Application of Geographic Information Systems in Hydrology and Water Resources Management

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Preface

In 1993 the first HydroGIS conference was held in Vienna. It gained considerable interest from the hydrological scientific community which was reflected by the fact that it was necessary to print a second edition of the proceedings (IAHS Publ. no. 211) in December 1993. Further, at the end of the 1993 conference many participants expressed their interest in a follow up meeting. These facts stimulated and encouraged the conference convenors to organize a second conference: HydroGIS'96.

The main goal was to track the progress in the methodology of GIS and in sophisticated applications in water-related areas during the last three years. Also, it was hoped that GIS will promote the development and application of hydrological models which are more physically based spatially. There is still a need to identify research directions with respect to the specific GIS requirements of hydrology and water resources. The second conference also aimed to help participants in determining critical factors in their evaluation of the applicability and benefits of GIS for their own field of work.

The response to the first circular clearly justified the decision to have another conference. About 280 abstracts were received from which 110 were selected for oral presentation while it was concluded that 70 papers would be more appropriately presented in a poster session. Finally, 83 papers have been included in this volume and a poster volume is being independently published by the local organizers.

The following topics were selected to set the frame for the conference:

* GIS Functions and Hydrological Modelling
* Methodological Aspects
* Coupling GIS with Hydrological Models
* Digital Terrain Models in GIS
* Application of GIS in Water and Environmental Management
* Application of GIS in Surface Water Systems
* Application of GIS in Groundwater Systems
* Remote Sensing and GIS
* GIS in Relation to Decision Support and Expert Systems

It is the opinion of the convenors that this volume documents the experiences and especially the progress in GIS applications in the hydrological sciences. It is expected that the specific requirements of hydrologists addressed to GIS will be reflected in the contributions and in future GIS development.

The interest and financial support of UNESCO in the conference are greatly appreciated. The conference is explicitly contributing to the new IHP-V programme (1996-2001): *Hydrology and water resources development in a vulnerable environment*.

The Conference Convenors:

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1 GIS Functions and Hydrological Modelling

HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996). IAHS Publ. no. 235, 1996.

An adaptive GIS toolbox for hydrological modelling

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Abstract An adaptive GIS toolbox for hydrological modelling (WET-SPA) is under development. The toolbox can be used for modelling elements of the hydrological cycle, including the evapotranspiration process, runoff generation, flow in unsaturated and saturated zones, by considering water and energy transfers. The toolbox supports different temporal and spatial scales. Dependent on these scales, the tools are numerical and/or parameterized distributed models, which are automatically adapted to the available input information. In this way, the toolbox meets various demands in hydrological practice. All the tools run under UNIX and most are programmed in an object-oriented fashion (C++), such that reusability and portability to other GIS packages is increased. Presently, GRASS is used to manipulate and present graphically spatial and temporal hydrological and geographical data.

INTRODUCTION

Reviewing the HydroGIS'93 proceedings (Kovar & Nachtnebel, 1993), it appears that the main contribution of GIS to distributed hydrological modelling lies in the use of its graphical and spatial analysis capabilities in existing hydrological models. Many models were interfaced to a GIS to improve their pre- and postprocessing. Only few hydrological models or functions are built in the GIS itself at batch or library level (Batelaan *et al.*, 1993).

The purpose of this work is to develop a generic set of tools for hydrological modelling which give both possibilities of integration and interfacing to different GIS. To make use of the power of GIS, the tools should be adaptive to the spatial and temporal resolution of the available data. In this way, the toolbox will be able to meet a range of demands in hydrological practice. To facilitate the integration, the hydrological model code should be, as much as possible, reusable and portable. These considerations lead to applying an object-oriented programming technique to develop these tools.

THEORY OF WET-SPA

Usually, in distributed hydrological modelling the hydrological processes are simplified or parameterized. The developed toolbox tries to minimize those simplifications as much as possible, in order to predict the dynamics of the Water and Energy Transfers within and between the Soil, Plants and Atmosphere (WET-SPA).

The land-surface and subsurface soil is divided in five layers, including atmosphere, canopy, root zone, transmission zone, and saturated zone. In order to deal with the heterogeneity, the toolbox divides a basin or an area into a number of grid cells. Each grid cell is further divided into a bare soil and vegetated part. By maintaining the energy and water balance for each zone in a grid cell, it calculates amongst other evapotranspiration, runoff, flow in unsaturated and saturated zone. Calculated groundwater recharge can be used subsequently in transient groundwater modelling. Both saturation excess runoff and infiltration excess runoff are simulated. Figure 1 gives a schematic picture of the considered hydrological processes.

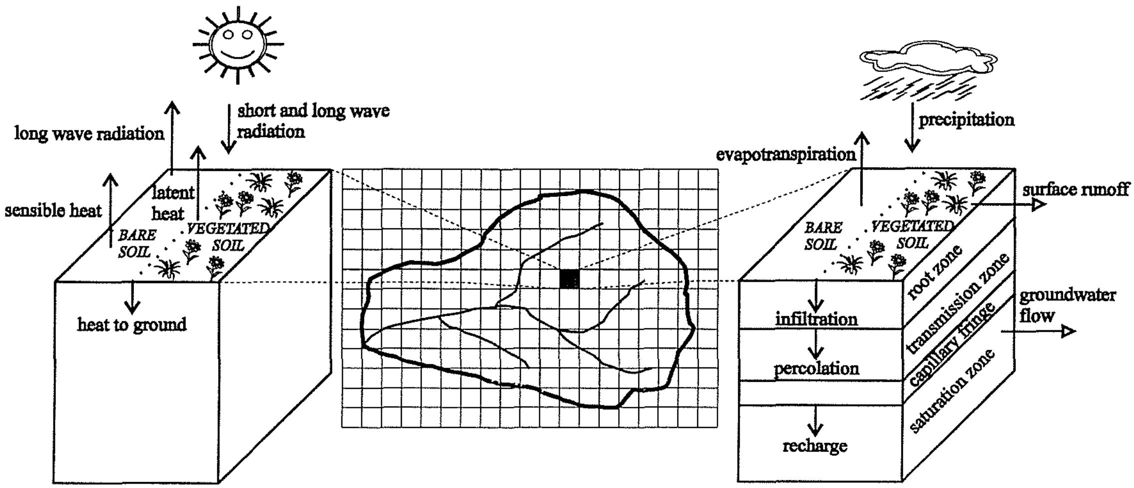

Fig. 1 Water and Energy Transfer considered processes in the Soil, Plant and Atmosphere system (WET-SPA toolbox).

In the following sections, each water and energy balance component is briefly discussed. Details can be found in literature e.g. Brutsaert (1982), Eagleson (1978) and Famiglietti & Wood (1994a).

Water balance in the canopy

The water balance for the canopy is given by:

$$\frac{\mathrm{d}w_c}{\mathrm{d}t} = p - e_{wc} - p_{net} \qquad 0 \le w_c \le w_{sc} \tag{1}$$

where w_c is the water amount in the canopy, t is time, p is the precipitation, e_{wc} is the wet canopy evaporation, p_{net} is the net precipitation under canopy, that is the precipitation that occurs when the canopy water storage capacity, w_{sc}, has been exceeded (Famiglietti & Wood, 1994a).

Water balance in the root, transmission and saturated zone

All the soil water transport in the unsaturated zone is assumed to be vertical and noninteractive between grid cells. By following the Brooks and Corey's notation (Brooks

& Corey, 1964) the hydraulic conductivity, soil matrix potential and the soil moisture content are defined in terms of soil properties.

When the groundwater table lies beneath the bottom of the root zone, the root zone water balance equation is:

$$z_{rz}\frac{\mathrm{d}\theta_{rz}}{\mathrm{d}t} = a_{bs}i_{bs} + a_v i_v + w - a_{bs}e_{bs} - a_v e_{dc} - g_{rz} \tag{2}$$

$$z - \psi_c \geq z_{rz} \qquad \theta_r \leq \theta_{rz} \leq \theta_s \tag{3}$$

where z_{rz} is the root zone depth, θ_{rz} is the uniform moisture content in the root zone, a_{bs}, i_{bs} and a_v, i_v are respectively the areal fraction and infiltration rate of bare soil and vegetated land surface, w is the capillary rise rate from the groundwater table (Eagleson, 1978), e_{bs} and e_{dc} are respectively the evaporation from bare soil and dry canopy, g_{rz} is the downward soil water flux from the base of the root zone, ψ_c is the air entry suction head, θ_r is the residual water content and θ_s saturated water content. When the groundwater table lies within the root zone and the depth to the capillary fringe is denoted by z^*_{rz}, the root zone water balance equation is:

$$z^*_{rz}\frac{\mathrm{d}\theta_{rz}}{\mathrm{d}t} = a_{bs}i_{bs} + a_v i_v + w - a_{bs}e_{bs} - a_v e_{dc} - g_{rz} \tag{4}$$

$$z^*_{rz} = z - \psi_c \qquad z_{rz} > z - \psi_c \geq 0 \qquad \theta_r \leq \theta_{rz} \leq \theta_s \tag{5}$$

According to Milly (1986), the infiltration is taken as the minimum of the infiltration capacity and the precipitation or the net precipitation under the canopy. Milly (1986) expressed the infiltration capacity in terms of cumulative infiltration, soil properties, and root zone moisture content at the start of each storm event.

The bare soil evaporation is taken as the minimum of a bare-soil controlled exfiltration capacity and the atmospherically controlled potential evaporation for bare soil, which is an energy balance variable. Following Milly (1986), the bare soil exfiltration capacity is taken as a function of cumulative exfiltration, root zone moisture content at the start of an interstorm period, and soil properties. The transpiration from dry canopy is obtained from the minimum of the vegetation-controlled transpiration capacity and the atmospherically controlled unstressed transpiration, which is an energy balance variable. The vegetation-controlled transpiration capacity is based on the macroscopic root system model (Feyen *et al.*, 1980). The downward soil water flux from the root zone base is assumed to be a gravity driven flow (Famiglietti & Wood, 1994a).

The water balance equation for the transmission zone is:

$$z_{tz}\frac{\mathrm{d}\theta_{tz}}{\mathrm{d}t} = g_{rz} - g_{tz} \qquad z_{tz} > 0 \tag{6}$$

$$z_{tz} = z - \psi_c - z_{rz} \qquad \theta_r \leq \theta_{tz} \leq \theta_s \tag{7}$$

where θ_{tz} is the transmission zone moisture content, z_{tz} is the transmission zone depth, and g_{tz} is the downward flux from the base of transmission zone to groundwater table, which is also assumed to be a gravity driven flow (Famiglietti & Wood, 1994a).

The water balance in the saturated zone involves updating the groundwater table altered by the recharge and depletion due to capillary rise, evapotranspiration, and base flow. The groundwater table depth affects the local water balance. When the water table reaches the land surface, the land surface becomes saturated. All rainfall on these areas, which are commonly called source areas, is transformed to saturated excess runoff.

A topographic representation of groundwater table dynamics is used. Under quasi-steady-state conditions, Sivapalan *et al.* (1987) derived a simple expression for the local water table depth in terms of a local topographic soil index. Alternatively, a transient groundwater model can be used, like MODFLOW, to calculate the initial groundwater depth and the dynamics of the groundwater table.

The basin water runoff is simply the average of the grid element values.

Energy balance

This toolbox uses the energy balance to determine evapotranspiration related variables, such as entire wet canopy evaporation, the transpiration of unstressed vegetation and the potential evaporation from bare soils.

A one-layer resistance model for the energy balance is used (Brutsaert, 1982). The horizontally homogeneous, one-dimensional surface energy balance can be written as:

$$R_n = \rho_w LE + H + G \tag{8}$$

where R_n is the net radiation, $\rho_w LE$ is the latent heat flux into the atmosphere, of which ρ_w is the density of water, L is the latent heat of vaporization, E is water evaporation from a surface, H is the sensible heat flux into the atmosphere and G is the heat flux into the ground. The net radiation can be expanded into several components:

$$R_n = R_s(1 - \alpha_s) + R_{ld} - \epsilon_s \sigma T_s^4 \tag{9}$$

where R_s is the global shortwave radiation, α_s the albedo of the surface, R_{ld} is the downward longwave radiation, ϵ_s is the surface emissivity, σ is the Stefan-Boltmann constant, and T is the temperature of the surface such as the wet canopy, dry canopy, or bare soil surface.

The latent heat, $\rho_w LE$ and sensible heat, H are functions of surface temperature and humidity, and also aerodynamic resistance and canopy resistance, if vegetation is available. The heat flux into the ground, G, is a function of the thermal conductivity of the soil and temperature gradients in the soil (Brutsaert, 1982; Famiglietti & Wood, 1994a).

The grid cell evapotranspiration is determined by summing the bare soil and vegetated components, weighted by their corresponding areal fractions. The basin energy balance flux is simply the average of the grid cell values.

