydrological modelling in various catchments in the world (Beven, 1997). In the mean time, various attempts have been made to improve the concepts, such as uncertainty evaluation when using the TOPMODEL model for hydrological modelling.

Efforts have also been made on integrating TOPMODEL with GIS mostly from a hydrological perspective. For example, Chairat and Delleur (1993) used GRASS for hydrological parameter determination, hydrological assessments and to link the TOPMODEL. The linking method, however, belongs to loose coupling as GRASS is mainly employed to access the input and output data from TOPMODEL. Another effort from Stuart and Stocks (1993) focused on the integration of a set of generic modelling tools into the SPANS GIS. As the macro language of SPANS, SPANS Modelling Language (SML), is relatively weak due to lack of a looping construct, a limited number variables and a limited precision for calculating with arithmetic, this inevitably restricted its usefulness for practical purposes. The outputs produced may be interpreted as indicative rather than precise. Furthermore, the visualization of dynamic changes of soil moisture that is important for understanding the model was left out, probably due to the lack of an advanced visualization tool within the GIS packages utilized. In AVTOP, with the help of the powerful GIS package ArcView and its macro language — Avenue, the weaknesses in the above implementations are overcome. The whole simulation process including stream network generation, topographic index map, and computation of soil saturation deficit and the predicated streamflow is implemented solely by Avenue, in which the soil saturation status is visualized on top of the three-dimensional (3D) watershed surface for a better understanding of the predicted contributing area with respect to the distribution of the topographic index.

### 3. Development of AVTOP

#### 3.1. The ArcView GIS

ArcView is a desktop GIS with components including the view, table, chart, layout and script. Each of these

serves different purposes for spatial data processing and presentation. Among others, of importance is Avenue script which permits customization of the ArcView interface and provides some additional spatial functions. Avenue possesses important programming facilities such as lists and looping constructs for graphics manipulation, spatial queries and basic arithmetic calculations. ArcView also has a set of extensions such as Spatial Analyst and 3D Analyst. The Spatial Analyst presents generic spatial analysis functionality on grid and feature themes such as proximity analysis, cell statistics and multi-map calculation, while the 3D Analyst allows users to create, analyse and display surface data. With ArcView and its extensions, AVTOP is developed as a set of tools by modifying existing ArcView controls (menus, menu items, buttons and tools) and linking some scripts with new controls created in any of the multi-dimensional windows (i.e. Project, View, Table, Chart, Layout or Script).

### 3.2. Implementation details

The functions of AVTOP are illustrated in Fig. 2. All of these functions are coded in Avenue scripts by integrating the use of Views, Tables, Charts and 3D perspective views. A set of icons is created and linked to respective Avenue scripts for operation of the software package. In this implementation, Spatial Analyst is used for data preparation and 3D Analyst for terrain visualization of the catchment under study, while the full model is computed through the Avenue language.

The development of AVTOP mainly involves two parts. In the first part, Spatial Analyst is used to derive  $\alpha$  and  $\tan \beta$ , which results in a topographic index map.

At the same time, the stream network of the watershed is interactively derived through a hydrological modelling extension offered by ArcView 3.1. The second part integrates all hydrological parameters and precipitation records for simulation purposes. The calculations are made for areal subdivisions based on the  $\ln(\alpha/\tan \beta)$  subdivisions. The saturation deficit for each subdivision is calculated from the mean subcatchment deficit (SBAR) at the start of each time step.

Each increment also has a root zone storage (SRZ) and an unsaturated zone storage (SUZ). SUZ has an upper limit of the local saturation deficit SD. The local contributing area is where  $SD - SUZ$  is less than or equal to zero. Finally, channel routing calculations are done. These steps are realized by making full use of the Avenue programming capabilities. For example, the code for calculating local storage deficit [related to Eq. (1)] can be sketched as follows:

```
'NStep: number of time steps
'NAC: number of  $\ln(\alpha/\tan \beta)$  subdivisions
'SZM: value of  $m$  in Eq. (1)
'TL: mean  $\ln(\alpha/\tan \beta)$  value
'lstSD: an array of saturation deficit values
'lstST: an array of  $\ln(\alpha/\tan \beta)$  values
```

```
for each IT in 0...(NStep-1)
...
for each IA in 0...(NAC-1)
'Calculate local storage deficit
lstSD.Set(IA, SBAR + (SZM * (TL -
lstST.Get(IA))))
if (lstSD.Get(IA)<0) then 'saturated
lstSD.Set(IA, 0.0)
```

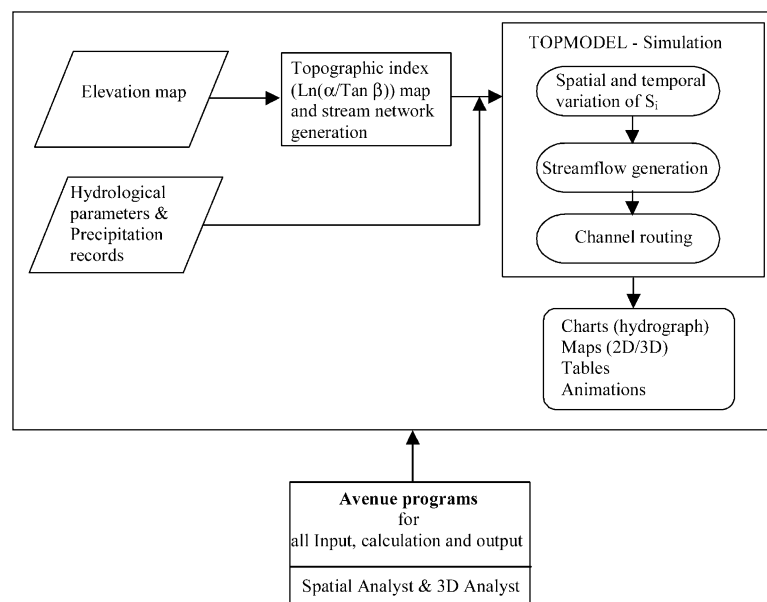


Fig. 2. Various functions developed with AVTOP.

```

'Display the saturated cells in the IATH
ln( $\alpha/\tan \beta$ ) subdivision
'thetheme can be a theme in a 2D view or a 3D
perspective view
theSymbol =
theTheme.UpdateLegend
end
end
...
end 'end of time step loop

```

List is utilized to represent the array such as the above `lstSD` and `lstST` by using `Set` and `Get` commands to set or get an array value. We also find that the 3D visualization of saturated contributing area is conducted along with the calculations. Only within a single language can such a sort of visualization be easily accomplished by GIS functions. Otherwise if some DLLs are built up inside the macro language, it would be difficult to organize these DLLs because there are two loops and to accept an array of output data from these DLLs. Furthermore, frequent passing of a pile of parameter values could lead to low efficiency of the program.

The output of AVTOP includes various graphical displays such as a hydrograph showing a curve of predicted streamflow, animation of soil saturation status at each time step in 3D perspective view, a two-dimensional (2D) map of soil saturation deficit, and other maps. All of these are made available by employing various parts of ArcView as well as Spatial Analyst, 3D Analyst and Dialog Designer extensions via Avenue coding.

#### 4. An illustration of the implementation

As we centre upon the integration approach and the environment development, we use sample datasets of the Slapton Wood catchment, Devon, UK to implement the model primarily due to data availability at the TOPMODEL website (<http://www.es.lancs.ac.uk/hfdg/topmodel.html>).

The Slapton Wood catchment covers 0.94 km<sup>2</sup>, 60% of which lies above the 90 m contour. Above 90 m, the slopes are gentle (generally less than 5%) and the land is intensively farmed, mainly as grassland and for cereal and root crops. Below 90 m, the slopes are steeper (up to 25%), and there is permanent grassland and a wood (which covers 13.5% of the catchment). The soils throughout the catchment are mainly freely draining acid brown soils with a clay-loam texture.