TOOLBOX DESIGN FOR GIS USE

The idea is to design the toolbox with the concept of objects and to relate objects *via* certain rules. As the object-oriented technique suggests, one must identify all different objects in the system of interest. In the toolbox, the basin is divided into a number of grid cells in which the water and energy transfer are calculated. Intuitively, we can treat the basin and grid cells as classes. The class *Basin* is responsible for the basin scale operations of the toolbox, and the class *Grid* for the grid cell operations. To get further isolation, in order to make coding easier, we also define each layer as a class, including classes *Atmosphere*, *Canopy*, *RootZone*, *TransmissionZone* and *SaturationZone*. A supporting class, *Data Bank*, is designed to manage all input data. All other classes inherit data and data-managing methods from it. An *Application* class is defined, too. In fact, this class simply calls the public methods of other classes and makes the toolbox function.

By following this scheme the WET-SPA toolbox gets an adaptive spatial character. The object-oriented coding assures relatively easy integration or interfacing with GIS. As an example, WET-SPA has been interfaced with GRASS for graphical and spatial pre- and postprocessing. To extend the toolbox, MODFLOW will be added for the saturated groundwater flow modelling. RIM, relational database is used together with GRASS for data management. These different hydrological tools, GIS and database functions will be grouped together under a new shell called "Water Resources Analysis Support System" (WRASS).

THE TERKLEPPE CASE STUDY

The area on which the toolbox has been applied is the basin of Terkleppe-Molenbeek (Fig. 2). The basin is 19.1 km^2 and a tributary of the Dender basin. The topography in the area ranges from 15 to 130 m above sea level. Within the framework of the basin committee for the Dender, an integrated water management plan was set up for the Terkleppe-Molenbeek (Batelaan & De Smedt, 1995).

A steady-state groundwater model was used to calculate infiltration and groundwater discharge areas, flow systems, flow times, and water balances for each hydrological zone. The model used average groundwater recharge for the basin, based on the analysis of a 21 year discharge series at the outlet of the basin. The results of this model,

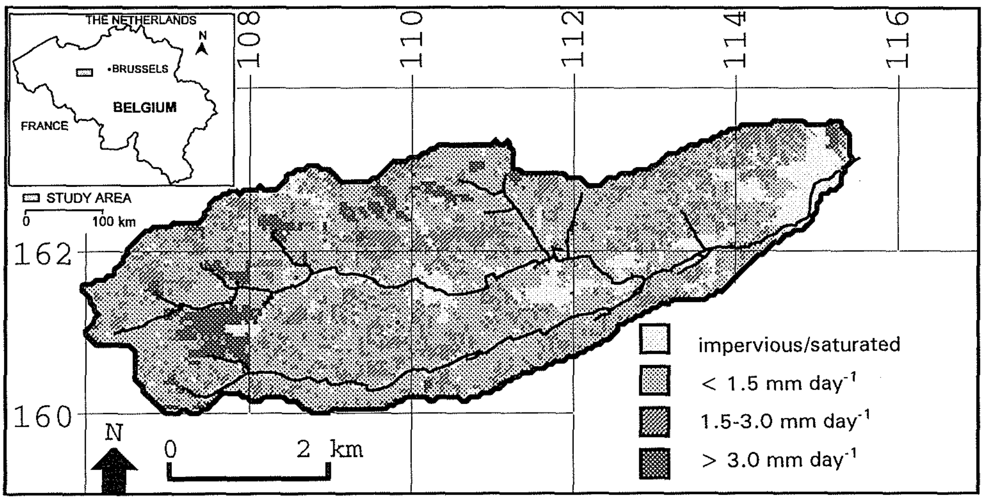

Fig. 2 Setting of Terkleppe Molenbeek and WET-SPA calculated groundwater recharge for Terkleppe-Molenbeek on 9 October 1977.

together with water quality analyses and biological evaluation of the area, were translated in the integrated water management plan in measures for protection of water and nature and development of nature.

In order to be able to investigate the effects of options for different land use within the basin on the water system, a more distributed model, especially with respect to the groundwater recharge, is required. For this purpose the WET-SPA toolbox is applied to this basin.

As a case study, the WET-SPA toolbox was applied on a daily scale for a period of 80 days in 1977. For the saturated zone, the steady-state groundwater level was used for the initial groundwater level in the toolbox. A digital terrain model (DTM), with a resolution of 10 by 10 m, was used to calculate the topographic soil index. A digital soil map was used to classify the soils in the basin. The soil types ranged from sand to clay (four classes). Also, a separate class for impermeable areas was taken into account. Different soil related parameters were taken from literature (Brutsaert, 1982; Dickinson *et al.*, 1993; and Famiglietti & Wood, 1994b). A land use map was derived from the biological evaluation map of the area. Five different vegetation types were considered, including bare soil. The parameters for those vegetation types were taken from Dickinson *et al.* (1993). Daily precipitation measurements were available from a station at the outlet of the catchment. Daily short-wave radiation, air temperature, relative humidity, wind speed and surface air pressure are taken from the Ukkel meteorological station, 30 km west of the basin. The meteorological data was assumed to be constant over the basin.

As an example of the results from WET-SPA, Fig. 2 shows the calculated distributed groundwater recharge for the Terkleppe-Molenbeek basin on 9 October 1977, a day after eight moderate rainy days with about 3 mm day^{-1}. Most of the basin has a recharge of about 1.5 mm day^{-1}. No recharge occurs in impermeable areas and groundwater discharge areas along the rivers. These areas are runoff source areas. It can be seen that in the eastern part of the basin a zone with higher groundwater recharge appears, corresponding to an area of sandy soils. Other results, like surface runoff, soil moisture content and evapotranspiration show good agreement with topography, soil type, vegetation type and land use. All this information can help in studying the natural evolution of the water system and the impact of human activities.

CONCLUSIONS

The developed toolbox analyses Water and Energy Transfers in Soils, Plants and Atmosphere (WET-SPA) on a regional scale with different time intervals, e.g. hourly or daily. It requires only routine meteorological observations and topographical, soil and vegetative information.

Distributed hydrological modelling can benefit from GIS, when the modelling tools are interfaced or integrated with the GIS and when they are spatially and temporally adaptive. Therefore, the developed toolbox WET-SPA follows an object- oriented approach. This results in increased portability and reusability of these tools for use with different GIS. In this study it is shown that WET-SPA can easily be integrated with GRASS and that distributed hydrological fluxes are obtained.

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Integration architecture and internal database for coupling a hydrological model and ARC/INFO

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Abstract This paper discusses an interface system that couples GIS (ARC/INFO) and an advanced hydrological model SWAT (Soil and Water Assessment Tool). The discussion emphasizes the design of the interface system and an internal database. Because both ARC/INFO and SWAT are mature and complex. The interface system, therefore, includes an external graphical user interface and an object-oriented internal database to couple the two systems. For the internal database, hydrological parameters are treated as different classes of objects, and their mathematical relationships are coded as associations.

INTRODUCTION

In the 1990s, hydrological modelling community has paid great attention to developing "front ends" (pre-processing of input data to prepare parameters for models) and "back ends" (post-processing of results visually, statistically, and numerically) for hydrological models. Up to date, seeking effective integration between hydrological models and GIS is still an on-going effort. This paper reports a case study, in which an interface system is developed to couple a GIS system and a hydrological model.

The primary objective of the interface system is to integrate ARC/INFO, a widely used comprehensive GIS software package, and SWAT (Soil and Water Assessment Tool; Arnold *et al.*, 1993), a hydrological model of advanced capabilities (the PC version). Specifically, the interface system aims to fulfil the following tasks: (a) streamlined GIS processes tailored toward hydrological modelling needs;

(b) automated data communication between GIS and the hydrological model; and (c) a user-friendly data management environment for the hydrological model. The first and the third task were discussed elsewhere (Blodgett *et al.*, 1995; Bian *et al.*, 1996). This paper emphasizes the design of the interface system and an internal database that fulfils the second task.

The paper proceeds with a brief description of the SWAT model and its input file structure. The section following discusses the design of the interface system and related issues. The last section describes the design and functions of the internal database.

THE SWAT MODEL

The SWAT model is designed to predict the effect of agricultural management decisions on water and sediment yields for large ungauged rural watersheds. The model consists of major water budget components and agricultural management factors. It runs on a daily time step for short or long term predictions. In terms of spatial consideration, SWAT accounts for spatial differences in many hydrological and agricultural management parameters. It allows a watershed to be divided into hundreds of areal units, either by polygon sub-watersheds or regular grids. This semi-distributed characteristic is well suited for integration with GIS. Using GIS data, SWAT has been applied to many major river systems in the United States with promising results (Koussis *et al.*, 1994; Srinivasan *et al.*, 1993).

Like many advanced models, SWAT is not without shortcomings. The model requires a large number of parameter input files that must be prepared prior to model execution. The input files are organized at either basin or sub-basin level. At the basin level, SWAT needs more than 10 separate input files; for each sub-basin, SWAT can use up to nine input files. For a 10-sub-basin watershed, a user may have to prepare nearly one hundred input files, with each containing 10-30 parameters. SWAT provides a simple user interface to facilitate data entry and editing, but does not have facilities to communicate directly with ARC/INFO. The data transfer between the two systems can be overwhelming. A more integrated, advanced user interface would significantly enhance the capability and usability of SWAT.

INTERFACE DESIGN

A range of integration architectures have been proposed and implemented for coupling GIS and environmental models (Abel *et al.*, 1994; Maidment, 1993; Chou & Ding, 1992; Nyerges, 1993). Abel *et al.* (1994) summarized three major integration architectures. A simple two-component architecture supports one-way data transfer between two independent systems. It warrants low cost for implementation but low usability as well. An "embedded" two-component architecture allows a master component to use the capabilities of an agent component. This is a more integrated approach; the usability and costs depend on the capabilities of the master component. A many-component architecture consists of two or more master components; they share common agent components such as a database management system and/or an external user interface. This option provides a more integrated system yet tends to be costly but it is desirable when the component systems are complex.

The two systems being integrated, ARC/INFO and SWAT, are mature and complex, each with its own data model, operation mechanism, and user interface. ARC/INFO is a commercial software package and a closed system. Direct data access and function extension, though fast, are not practical; these are usually conducted through ARC macro language. The SWAT model is a public domain package and its data access is straightforward. Like ARC/INFO, SWAT is also a closed system; modification of the model can be intricate.

Using a two-component integration architecture n this case simply means to streamline the GIS procedures within ARC/INFO and transfer the results to SWAT. This approach avoids modification of the two systems but is a low level integration; the user must operate in two different interface environments as pointed by Abel *et al.* (1994) and Chou & Ding (1992). The amount of the transfer can easily trade off with the easy implementation.

A second scenario, the "embedded" architecture, may apply to the two systems differently. If ARC/INFO is the master component, executing SWAT within ARC/INFO environment is not difficult but preparing SWAT input files in ARC/INFO requires significant (probably inefficient) effort. Alternatively, SWAT may not be able to operate as a master component. It does not facilitate direct communication with ARC/INFO, so a new set of operations must be developed. With the same amount of effort, a more integrated interface can be developed.

The many-component architecture is adopted for this study. The two systems, ARC/INFO and SWAT, are dealt with as two independent master components. The conceptual design of the interface system includes an add-on external user interface and a shared internal database to couple the two systems. This approach avoids direct modification yet uses operations already present in the two systems. It is the most appropriate for complex, closed systems like ARC/INFO and SWAT. The interface system uses ARC/INFO macro operations to streamline the GIS processes. The external graphical user interface (GUI) is developed using Visual Basic. The interface provides a user-friendly environment for data management. The internal database is developed in an object-oriented environment for effective communication between ARC/INFO and SWAT.

INTERNAL DATABASE

The specific tasks of the internal database include importing spatial information extracted in ARC/INFO to the database, managing both spatial and non-spatial data, and transferring data into SWAT input files. The user communicates with the internal database via the external GUI. The database is developed with an object-oriented approach using C++.

Object orientation has become a key issue in database related research in recent years. The primary contribution of object-orientation to database development lies in several aspects. Its data model captures the semantics of the real world; this is perhaps its single most important contribution toward a natural representation of reality. In addition, object oriented approach binds data and their schema, thus providing flexible customization. Encapsulating behaviour with an object forms a natural, integrated entity and differs greatly from the conventional approach. Inheriting properties and behaviour along the object hierarchy allows code reusability and efficient programming. All these features promise the object-orientation to surpass conventional databases in dealing with objects (Gunther & Lamberts, 1994: Roberts & Gahegan, 1993; Ochuodho, 1992).

The object-oriented database developed in this project aims at supporting the SWAT model; its design and usability are thus dictated by the specific needs of SWAT. At the current point, the database is not a full-scaled database management system (DBMS). Several features of a full-functioned DBMS, such as concurrence, recovery, and distribution are not addressed. In particular, the database is designed for storage and retrieval of persistent real world objects, handling their relationships, and providing an object class library. Although a rich volume of object-orientation research is published; the actual implementations are few. The design principle and implementation experience learned from developing this database is valuable for more advanced work, such as a more generic hydrological DBMS or object-oriented hydrological models.

Development of the database requires an object-oriented requirement analysis. Typically, the requirement analysis consists of three basic components: an object model, a dynamic model, and a functional model. Object modelling describes objects and their relationships, normally through graphic type views. Dynamic modelling uses graphic statecharts to specify sequences of events. Using data flow diagrams, functional modelling depicts the processes exerted on objects and flow of object attributes (Khoshafian, 1993). Obviously the latter two are not applicable in this case because they are actually realized in the hydrological model. The object modelling is discussed in detail.

The basis of the object model are objects and their relationships. The latter can be represented by classification, association, and aggregation (Khoshafian, 1993; Kainz & Shahriari, 1993; Milne *et al.*, 1993; Egenhofer & Frank, 1992; Van Oosterom & Van den Bos, 1989). Figure 1 presents a type view of the data model for the database using methods described in Cook & Daniels (1994). Each rectangle represents an object and all linear symbols represent relationships between objects. The name of the object is at the top of the rectangle. The portion below the line is for descriptions of object properties (attributes) and object operations (behaviour).

The lines with triangles indicate the classification hierarchy, in which the super-classes are at the points while the contributing subclasses are next to the triangles. A sub-class is specialized objects of its super-class; it inherits all the properties, operations, and associations of its super-class. Lines with nodes on either end depict associations or aggregations. A filled node indicates that the object next to it has a multiple association. A many-to-many association occurs when multiple associations are at both ends. An aggregation can be recognized by a diamond and a node at either end; objects at the node ends are components of the composite objects that are adjacent to the diamonds. Again the filled nodes indicate a multiple aggregation.

There are two main object types, GEOMETRY that contains all spatial objects, and MODEL that contains all model parameter objects. The spatial and parameter objects are dealt with as two distinct objects types, and the geometry is a component of the model objects. This basic design captures the semantics of the hydrological world and is well suited to the role of the interface in supporting hydrological modelling.

The GEOMETRY object type is used primarily to handle spatial information derived from ARC/INFO. Because of performance concerns, ARC/INFO procedures only provide intermediate data such as the areas of individual soils polygons in a sub-basin. The actual calculation for preparing, for example, area-weighted parameters, is carried

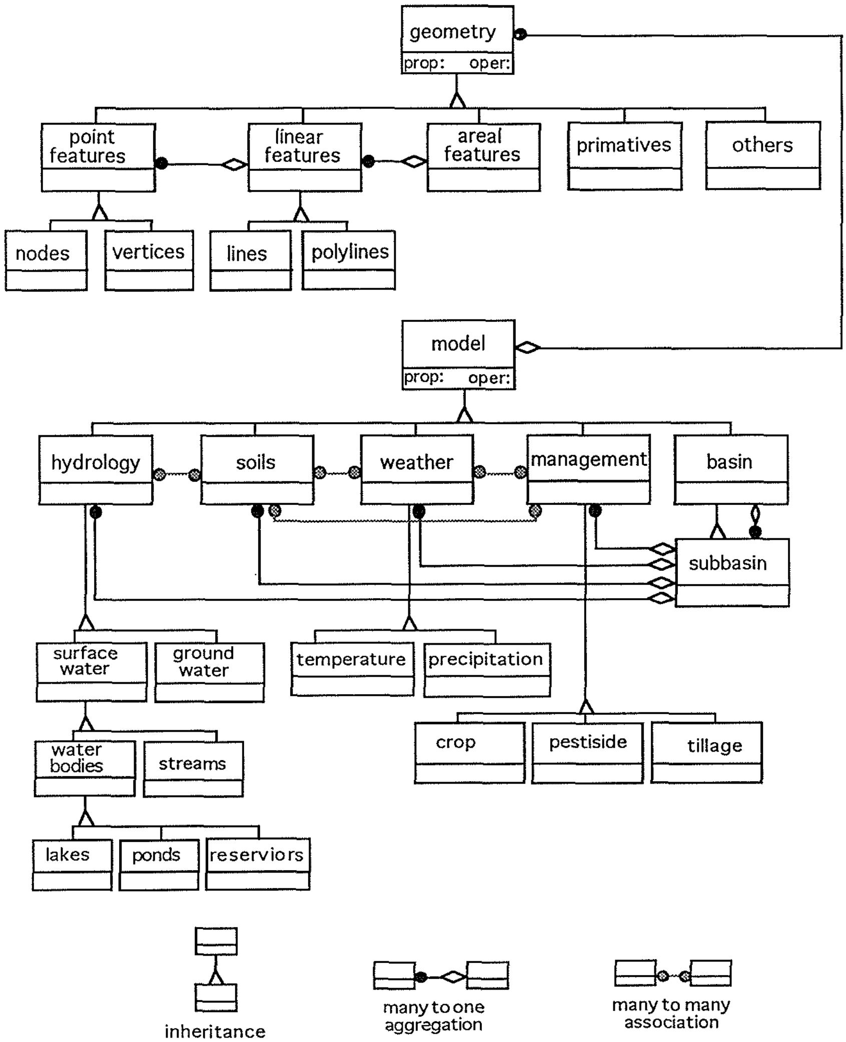

Fig. 1 The type view of the data model for the internal database.

out by the internal database. The GEOMETRY object type includes typical geometric objects such as point, line, and areas. Typical properties of the geometric objects are area or length. The operations for the objects include computation of areal percentage for areal features or sum of lengths for linear features. Overall, GEOMETRY has a shallow hierarchy as suggested by Gunther & Lamberts (1994) because operations are too specialized to be efficiently inherited through a deep hierarchy.

The MODEL objects are so defined that they closely correspond to the real world entities. In the mean time, the definition retains as close as possible but not restricted to the file structure of SWAT, in which many input files already correspond to real world entities such as soils, water bodies, weather, and agricultural practices. Objects that directly correspond to an actual SWAT input file may be at different levels in the hierarchy, but the file-equivalent objects are always the primitive objects that are no longer decomposable. This design is easy for data passing and keeps the integrity of hydrological objects. All the associated MODEL objects have many-to-many relationships between themselves.

In the database, hydrological parameters are treated as properties of the primitive objects, similar to the way they are organized in the SWAT input files. For example, all soils parameters such as soil texture and depth are the properties of primitive object SOIL. The primary operations of the MODEL objects are checking data types and value ranges. The object SOIL inherits all properties and operations of MODEL and has parameter properties and operations unique to itself. A particular soil series is an instance of SOIL. As part of a sub-basin, most the subclasses of the MODEL object are aggregated to SUBBASIN object, which in tern is aggregated to the BASIN object.

The mathematical relationships between the hydrological parameters are implemented as associations. Typically, hydrology, weather, soils, and agricultural management are related to each other in hydrological processes. Implementing such associations can help validate internally the input parameter values. For example, water stress factor is computed by considering several parameters including evapotranspiration, which is in turn calculated using temperature. Water stress factor can also be entered independently; thus its input value can be evaluated according to its associations to temperature input. This is a more advanced validation mechanism than the simplistic maximum and minimum checking, and the validation is easy to implement in an object oriented database.

The database is implemented in Dynamic Linked Library (DLL) format to communicate with the external GUI. An Application Programming Interface (API) internally interfaces the DLL and the GUI. All operations for data management and data transfer initiated at the external user interface can be implemented in the database.

Object-oriented database emphasizes natural representation of the real world. The behaviour and data of a real world entity can be represented by a single object . The association and inheritance are powerful for data and hydrological modelling. In short, Object orientation promises bright future for generic hydrological DBMS and highly integrated hydrological modelling. It is hoped that this research will contribute to the better understanding of hydrological model and GIS integration, and ultimately contribute to effective water resources management.

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ATHYS: a hydrological environment for spatial modelling and coupling with GIS

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Abstract ATHYS was born out of the need to define and develop an operational tool for using spatially distributed hydrological models. These models require processing of a large volume of hydrological and geographical data and the use of specific tools and complex software (DBMS, image processing, GIS). For hydrologists, these tools are not always easy to manage. Contrary to the solution by integrating models in GIS, ATHYS offers an environment designed more specifically for hydrologists. This environment regroups in a homogeneous framework three main modules: (a) a preprocessor for hydrological data, which reads, displays, selects and stores discharge and rainfall time series data; (b) a preprocessor for geographical data, which includes a viewer for map files and a DEM processing tool; (c) a list of distributed models which can be used and compared according to the user's choice. ATHYS's interface is based on Tcl/Tk, which was developed in a UNIX/X-Windows environment. An application of ATHYS is also presented, showing the importance of such tool in hydrological modelling.

INTRODUCTION

The use of spatial hydrological models is often not easy. It implies the processing of hydrological and rainfall data, manipulation of geographical information and DEM data, programming of algorithms and display modules. The latter have to be adapted to a distributed parameter structure. Most of these tools exist as separate modules which are not necessarily adapted to the needs of the hydrologist. GISs are essential for processing spatial information, several of which have been adapted to include a hydrological dimension (Chairat & Delleur, 1993; Delclaux & Boyer, 1993; Romanowicz *et al.*, 1993; Stuart & Stocks, 1993). Their use implies an important investment for hydrologists even though they only use a limited number of functions. On the other hand, hydrologists require specific processing, such as data generation derived from DEM, spatial interpolation of rainfall, etc. These exist in various environments.

Also hydrological models themselves use different systems and are difficult to compare. Thus in order for a hydrologists to model distributed hydrological processes, one must be competent in geography, satellite imaging, geomorphology, geostatistics, algorithmic programming and data processing.

Since ORSTOM collaborates with many developing countries, it was necessary to develop an open system in order to enable cooperation with its partners while remaining compatibility with existing data.

When developing ATHYS (ATelier HYdrologique Spatialisé), our objective was to minimize the external knowledge required by a hydrologist and propose an open, user-friendly environment specific to hydrology. Such system would allow the user to focus on the modelling itself.

STRUCTURE OF ATHYS

Basic principles

The basic principles which preceded the development of ATHYS are:

(a) a dedicated hydrological environment for distributed modelling, including a series of models, DEM processing, hydrological and rainfall data and geographical display, spatial data interpolation;

(b) an application environment completely separated from GIS, image processing and databases. The bridge between these tools is performed using standard file formats (e.g. TIFF, DXF, etc.);

(c) a modular environment which permits integration of external applications and future developments;

(d) work station environment under UNIX/X-Windows with a Tcl/Tk as the user interface language and the Xf program generator (Delmas, 1993; Ousterhout, 1993).

ATHYS is composed of three principal modules (Figs 1 to 3): a preprocessor of hydrological data, a preprocessor of geographical data and the models.

Hydrological preprocessor

This module permits the fusion of stream flow and rainfall data for a water basin including the selection of events for modelling. It also allows display and modification of the selected data.

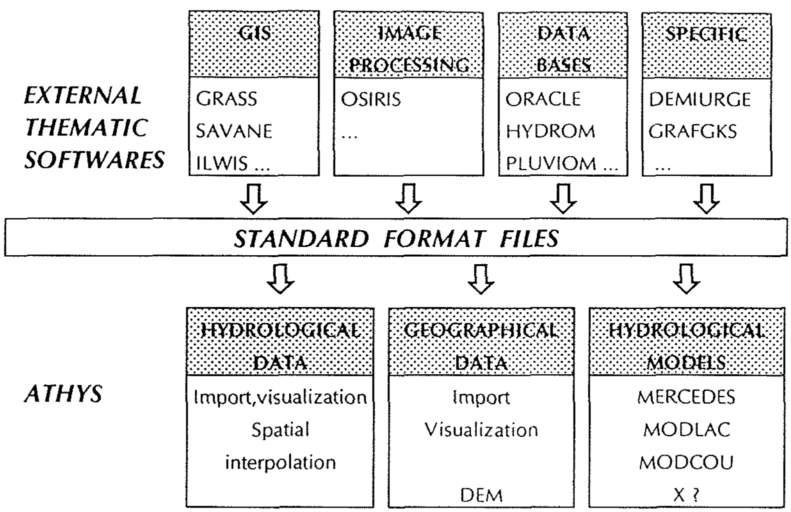

Fig. 1 Functional scheme of ATHYS environment.

A second module generates a spatial rainfall grid using specific data and interpolation using spline functions or kriging (Delclaux & Thauvin, 1991).