The sample datasets include the  $\ln(\alpha/\tan \beta)$  subdivisions, the rainfall, potential evapotranspiration and observed discharge data. Using these datasets, a set of examples has been developed mainly for deriving the topographic index map and supporting the whole simulation process of TOPMODEL.

#### 4.1. Topographic index

According to TOPMODEL, the predicted hydrological responses depend upon the distribution of the topographic index. In this study, the  $\ln(\alpha/\tan \beta)$  index map is derived by using grid cell-based functions in the Spatial Analyst.

Fig. 3 shows a catchment DEM and the resultant  $\ln(\alpha/\tan \beta)$  index map. The DEM has 71 rows and 51 columns with the cell size of 20 m. By analysing the range and areal extent of  $\ln(\alpha/\tan \beta)$  values, a single distribution function can be derived (Fig. 4, left). A distribution function for accumulated ranges of the  $\ln(\alpha/\tan \beta)$  index can also be derived (Fig. 4, right). Pixels having the same value of  $\ln(\alpha/\tan \beta)$ , or within the same range of  $\ln(\alpha/\tan \beta)$ , are assumed to behave in a hydrologically similar manner. These pixels are therefore modelled simultaneously, hence reducing the number of calculations performed by the model.

#### 4.2. Simulations

One of the important TOPMODEL predictions is the amount of streamflow, which is presented by a hydrograph as shown in Fig. 5 (for presentation purposes, only 300 of the whole 950 time steps are displayed). This hydrograph is drawn upon completion of the modelling process by using the Layout and Graphics related commands, from which the difference between the predicted flow data and the observed data can be found. In this case, the value of `SRinit` (initial value of root zone deficit) is '0.5'. By changing it to '0', the difference between the two curves becomes much smaller (Fig. 6). This indicates that the value of `SRinit` is very sensitive to the prediction result since it determines the amount of saturated deficit  $S_i$  that is essential to run-off generation in TOPMODEL.

The prediction of streamflow involves a series of calculations such as local storage deficit, root zone deficit, unsaturated zone storage and saturation excess. During this process, visualization of the dynamic changes of soil saturation status and saturation deficit is very helpful to understand the catchment responses to rainfall, or how the model works, from which users may be able to decide if TOPMODEL is suitable to represent a particular catchment under study. The saturated contributing areas are therefore displayed at each time step using a 3D perspective view (Fig. 7). The colour of the terrain surface stands for the topographic index value, while the saturated cells are displayed in yellow. The saturated cells in this case are closely related to the areas with higher topographic index values, which are close to the channel in the catchment.

The information about the time step is shown at the bottom of the window by using a working status bar. The saturation status map is updated at each time step

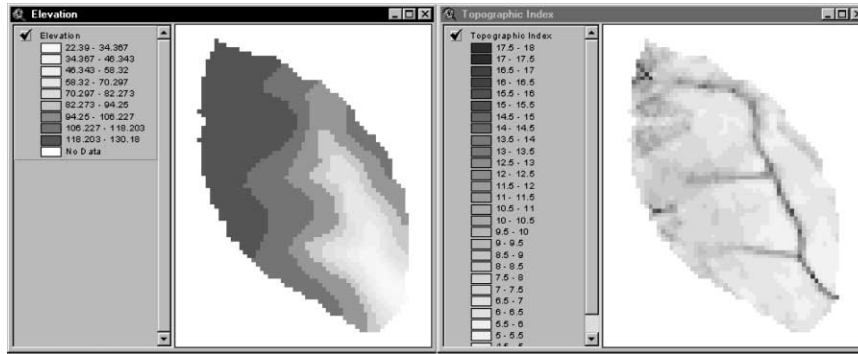


Fig. 3. Elevation data and the derived topographic index map.