Geographical preprocessor

A visual display of cartographic data, VICAIR (VIsualisation de CArtes et d'Information Raster) displays spatial information required by the models: raster, vector and point. VICAIR was adapted from the visual display module of a public domain program

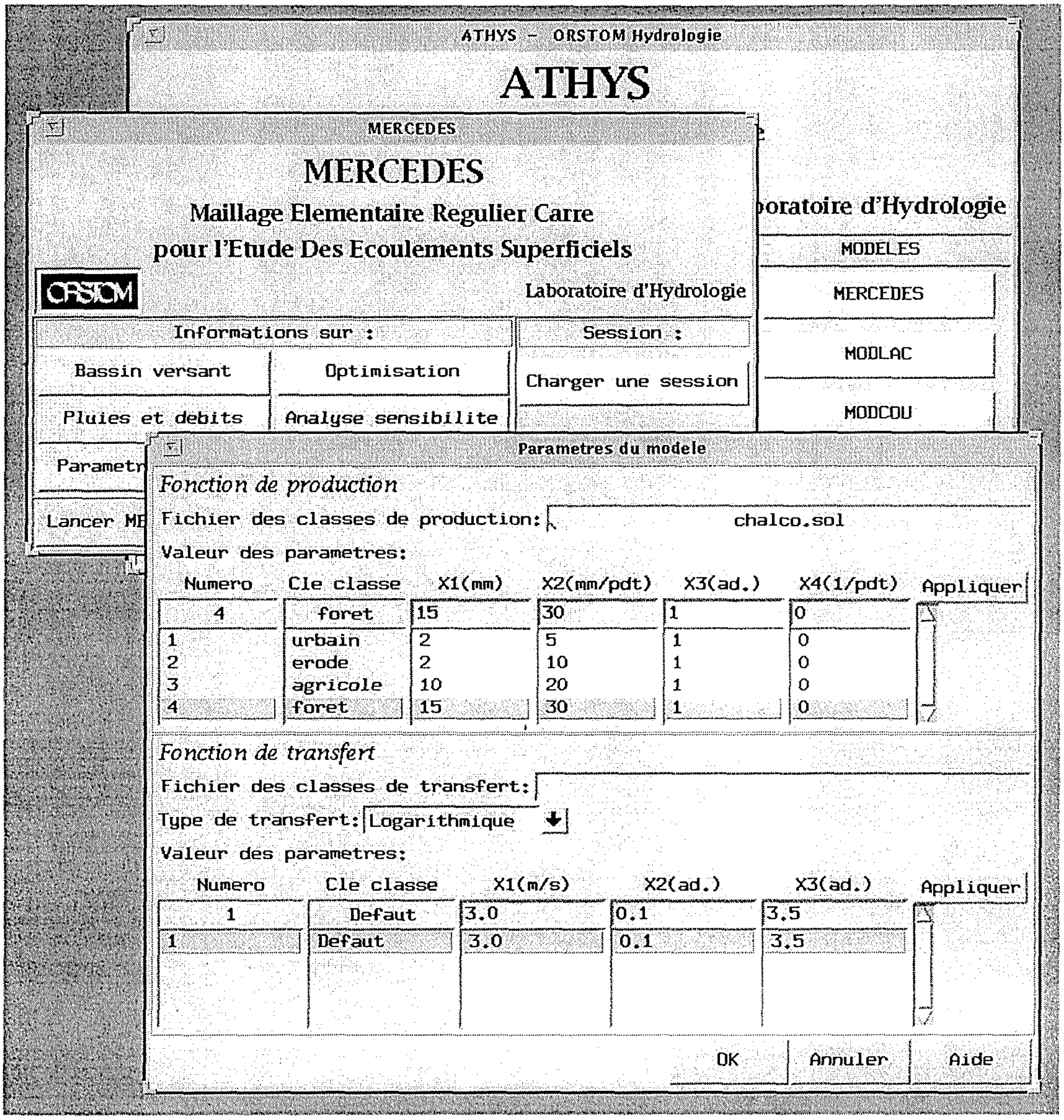

Fig. 2 Example session of ATHYS.

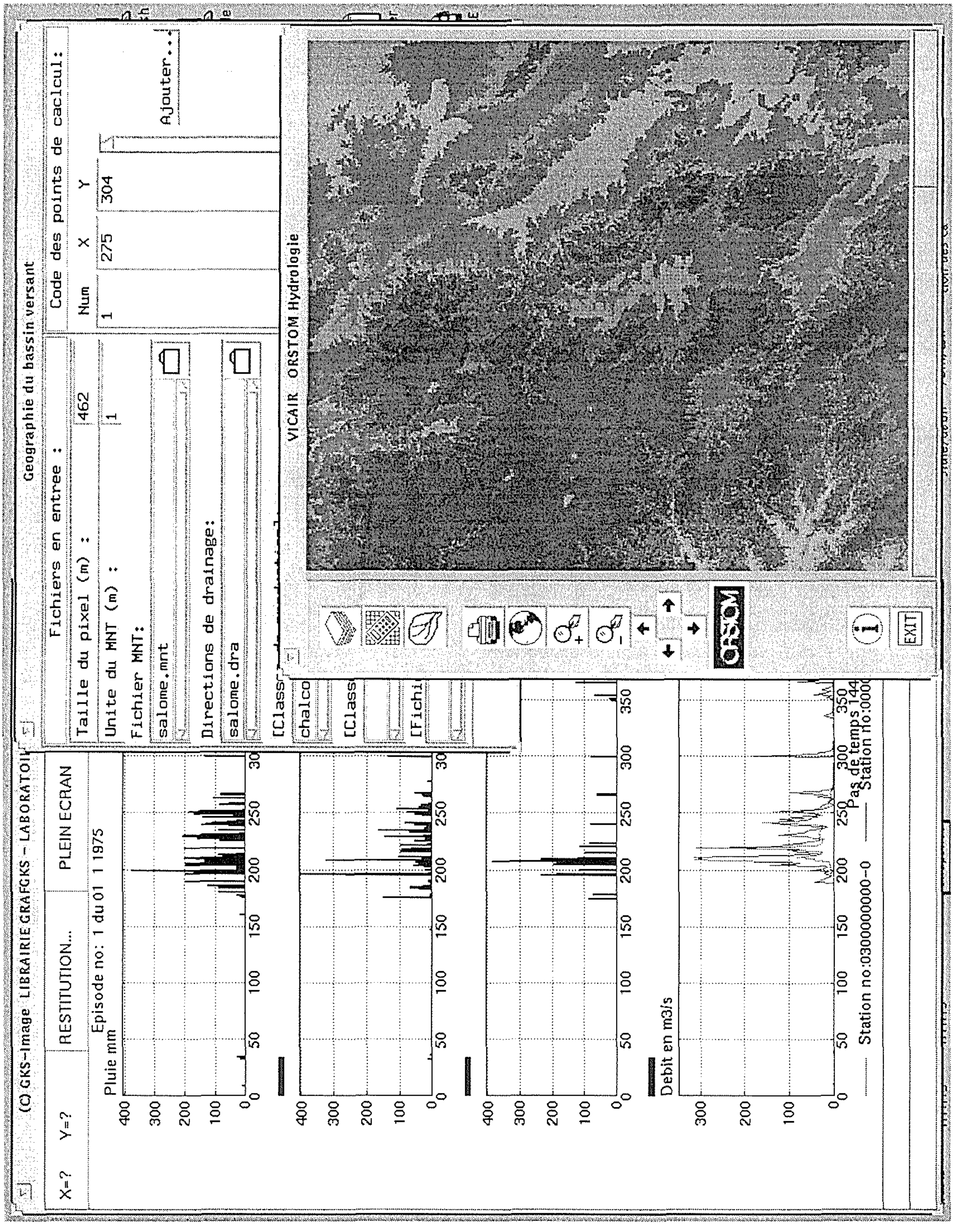

Fig. 3 Example viewers of ATHYS.

GRASS/TclTk developed by a Canadian company LAS. Integrated with a layer manager, this module permits the superposition of maps and verifies their coherence. Even though the internal data structure is compatible with GRASS, VICAIR permits access to other data formats such as TIFF, ASCII, etc.

The second module is a DEM which was developed by Depraétère (1991) and contains the following modules: calculation and correction of drainage basins, generation of slope maps and derived files (convexity, horizontal and vertical, etc.).

Hydrological models

Three models are integrated or currently being integrated into ATHYS.

(a) MERCEDES, developed by Bouvier (1994) and Bouvier *et al.* (1994), is a conceptual spatial model based on square grids adapted to surface runoff. It includes four production parameters, simulation of groundwater (levels and drainage flux) and two continuous losses (subtractive and/or multiplicative). The contribution of each grid to the stream flow at the discharge is considered using two parameters which establish propagation speed and a third parameter which determines the behaviour of the crest wave. The main advantages of MERCEDES are that it is simple and easy to use and can be applied to a large range of water basins: urban basins of only a few hectares up to tens of square kilometres, natural mountainous water basins of 30 to 100 km^2, large basins with thousands of square kilometres. We will present an application of this model, using a complete example which simulates overland runoff in an urban area, using several layers of drainage.

(b) MODLAC, developed by Girard (1982), is a distributed conceptual model adapted to rural water basins with or without retention equipment. It permits the modelling of the basin's behaviour or the simulation of land use or development scenarios. It functions on a scale of 1-day time steps for water basins greater than 100 km^2. The surface layer is divided into square grids of varying sizes depending upon the amount of spatial data. The model integrates thirteen production functions determined by the availability of diverse data which divides flow into surface runoff, infiltration, groundwater storage and evapotranspiration. The discharge is calculated by taking into account the length and time required for the water to pass through a grid to the outflow point of the basin.

(c) MODCOU was developed using the same principal as MODLAC: same spatial land division, same scale, production function and transfer per layer. In addition, MODCOU contains a subsurface model with functions for the transfer in nonsaturated area, simulation of subsurface drainage between aquifers using Darcy's law, and a function for the flux exchange between the aquifers and rivers.

AN APPLICATION OF ATHYS: CHARACTERISTICS OF FLOOD RISK IN AN URBAN AREA

The risk of flooding due to runoff is a major concern in urban areas because of impermeable surface and inadequate drainage. These factors can lead to violent flooding in a short time within a limited region.

Even though this phenomenon is a real problem, the tools required to predict and simulate the risk of flooding are still relatively crude. The development of GIS provides a means to objectively describe and quantify these risks. We provide an example using the program ATHYS in combination with a distributed hydrological model, MERCEDES and a fine spatial distribution in an urban area.

Method

In our approach, the characterization of flood risk requires three distinct steps:
(a) determine all the potential tributaries within the basin;
(b) compare all the tributaries to drainage capacity;
(c) in the case of saturation calculate flooding of urban areas.

We wish to simulate all areas of flux within the basin, including the points with inadequate drainage. This is the advantage of our method.

When considering and calculating runoff, drainage in urban area can be artificially modified in relation to natural topography. The different channels, collectors, pipes and streets can considerably modify drainage in relation to natural slope. It is this combination of natural and artificial drainage which our method simulates. If drainage capacity is sufficient, drainage follows the imposed path. If flooding occurs, the excess water drains according to the natural topography. In our example, runoff is calculated using the MERCEDES model which uses functions with two layers of drainage.

We have applied this method to a pilot zone in Ouagadougou (Burkina Faso). This urban area is particularly good as it represents many of the possible flux conditions. This zone covers 610 ha, for which a grid of 10×10 m^2 is used. This scale provides all the necessary geographical information.

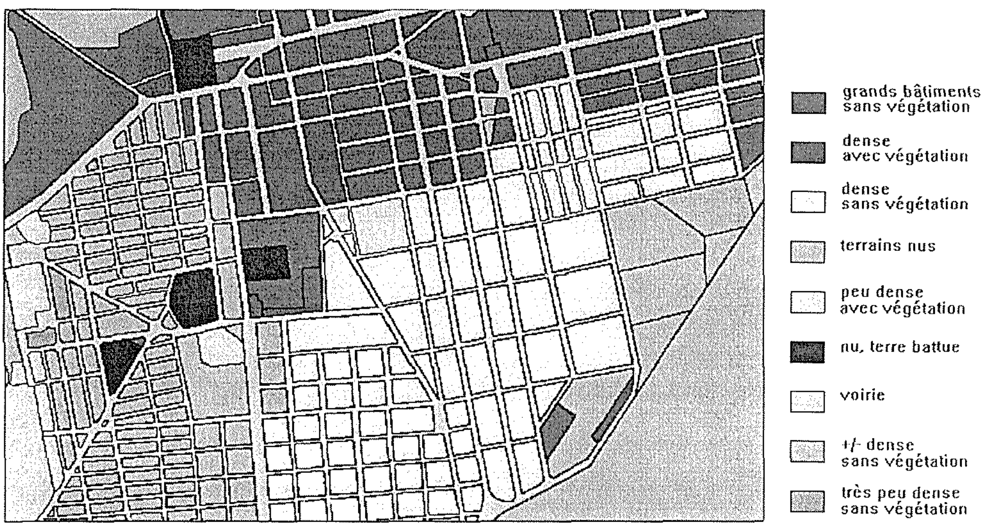

Fig. 4 Urbanization of the Ouagadougou pilot zone.

Required data

(a) *Land use maps.* The digitization of parcels permits the differentiation of potential runoff. The image in Fig. 4 (originally from a GIS) was recovered by ATHYS in a raster format, then converted and formatted by the data exchange module.
(b) *Slopes and drainage directions.* This data is provided by ATHYS via a function associated with a DEM. The module performs interpolation of the barycentre or by spline functions, extraction of the slope and direction of natural drainage with corrections and consideration for the urban drainage system (Fig. 5).
(c) *Level of drainage.* This information, which is difficult to obtain, is defined with default values for all the different drainage "objects", 1 $m^3 s^{-1}$ for streets, 20 $m^3 s^{-1}$ for different collectors in accordance with their known dimensions.

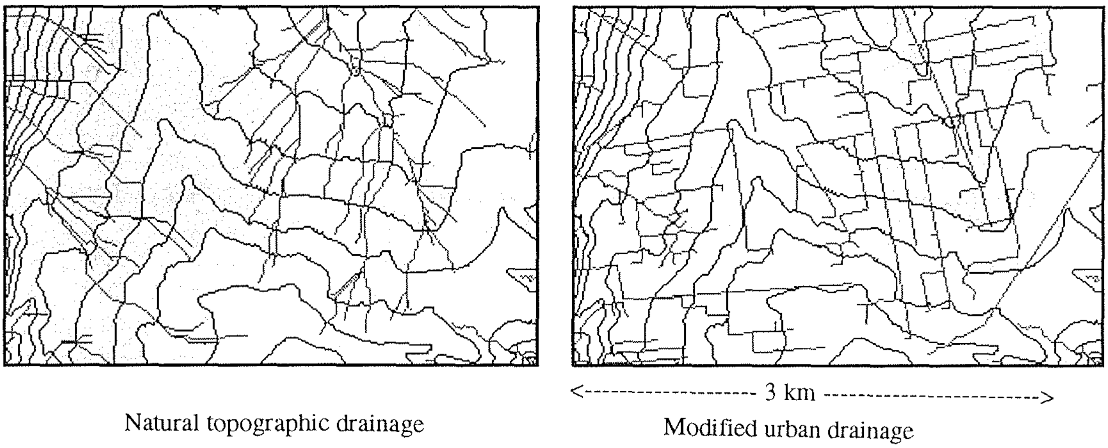

Fig. 5 Correction of the drainage topographic model in relation to the network.

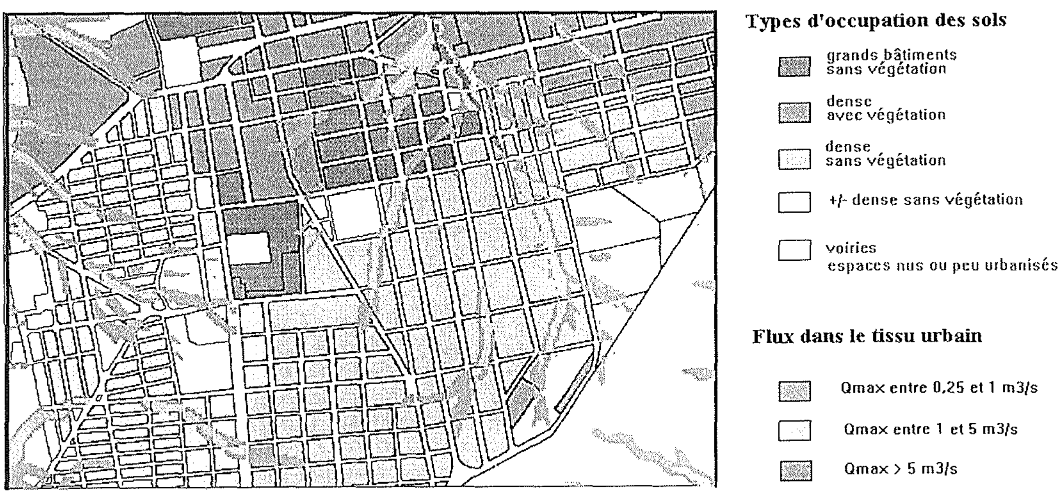

Fig. 6 Distributed peak flows in the urbanized areas of the Ouagadougou pilot zone.

Simulation results

The model MERCEDES was applied to the pilot zone and a 50 year flood was simulated. Figure 6 illustrates:

- Areas where flux occurs within the zone. This includes all the points within the basin, including collectors and streets. These areas are represented as maximum possible runoff which can pass through a grid.
- The same areas, limited by the different areas which are outside the urban zone. The values for the maximum flow have been averaged for clearer visual display and superimposed upon the land use maps in order to provide a better representation of risk flooding areas and flooding extent.

Other results are also accessible. Critical points within the drainage network, the classification and surface area of different urban classes, their drainage potential and exposure to flooding, for example x m^3 s^{-1} every N years, etc.

Limitations of the method

Even though the perspectives of this method are promising, one must consider that its validity depends upon certain conditions, most of which are satisfied, e.g. validation of hydrological operations, data transfer, communication between the different drainage levels, etc. The program opens many perspectives concerning calculations and representing results. As further in-depth analysis is necessary to validate this method, it is necessary to remain prudent when considering the results obtained.

CONCLUSION

The objective of the ATHYS project is to make available an operational hydrological modelling environment. The starting point of this project was to define an open framework between specialized complex software and simple hydrological computational programs. The most suitable computer tools were chosen, the existing applications were gathered and two models, MERCEDES and MODLAC/MODCOU, were updated. This open structure allows an easy integration of new tools and models.

Concerning the next development, a second part, which is presently being analysed, will be undertaken. It will be based on the development of a "personal" distributed model. In this model, the user will be able to choose from a database of hydrological predefined objects the components and modules, which are consistent with the processes he wants to study. Examples of components and modules are loss and transfer functions, physical laws and optimization procedures.

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Linking multiple process level models with GIS

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Abstract The issues of linking single process models with GIS have been well rehearsed. Linking several models raises some new issues. Rewriting the logic and relationships of existing models into one large model cannot always be justified. An alternative approach is to construct links from a GIS to the models using a network of programs and structures. Issues of this approach are: (a) reconciling the representations of reality used by the models and the GIS; (b) simulating the interactions between the subsystems by controlling the flow of data between different models; (c) constraints such as the system resources, user expertise and model limitations; (d) coping with data requirements and with error and; (e) fusion of models and data with different scale properties. This paper describes how these issues are being addressed for a project where several process models are being applied to simulate the agricultural effects of water table drawdown.

INTRODUCTION

This paper describes how several different environmental process models are being linked using a GIS in order to evaluate the effects of the Shropshire Groundwater Scheme (SGS) on crop production. The SGS was designed to augment flow in the River Severn during drought, with water pumped from the Triassic sandstone. The area of interest is the borehole group within the River Tern basin. Here the water table is close to the surface and the soil is in hydraulic continuity with the aquifer. Under these conditions pumping can reduce the soil moisture available to crops (Hedges & Walley, 1985).

Effects on agriculture arise through the interaction of several different environmental subsystems, principally; groundwater flow, soil moisture movement and the crop growth. Whilst each subsystem has been the subject of considerable modelling effort, it requires a combination of models to evaluate the whole system. This can be achieved either by constructing a single integrated model from the relationships of the different subsystems or existing models can be more loosely linked using communicating programs and structures.

THE CURRENT STATE OF GIS AND PROCESS MODEL LINKAGE

It is clear from the literature that there are many different approaches to linking process models to GIS and that an important component of each linkage is translating between the different representations of reality used by the GIS and the process models.

Fedra (1993) described levels of integration from the very simple, where the GIS is used for writing model input and the analysis of model output, to closely integrated systems, he presented a conceptual design of a closely integrated system and stressed the importance of user interfaces and the use of expert systems or knowledge bases. The Hydra Decision Support System is an example of this approach. Hydra links soil moisture, crop models, and embedded GIS functions. It has a sophisticated user interface; essential given the different types of users targeted. Development took 3 years with 25 people working on the project at any one time (Ireland, 1995).

Elgy *et al.* (1993) produced links between existing urban drainage models and different GIS's using "gluing" routines. This project required less than two man years. Harris *et al.* (1993), linked CFEST (Coupled Fluid, Energy and Solute Transport model) with the ARC/INFO, for a large groundwater investigation. The GIS and model were left intact but linked by a "network of programs".

Hydra and the systems of Elgy *et al.* (1993) or Harris *et al.* (1993) represent opposite ends of a spectrum of approaches to system design. At one extreme, e.g. Hydra, a total modelling system is constructed, models are implemented as new code, often by combining relationships from several different models. Considerable effort may be expended on the user interface and compiling expert systems or knowledge bases. The advantages are that a complete, commercial, product is produced, that is easy for a non-expert to use. However, such systems incur considerable cost and as Fedra (1993) states, there is "a tradeoff between efficiency and ease of use and the flexibility of the system".

The other extreme, e.g. Elgy *et al.* (1993) or Harris *et al.* (1993), involves linking existing model codes to GIS with communicating programs. This gives savings in time and expense, but needs expertise from the user, and relies on the GIS to be adequate for the tasks of data handling. There is, of course, scope to follow a middle path. The choice of approach should be a response to: end user expertise, the size of the user base, resources, time schedules, and the importance of the decisions being made. If the model is to be used by experts then an integrated package is not justified. If the user base is inexpert then the decision to supply a system within user capabilities must be based on the worth of the decisions to be made.

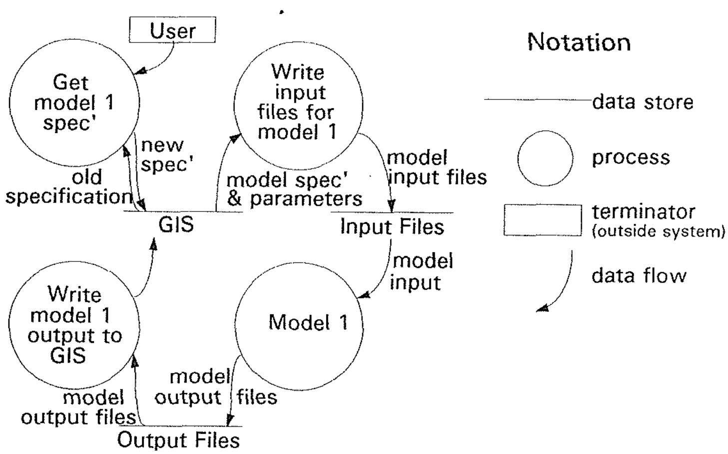

Fig. 1 Data flow between the GIS and process models (for clarity only one model is shown).

The representations of reality used by GIS and process models are developed in response to the priorities of the GIS and model designers and can be very different. Linking a process model to a GIS means reconciling these different representations. The current generation of GIS have 2-dimensional (2D) functionality with time and depth relegated to simple attributes. Generally process models use the time dimension but have any combination of spatial dimensions. Hazelton (1991) suggests two ways of dealing with this incompatibility. Firstly to use "ad hoc" solutions and "complex linkages". Or secondly "to develop a 4D GIS" which could interact directly with the models. With a few exceptions, 3D and 4D GIS are still at a research stage, and 2D GIS dominate in operational environments. Given the level of investment and the predominance of 2D GIS applications, this is likely to remain the case for a long time. However, environmental problems must be addressed now, which means that, despite the drawbacks, 2D GIS and process models must be linked.

MODELLING SYSTEM DESIGN

To model the effects of drawdown on agriculture a modelling system is being developed. Limitations on cost and time mean that model code cannot be substantially changed and neither can a larger model be constructed, because of all the cycles of coding, testing and debugging that this implies. Little effort can be put into a user interface or into a knowledge base. To allow the models to be used in *ad hoc* fashion for this and other projects, flexibility must be maintained, even at the expense of ease of use. Given these constraints, the strategy has been as follows. Each model will be linked into the GIS separately using a network of communicating programs, as with Elgy *et al.* (1993) or Harris *et al.* (1993). The linkage will allow each model to be applied to the data just as any other GIS function might be. In this way the GIS provides channels of communication between the models and allows them to be combined together for more sophisticated and complex analysis.