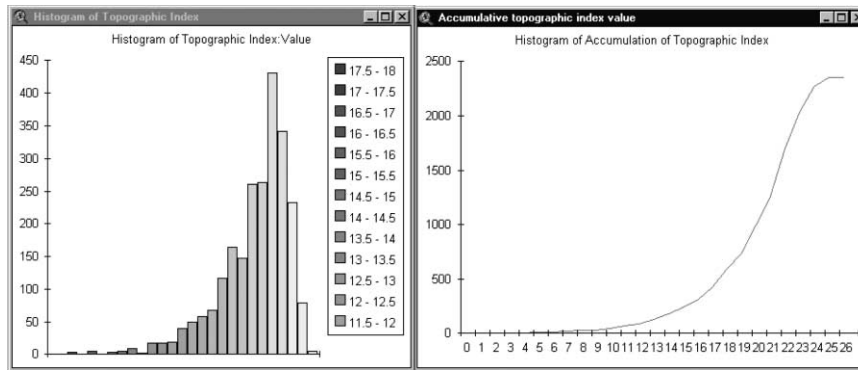


Fig. 4. A histogram of the topographic index value and a curve of the accumulative topographic index value.

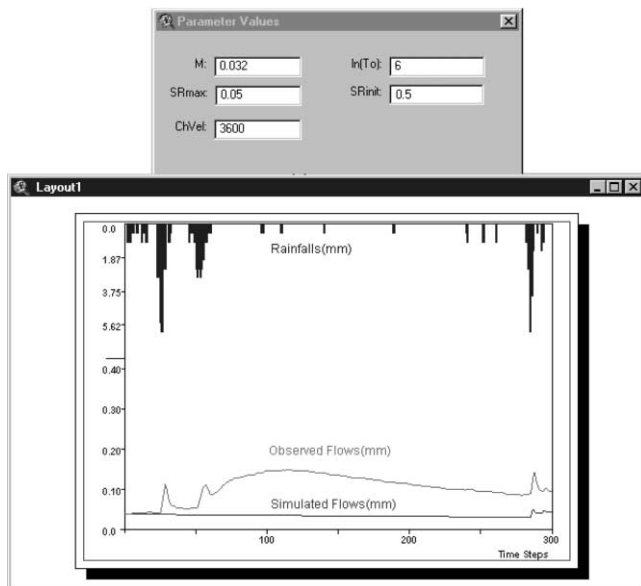


Fig. 5. Prediction of streamflow at each time time step with SRint value as '0.5'.

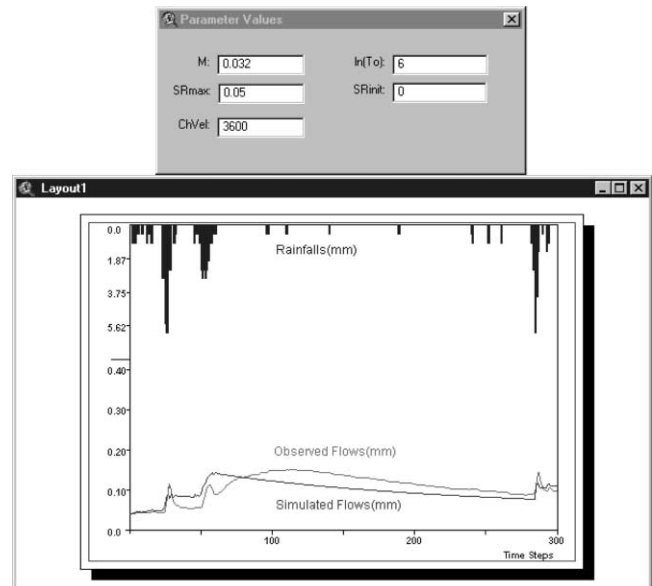


Fig. 6. Prediction of streamflow at each time time step with SRint value as '0'.

once the calculation is done, which possesses animation effects. Such an intuitive and dynamic view greatly facilitates users' understanding of the relationship between the hillslope run-off production and terrain characteristics. This commends itself to the objective of

TOPMODEL development as the model is always suggested as an aid to understanding before it is used as a predictive tool (Beven, 1997).