Figure 1 illustrates the system as data flows. Communication between the GIS and the models is via the data files, so there is a need for a controlling process to call the components in the correct order. Figure 2 illustrates the system as a hierarchy of control

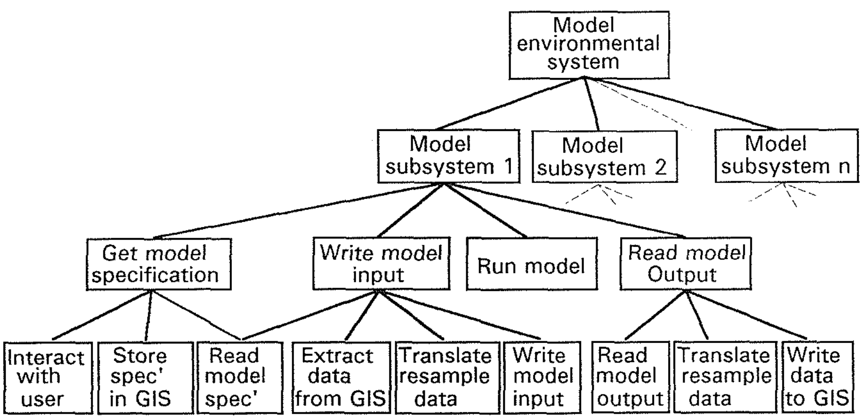

Fig. 2 Structure diagram or breakdown of the system into tasks (only one subsystem is shown).

and shows the passing of control between the GIS, the models and the controlling process. The controlling process could be the user interacting directly with the system components or a script which specifies the order of operation.

The GIS selected is GRASS (Shapiro *et al.*, 1993). The groundwater model selected is the US Geological Survey model MODFLOW (McDonald & Harbaugh, 1988). Various models are being assessed for the soil and crop subsystems. For this project the movement of the soil moisture profile in horizontal or near horizontal regions is important, so the appropriate soil models are vertical 1D models, those being evaluated include SWATRE (Belmans *et al.*, 1983) and SWMS_2D (Simunek & Van Genuchten, 1994). For this project field scale crop production models are required, and those being evaluated include WOSFOST (Van Keulen & Wolf, 1986) and CROPR (Feddes *et al.*, 1978).

IMPLICATIONS

Reconciliation of data models

To reconcile the data models used by the process models and the GIS, support structures are used which link basic GIS data structures into more complex ones. These are examples of Hazelton's (1991) "*ad hoc* solutions", but they are not necessarily as complex as has been suggested.

MODFLOW structures spatially varying data as irregular grids, and the third dimension as a stack of irregular grid layers. Some grids hold depth information which modifies the 3D representation so that layers can follow the surfaces of geological units. This 3D representation is easy to handle in the GIS using rasters and a list structure to link them (Fig. 3). MODFLOW represents time as irregular stress periods, again a list structure can easily handle this. The user interface is simply a set of forms that allow these lists to be assembled and edited.

As well as being irregular, MODFLOW grids need to be orientated parallel to the major axis of flow, whilst GRASS grids are regular and generally orientated north-south. To move data from GRASS to MODFLOW and back requires specially written resampling functions.

There are perhaps two approaches to linking a 1D soil moisture model to a GIS. One method is the apply the model to homogeneous areas. The second method is to represent the input parameters, such as saturated conductivity of a particular horizon, depth of a particular horizon etc., as rasters that vary across a landscape. When a model run is

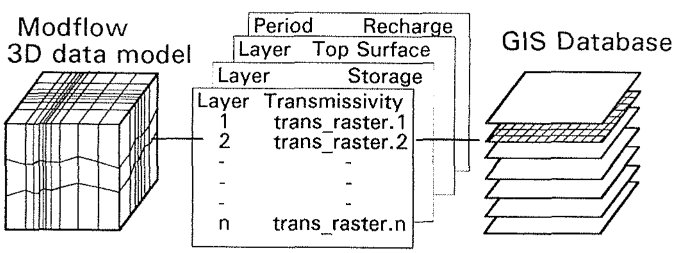

Fig. 3 Linkage between the MODFLOW 3D data model and the GRASS raster database.

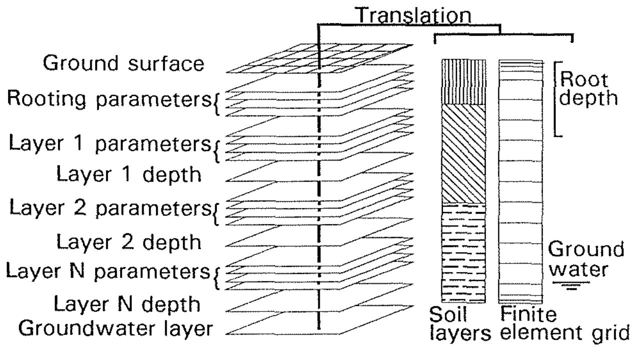

Fig. 4 Linkage between the soil model structure and the GRASS raster database.

performed at a particular point the translation program will sample the rasters at that point, construct an appropriate grid definition (which will depend on the values and geometry of the input parameters) and write the input files (Fig. 4). In both methods the model would be repetitively used across the landscape. Crop models like soil moisture models can be run for homogeneous areas or at points on "continuous" surfaces.

Logical links between models

Once the models have been linked individually into the GIS, channels of communication are effectively opened between them. To simulate the environmental system of interest the real significant interactions between the subsystems must be represented by the order in which models are called and the movement of data from one model to another. This can be easily achieved using a macro language.

For the investigating the effects of water table drawdown on crop production the interactions between soil moisture movement and the water table, and between evapotranspiration (ET) and soil moisture, are significant. Because these processes are modelled in separate models, depending on the significance of the interaction, it may be necessary to run the models in a repetitive fashion; stopping one and starting another and moving data between them.

Models designed for different purposes rarely fit exactly together, there is generally some overlap at the model boundaries, so there is need to assign different models the responsibility for different subsystems. For example MODFLOW applies simple assumptions to account for ET losses; a linear reduction from maximum ET losses at some height (at or near ground surface) to some extinction depth. Soil moisture and crop models simulate ET in a more sophisticated fashion. A more realistic approach is to apply ET calculated from the soil-crop models to MODFLOW as a sink term.

Practical considerations

The data flow pictured in Fig. 1 implies considerable movement of data to and from storage. If models are used repetitively then this will significantly effect system performance. With a more integrated system data flow could be optimized. Similarly the GIS gives the capability of creating input and output files which can be several megabytes in size. Again if the models are used repetitively this can be a problem, model re-engineering would largely eliminate this.

This approach to system development demands high levels of skill from the eventual user. It is possible with this system to make gross blunders or to apply the system to situations or scales that are inappropriate. However, it would be possible to construct an interface with a language such as tcl/tk which would obviate these problems but which would, of course, reduce flexibility and increase cost. Similarly this approach to modelling system design places great reliance on the GIS having the functionality to assist in assembling the input data. The MODFLOW 3D structure is easy to emulate with GRASS, but GRASS has limited 3D manipulation and visualization functionality. This makes the task of building a conceptual model of the subsurface environment using a GIS difficult. In this project it was found that paper geological maps, borehole logs and sketched cross-sections were needed in order to develop a concept of the relationship between geological units. Once a conceptual model had been developed however, the GIS helped greatly in assembling the data in MODFLOW layers.

Coded models have inherent limitations, in Fig. 2 control is only passed back from a model to the controlling process when a model finishes a run. A model cannot be interrupted when a particular value, say groundwater level or soil moisture etc., reaches a certain threshold, unless this facility is implemented within the model or the model code is altered. However, this can be imitated by running the model over short periods.

Data requirements and error

In order to adequately model a subsystem, a model's data requirements must be met even if they are more demanding than the overall project justifies. For example, the Tern groundwater unit is considerably larger than the area of potential agricultural effects (which depend on water table depth and hydraulic continuity between soil and aquifer), even so input data, such as transmissivity and initial heads etc., must be provided for the whole unit. To what extent data accuracy can be relaxed in areas away from the area of interest remains to be examined.

Error is a perennial concern both in GIS and environmental modelling, and has been discussed in many papers, Goodchild (1993) described an ideal GIS which would track error through the system, and "accuracy would a be feature of every product generated by the GIS".

If process models are to be fitted into Goodchild's (1993) system then error estimates would need to be part of the output of each model. However, most models, including MODFLOW and the others being evaluated, do not explicitly give a measure of error, and, current GIS do not meet this ideal. This project uses several models together, each will have an associated innate error as well as errors in the input data. To what extent these errors add up or cancel out when the models are run together remains to be tested. Until general error quantification techniques are developed little can be done except compare model outputs with observed data to get an estimate of accuracy. This also has problems, the calibration process of a model for a particular area or problem is an attempt to minimize error under those particular conditions. The final measure of error gained from such a calibration process cannot be assumed to be the innate error of the modelling system when applied to other areas.

Scale

Process models have an innate scale range in which it is appropriate to apply them, and outside of which they are increasingly less able to model the environmental processes accurately. For example, MODFLOW does not adequately model fissure flow, so it is necessary to have a grid spacing sufficiently large that fissure flow does not become significant, in the SGS study the smallest valid grid would be 20 to 30 m. The appropriate scale for soil moisture models depends on the heterogeneity of the soil parameters. Under very homogeneous conditions a soil moisture model such as SWMS_2D or SWATRE might be representative of an area up to field size. The appropriate scale for crop models can vary from continental scale to single plant growth, for this project a model of a similar scale to the soil moisture models is be appropriate.

Similarly, data has an innate scale range, which depends on original sampling, on any intermediate data format and on any generalization function that has been applied. For successful modelling it is important to match models and data which are appropriate to use together.

CONCLUSIONS

This paper describes a system to bring GIS and process modelling technology together to investigate the impacts of groundwater abstraction on crop growth. Due to constraints of cost and time and the need to maintain flexibility, the approach to system design has been one of minimal changes to the individual components whilst linking them with a network of communicating programs. In effect, therefore, the models become GIS operations that can be applied to GIS data and combined for more complex analysis. This raises several issues: (a) reconciliation of essentially 2D GIS with 0 to 4D process models; (b) the means to simulate an environmental system by linking and ordering models that represent different environmental subsystems; (c) practical problems of system resources, user limitations and model limitations; (d) model data requirements and error propagation through interacting model packages, and; (e) matching process models and data with different scale properties.

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Coupling GIS and DEM to classify the Hortonian pathways of non-point sources to the hydrographic network

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Abstract Water flowing over slopes is the dominant mechanism for the delivery of contaminants to streams. Hierarchical drainage algorithms capable of deriving the pathways followed by water are not readily available as spatial algebra primitives in commercial, general-purpose GIS software. The present work uses the DEDNM software system that simulates overland flow by extracting drainage network information from digital elevation models (DEM). Its results can easily be interfaced as information layers in raster format into a GIS such as IDRISI. A new algorithm has been developed for use with DEDNM to compute, for each cell, its terrestrial distance to the first water course. This information can be applied to assess the vulnerability of stream reaches to surface water contamination. An example of the results obtained with DEDNM and the new algorithm interfaced with IDRISI under a Windows environment is provided. It deals with the distance to water course on a small watershed supporting intensive agriculture, including livestock breeding operations and their associated manure disposal problems.

INTRODUCTION

Within the global framework of integrated watershed management, an accurate representation of the transportation of contaminants from their point of application to receiving surface waters is needed. Non-point sources, notably those of agricultural origin are becoming a concern for the long-term quality of the surface water and its continuing use for different purposes. Therefore, a better understanding of the origin, transfer and contribution of contaminants to surface waters is necessary.

Researchers around the world are reporting steadily increasing levels of nitrates in surface and ground waters; they are expressing concern about the accumulation of phosphorus in the ploughed layer of over-fertilized plots (Breeuwsma & Reijerink, 1992), making it available to surficial erosion and delivery to running waters where it may enhance eutrophication.

When monitored river water quality data are observed to exceed allowable limits, a typical response is to first locate and identify globally problematic subwatersheds, using municipally aggregated census data on the various land uses and their unit contributions. Then, via detailed studies, questionable practices at the farm level are identified to suggest interventions and develop Best Management Practices (BMPs) and promote the reduction of both contaminant inputs in the terrestrial ecosystem and their delivery into the hydrographic network. Such vulnerability studies can usefully exploit GIS information layers such as the slopes, the soil types and the farming practices. They also require accurate information on watershed boundaries and the slope directions (aspects) along with the distances the runoff water and its contents will travel. Distance from the contaminant sources to the first surface water is also an important factor to consider, as this information is closely related to the delivery ratios of the various sources and determine the important riparian buffer zones. This information on distance from a contaminant source to surface water can be automatically extracted from digital elevation models (DEM) with the use of specialized drainage algorithms.

THE HORTONIAN DRAINAGE MODEL

Background

A Hortonian drainage model uses elevation to reproduce synthetically the detailed pattern of overland flow along the path of steepest descent across the land surface. Once the overland flow pattern has been defined, it can be used to automatically derive, through various algorithms, upstream catchment areas, drainage network, subwatershed boundaries, overland flow distances and other hydrologically meaningful variables (Martz & Garbrecht, 1993).

Three general classes of DEM are recognized, and techniques for basic Hortonian drainage analysis have been developed for each. They are (a) the triangular irregular networks (TIN) used by Vieux *et al.* (1988), (b) the contour structure used by Moore & Grayson (1991) and (c) the grid structure used by Fairchild & Leymarie (1991). In this application we choose to work with the square-grid DEM because its spatial structure makes it easy to implement in a computer algorithm and to generate output that can be smoothly interfaced with a raster-based GIS such as IDRISI. The original DEM used in this analysis was obtained by an interpolation from isoelevation lines printed on topographic maps, to define the average elevations of square grids of a given size and orientation. This operation is realized directly within a raster-based GIS.

The DEDNM software system

DEDNM is a drainage analysis software system, written in Fortran 77 and fully described in the literature (Garbrecht & Martz, 1993; Martz & Garbrecht, 1993). It is designed for the automated segmentation and parameterization of drainage basins from raster DEM of size limited only by the memory limits of the computer. It pre-processes the input DEM to correct data errors and ambiguities which are particularly common in models of low-relief landscapes. Basically, it exploits the D8 drainage technique to derive from the pre-processed DEM the flow direction or aspect encoding at each grid cell (Fig. 1). It employs this aspect encoding to trace flow paths through the landscape to find the upstream catchment area at each grid cell and then defines the drainage network from user-specified threshold catchment area and channel length parameters. The drainage network is subsequently evaluated to determine the subwatersheds (left and right bank, stream head) of each network link, to apply consistent numbering and referencing schemes to the subwatersheds and network links. It also provides informative reports on the topologic structure which allow the implementation of an algorithm for optimized cascade flow routing (Garbrecht, 1988).

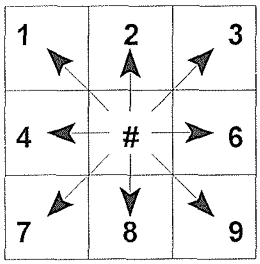

Fig. 1 Aspect encoding of the flow directions using the D8 drainage technique.

The terrestrial transport problem

The quantification of runoff-induced loads originating from various land usages on a watershed is a necessary step in the evaluation of relative responsibilities and the development of optimal interventions aimed at the reduction and control of non-point sources of contamination. This terrestrial transport and delivery problem has recently been called the "missing link" problem (Jolankai, 1992). It can be solved by establishing relationships between different land uses, crops, practices, fertilization rates, soils, slopes and their specific regional loading factors and delivery rates into the first encountered water course. These delivery rates are closely related to the average time of travel which, in turn, is related to the overland travel lengths from each contaminant source to the stream channel.

Advance in this field can be achieved by conjunctive use of a GIS and of specialized algorithms. Due to the diversity of local agricultural, climatological, pedological and hydrological characteristics, most readily available tools such as AGNPS (Young *et al.*, 1987) and ANSWER (Beasley *et al.*, 1980), distributed only as compiled software are very difficult to transpose outside of their development context and, as such, give generally poor results (Kauark-Leite, 1990). Jolankai (1992) qualifies the terrestrial transportation of non-point source pollutants as the "missing link problem" in the evaluation of contributions of all land uses in a watershed to the resulting surface water quality. Using the mass balance approach, he first estimates the net unit areal loadings (kg ha^{-1}) of each land-use type for different runoff depths (cm), then following the overland flow path of each homogeneous land-use patch, computes the loadings L_d delivered to the river for each meteorological event assuming an exponential decay (first order reaction kinetics of the transported loads) as:

$$L_d = \Sigma_j \gamma_j A_j \exp(-k_j t_j) \quad \text{with} \quad k_j = (\Sigma_i k_i t_i)/t_j$$

where
A_j = the homogeneous areas of different types j;
γ_j = the corresponding areal loadings for the event;
k_j = a coefficient related to the local slopes, soils and local physical factors;
t_j = is a time of travel for the duration of the event.

This is a simple additive model giving no consideration to the state variables (antecedent concentration levels) where, in the context of a raster drainage model, delivery rates are clearly function of the raster distance to the water courses, combined with other local physical factors.

The new DISRIV function

To analyse the contamination from non-point sources of agricultural origin, a new analytical function (DISRIV) has been developed to work with the DEDNM software system and to derive the actual runoff distances to rivers. This information, produced for each cell as a raster attribute, is much more meaningful for hydrological purposes than the one obtained with the GIS spatial algebra function DISTANCE. Where DISTANCE function determines the Euclidian distance from each cell to the nearest cell in the hydrographic network, the DISRIV function uses the aspect codes generated by DEDNM to determine the overland flow travel distance from each cell to the nearest cell in the hydrographic network. The output raster file (DISRIV.OUT) contains, for each cell, the travel distances to the outlet of the watershed. By arithmetical operations with the DEDNM output files, the total distance to the basin outlet, the distance along stream channels and the distance over slopes can be extracted. In addition, the partial overland flow distance through up to four categories of land surface type defined in external raster files can be determined. For example, given a raster file representing land use in a basin, a cell with a total distance to the first stream of 12.3 km, could be evaluated to find that 6.1 km of that travel distance was through pasture, 3.3 km through cereals, and so on. This information provides seamless integration with GIS, permits the direct application of vulnerability models such as the USLE equation and allows the efficiency of vegetative buffer zones to be assessed.

These combined results provide useful information comparable to that obtained by the COST spatial algebra function to assess vulnerable areas. A typical result could be to evaluate the delivery originating from areas supporting row crops both on loamy soils and on slopes exceeding 5% to surface waters.

APPLICATION

Case study: the Boyer River

The Boyer River, a small, south bank tributary of the Saint Lawrence River, is located

45 km southeast of Quebec City. Its watershed covers about 220 km^2 and contains more than 300 km of water courses. About 163 km^2 are used for intensive agriculture. This includes 1500 ha of corn, 2600 ha of cereal crops, 10 000 ha of hay and pasture land, 8000 ha of forest and livestock breeding operations with 15 000 cattle, 7500 pigs and over 340 000 poultry (MAPAQ, 1994). Smelt spawning areas at the function of the Boyer and the Saint Lawrence rivers have deteriorated lately and intensive agricultural practices typical of the region have been identified as a possible cause of this degradation (GIRB, 1995). Because of this, the watershed and its land uses are being studied in detail under the Canadian Green Plan (Environment Canada, 1995).

Methodology and results

Isoelevation lines at 10 m intervals were digitized from National Topographic Series (NTS) 1:50 000 topographic maps of the basin and used to interpolate a raster DEM of 315 $\times$ 215 cells, each covering 1 ha. The DEM was processed using DEDNM to extract the drainage network for streams up to Strahler order four. A visual representation of this synthetic network and its corresponding subwatershed delineation is presented in Fig. 2. It is compared with the network "blue line" of rivers digitized from the NTS maps. This figure shows that the agreement between the true and the synthetic network

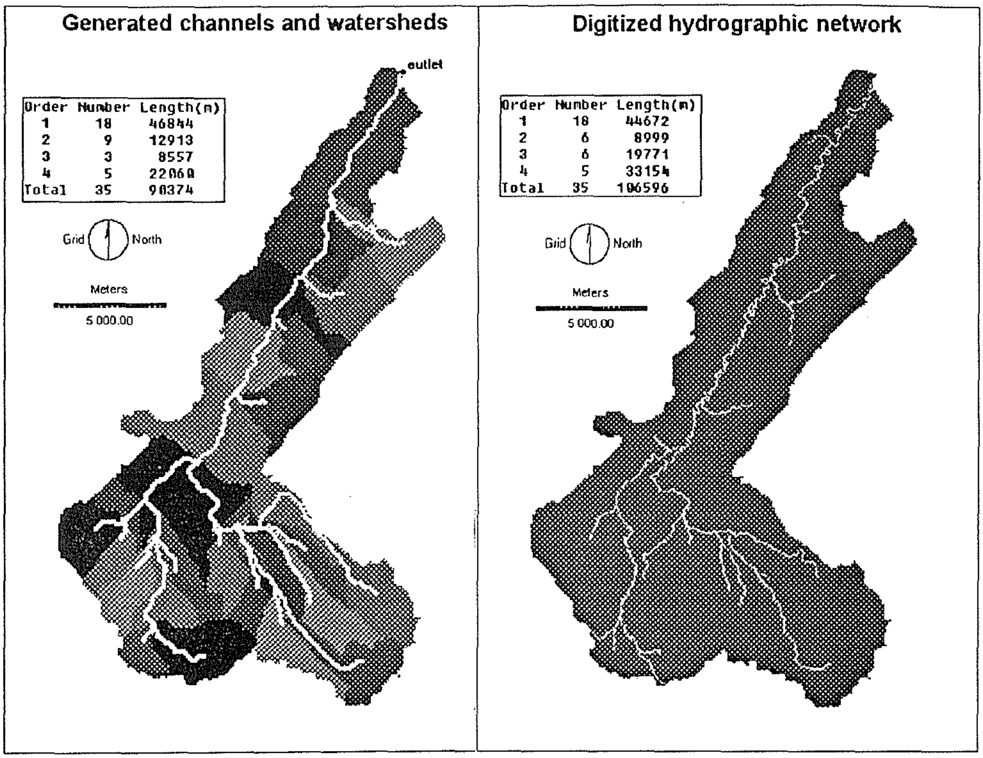

Fig. 2 Comparison of the Boyer river channel network generated by DEDNM and digitized from the "blue line" rivers extracted from the NTS maps (1:50 000).

is good, even if some low order ditches are not precisely located, due to the inaccuracy of the original NTS maps and the derived DEM and to the artificial digging that has occurred on the watershed.

The DISRIV function was applied to the DEDNM output and its results compared with those of the GIS spatial algebra function DISTANCE. The DISTANCE function determines the Euclidian distances from each cell to the nearest cell in the hydrographic network. The DISRIV function, on the other hand, uses the aspect codes generated by DEDNM to determine the overland flow travel distance from each grid cell to the nearest cell in the hydrographic network. The results, presented in Fig. 3, show a major discrepancy between the distance values generated by the DISTANCE and the DISRIV functions. On average, the DISTANCE values are 35% less than those given by DISRIV. For some of the most distant cells, the discrepancy is up to 98%. This discrepancy is very significant for hydrological studies that are generally concerned with overland travel distance of runoff.

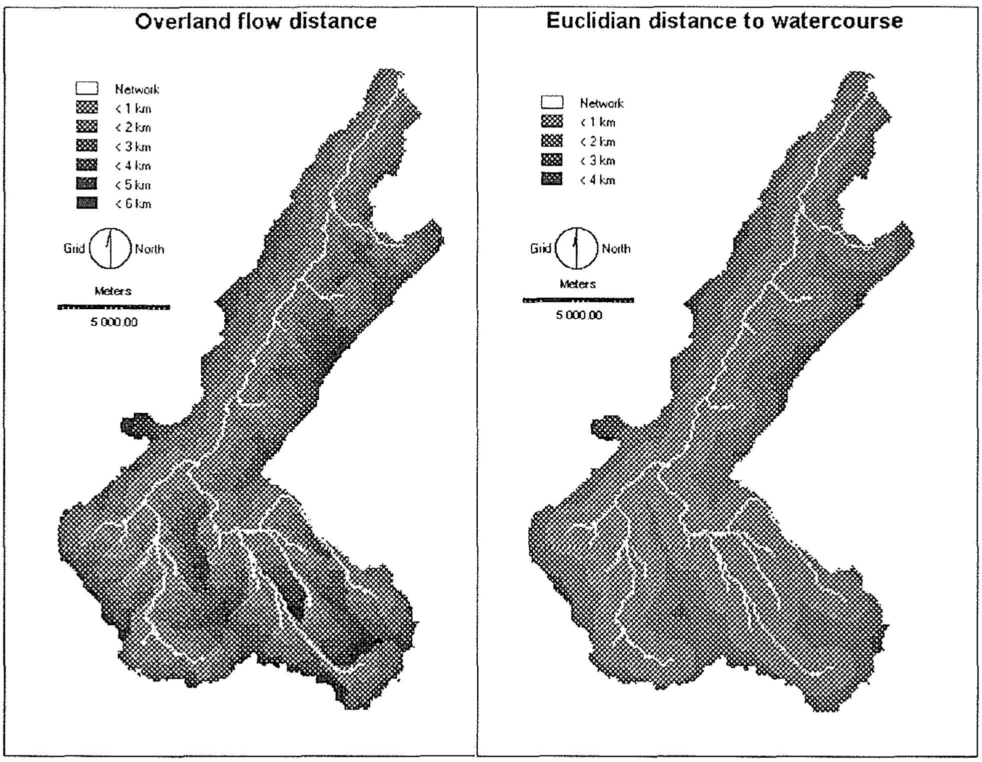

Fig. 3 Comparison of the overland flow distance generated by DISRIV and by the spatial DISTANCE function of the GIS.