The saturation deficit map can also be displayed (Fig. 8), which is derived from the stored saturation deficit

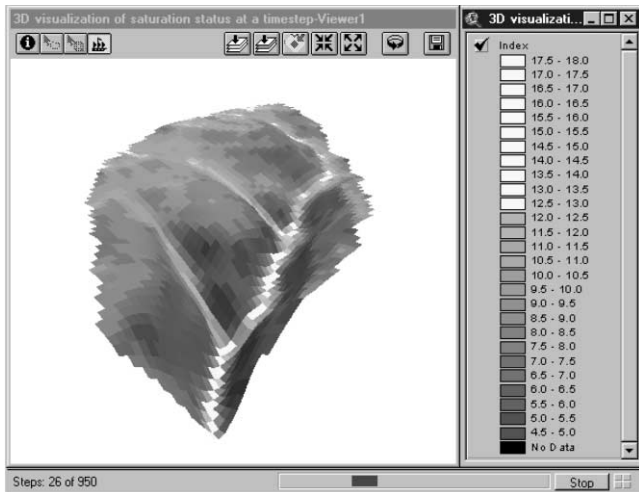


Fig. 7. A 3D perspective view of the saturation status at a time step.

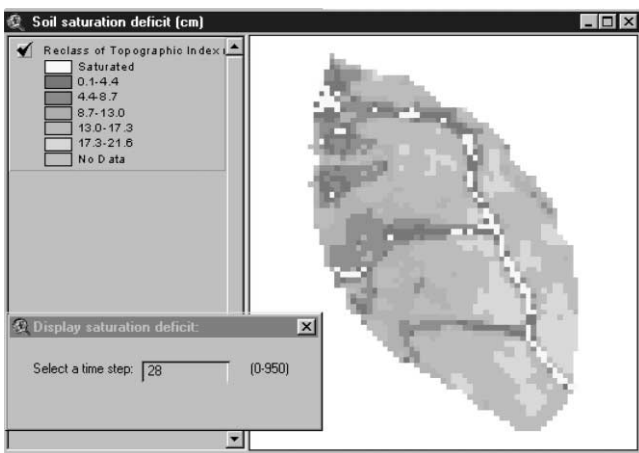


Fig. 8. Local saturation deficit map at a time step.

data at each time step by using the reclassification function. For this users need to input a time step number at a dialogue window.

To sum up, AVTOP developed here illustrates how it can give some insight into the spatial patterns of hydrological responses in a visual way, in terms of presenting both hydrographs and maps of the predictions of saturated area in the catchment under study based on the distribution of the topographic index.

## 5. Conclusions

This paper has sought to achieve a full integration of environmental models into GIS through the use of GIS macro languages. This is illustrated by the implementation of a typical hydrological model, TOPMODEL, fully through the macro language Avenue of ArcView. This full integration provides an exciting environment for the authentic fusion of environmental models and

GIS, within which all stages of model building can be undertaken — from the initial selection and transformation of datasets, to the final visualization of results in various ways such as chart, layout, 2D map and 3D perspective view in their spatial context. This environment is also high interactive, and it allows for users to conduct ‘what-if’ modelling easily. Through adjusting parameters and dynamically observing the corresponding results, it significantly facilitates exploratory data analysis, and makes better use of the model for decision making.

The new implementation of TOPMODEL in this study can serve as a tool to demonstrate how the integration of environmental modelling and GIS could be mutually beneficial. Environmental models may become more easily accepted due to the visual presentation provided by GIS, while GIS shows its potential in supporting a wider range of applications by exploring its existing functions. Such an implementation could also be a good example for environmental visualization (Bishop and Karadaglis, 1996), which attracts increasing interest in the field of environmental modelling.

The implementation of TOPMODEL can also include interactive parameter calibration and sensitivity analysis. We hope that the implementation described in this paper provides a basis for further implementations of this model.

It is noted that the implementation speed of a macro language may not be as fast as the programs written in low-level languages such as C/C++ and FORTRAN. To tackle this problem, an ideal alternative is to use the software components of GIS, providing that these components can fulfill the spatial analysis and visualization functions as required, and can be easily interfaced. We are looking forward to such a development of GIS industry towards more interoperability that is able to provide a more convenient environment for facilitating environmental applications.

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