Other possible developments

Used with a raster GIS, the drainage information provided by DEDNM and DISRIV can be exploited for numerous applications. In quantitative hydrology, Maidment (1993) has shown that incremental drainage areas of a watershed can be used to derive a unit hydrograph as water surface velocity is related to land cover and slope. This is obtained by a function of the form $V = a\, s^b$ (Sircar *et al.*, 1991), where s is the local slope and a and b are coefficients related to land uses and soil types (McCuen, 1982) and determined following the USDA Soil Conservation Service curve number (CN) technique. In qualitative hydrology, Boies *et al.* (1993) have shown that the efficiency of riparian vegetative strips in regulating the delivery ratio to surface waters depends of the width of the buffer and a coefficient related to the local slope, soil type and vegetation.

CONCLUSIONS

DEDNM has been developed as a software system able to derive from a DEM a synthetic raster representation of the surface drainage characteristics (hydrographic network and subwatershed boundaries). As an open software, its basic version aimed at a topographic representation of hill slopes, can be complemented with new specialized algorithms providing information on the surficial transport mechanisms within the watershed, both for water and contaminant transport to the river network, taking full advantage of the information stored in a GIS and of its analytical capabilities. Such coupling of a drainage model and of a GIS is very useful to provide the bases for mass balance models (fertilizer inputs, accumulation and transformation in the till zone, losses to groundwater, exports by the harvests and delivery to the water system) representing the functioning of a small agricultural watershed.

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2 Methodological Aspects

MEDRUSH – spatial and temporal river-basin modelling at scales commensurate with global environmental change

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Abstract New macro-models are required to address desertification issues associated with global climatic change. These models must work at large scales and be able to simulate long periods of time. Most existing models suffer from in-built spatial (limited scale) and temporal (fixed variable) constraints, require an extensive curve-fitting calibration exercise, and demand an enormous amount of detailed data. The MEDRUSH model offers one possible solution based on three levels of generalization: sub-basin, flow-strip, and section. A geographical information system is the principal run-time database management and visualization tool, working in tandem with other components as an integrated part of the larger model.

INTRODUCTION

Southern Europe comprises a fragile environment, with major changes occurring in terms of tourism, immigration, agricultural practices, water management and domestic and industrial pollution. These influential changes, unless managed, will cause rapid and perhaps irreversible environmental degradation i.e. desertification. Moreover, global warming, while increasing temperatures only slightly, is expected to produce a significant decrease in the rainfall for this area and thus compound the problem. In general terms, existing distributed process models are designed to work at the scale of the "research catchment", where detailed data are available to meet the exacting requirements of their numerous internal equations. Such models are also intended to be applicable to single storm events, or for relatively short periods of a few years, wherein intricate finite difference modelling is still able to produce an acceptable run time. It is often the case, however, that these models are just too demanding in terms of spatial data requirements and computational processing time to be of widespread use as effective management tools. Indeed, in terms of land degradation associated with global warming, the required data are often not available for those regions that are most at risk. Moreover, in these threatened lands, it is also the case that modelling would need to be implemented at the larger scale of the "management area", and to be extended over periods ranging from single storms to several decades, this being the time frame in which the distribution of important environmental variables could change.

GENERAL CONCEPTS

MEDRUSH, a combined geographical information system and large scale distributed process model, has been built to meet the need for a dynamic macro-model that can overcome existing spatial and temporal bottlenecks (Fig. 1). MEDRUSH is intended to be applicable to areas of up to 5000 km^2 and for periods of up to 100 years. The model is designed to provide scenarios of vegetation growth and the distribution of functional types, to forecast water runoff and sediment yield, and to predict the various ways in which these factors evolve in response to short term sequences of storms, seasonal/annual variations in climate, and long term trends in climate or land use. MEDRUSH is innovative in several respects, in particular with regard to the scale of its spatial and temporal modelling, its specific application to desertification processes, and its high level of integration with GIS.

Detailed, purpose-built, digital elevation models are divided into sub-basins, which are smallest in the headwater regions, and increase in size downstream. Each sub-basin is treated as a distribution of elementary flow-strips that are defined by their profile and

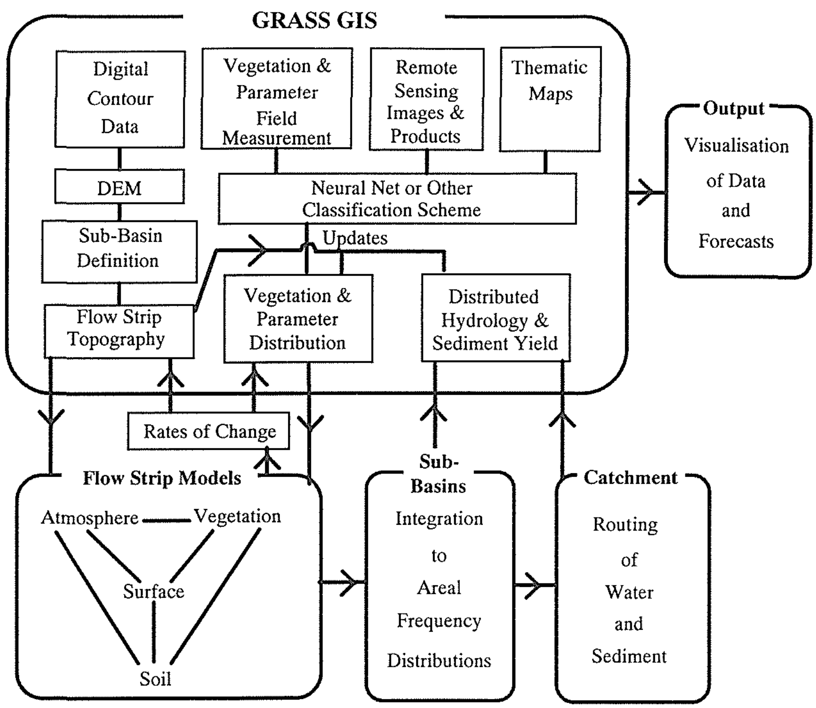

Fig. 1 The MEDRUSH model.

plan morphology, a flow-strip in this instance comprising a hillslope catena of varying width, that runs from the perimeter of a sub-basin to the outlet point of that sub-basin. The behaviour of one representative flow-strip per sub-basin is then simulated in detail, to generate water and sediment yield in the short term, and changes in vegetation, surface particle armour, microtopography and soil in the longer term – up to 100 years. This part of MEDRUSH is an explicit generalization of the MEDALUS Catena Model (Kirkby *et al.*, 1993), but with simplified soil water, vegetation, and evapotranspiration components. Calculations are computed for a limited number of sections on each representative flow-strip wherein statistical functions are used to represent grain size distributions, microtopography and inter-hour rainfall intensities. The diversity of vegetation is generalized with mechanistic functional type models, covering groups of species that are similar in structure and phenology, which are expected to show common responses to changes in climate. The output from each representative flow-strip is converted to a total output of water and sediment for that sub-basin, and these figures are passed to a channel routing mechanism. Water flow in the main channel network is simulated using a linear transfer system, with water being routed between sub-basin outlets, to the end of the network (catchment outlet). Routing provides catchment total, as well as internal forecasts of fluvial outputs and flood conditions, where appropriate. At present the model is restricted to physical processes, although it is intended to incorporate human influences at a later date, via an integrated "expert system" shell. MEDRUSH is at present being applied to the Agri basin, Basilicata, Italy (1700 km^2), and to the Guadalentin basin, Murcia, Spain (3300 km^2), so as to illustrate its use in the development of guidelines for integrated catchment management in threatened Mediterranean areas.

DATA TRANSFER

The method with which data are transferred to and fro between the spatial database that resides in the GIS and the representative flow-strips where detailed computations are carried out, is a crucial element in the modelling process. Instances on the representative flow-strip are assumed to represent sub-basin areas with a similar "unit area" value – in this case accumulated drainage area divided by gradient. This generalization has been shown to be an appropriate empirical basis for modelling the evolution of slope gradients over moderate periods of time, and it is reasonable to infer that other variables which are related to soil properties and erosion will change with gradient in a consistent manner, and in turn provide common environmental influences for the vegetation. The evolution of each representative flow-strip is modelled in detail, and the rate of change for each variable is applied to all points in the sub-basin that have the same unit area value, to provide a spatial distribution of soil properties and vegetation at the end of each year. Since unit area values do not change within the time span of the simulation, it follows that the relative proportions of the different input variables will remain constant over time, an approximation that is considered valid based on the small changes that are expected to occur within the time frame envisaged.

HILLSLOPE PROCESSES

Within each flow-strip, runoff and soil erosion are simulated with a focus on semi-natural uncultivated surfaces, and with the various wash erosion processes as the dominants. Soil moisture and lateral subsurface flow is modelled as a single unsaturated store, underlain by a saturated store with the characteristics of TOPMODEL (Beven & Kirkby, 1979). The soil surface microtopography in the cross-slope direction is described by an empirically fitted normal distribution, and overland flow is distributed across this micro-relief, giving greater flow depths and greater sediment transport within the depressions. Microtopography is also used to distribute vegetation (with larger plants concentrated on the highs) and infiltration rates. Finally microtopography generates exfiltration of subsurface flow along the depressions, and this can occur at significant rates in wet winter periods.

The duration of overland flows is calculated by fitting a fractal distribution of intra-storm rainfall intensities. Short bursts of high rainfall intensity produce overland flow even at low mean intensities, but these flows do not travel far down slope before re-infiltrating. Thus discharge and overland sediment transport increase less rapidly down slope at lower mean rainfall intensities. Thus overland flow routing, as a kinematic wave, responds to both storm intensity and micro-relief by summing across the spectrum of possibilities. Sediment transport is integrated over the microtopography and over the distribution of rainfall intensities, as a combination of rain splash, inter-rill wash and rill wash.

Microtopography is allowed to evolve in the medium term (~ 100 years) by a combination of three processes. First, rain splash tends to degrade microtopography except where it is protected on the vegetated mounds. Second, plant growth, litter collection and animal burrowing around plants all increase microtopography by raising the vegetated highs. Third, flow within the depressions can either reduce microtopography when conditions in the depression are depositional, or increase it when conditions are erosive.

VEGETATION

Vegetation modelling is an important factor, because it affects the potential for desertification and regeneration, and may in turn be affected by future climate change. Semi-natural Mediterranean vegetation presents a challenge for modelling in that it is both sparse and diverse. Within MEDRUSH, vegetation is generalized by functional type models covering groups of species with similar structure and phenology, which are expected to show common responses to climate change. These models are derived from the vegetation components of the MEDALUS Catena Model, retaining the use of functional relationships to describe physiological processes, but being simplified to reduce computational demands.

The main simulated vegetation processes are assimilation and respiration, which are driven by net solar radiation and temperature respectively, and partitioning and litter production, which are controlled by pre-set plant phenology. The interception of radiation by the functional type models governs the split between evaporation and transpiration. The vegetation components are designed to be run at flexible time-scales so as to update the larger model as and when required.

The outputs are those important both as physical attributes entering the MEDRUSH model, and as factors useful for understanding the processes of desertification. Canopy leaf area index controls the interception of precipitation and radiation, litter production affects soil erosion, and standing biomass is important for validation of the vegetation components. Daily predicted evaporation and transpiration values are passed to the MEDRUSH model for updating the soil water balance, and soil water potential is returned for input into the functional type models, as a controlling variable for plant growth. At a later date, it is intended to incorporate an over-model that will be run on an annual basis, using information from the functional type models to provide long term changes in vegetation distribution, both within and between sub-basins.

Stand-alone comparisons have been made at several levels to evaluate the performance of the functional type models. For example, the canopy photosynthetic response to elevated CO_2 was evaluated using a model parameterized in Portugal for *Quercus coccifera* (Caldwell *et al.*, 1986), whose response to CO_2 has been investigated (Reynolds *et al.*, 1992). Leaf area index of the shrub model was matched to that of Reynolds *et al.* (1992) using data from the nearest climate stations, Lisbon and Praia de Rocha. With leaf respiration removed from daily assimilate production to provide net photosynthesis for comparison, the model outputs resembled those of Reynolds *et al.* (1992), which provides a test of both assimilate production and respiration, since the two sub-models were developed as independent mechanisms (Fig. 2).

The effect of a 10% increase or decrease in each input variable upon several output variables has also been explored for Madrid and Naples (Fig. 3). In general, increased temperature, reduced incident solar radiation and reduced precipitation all produced decreases in annual productivity, annual litter production and transpiration. However, the two sites exhibited marked differences in the degree of response, which can be attributed to climatic differences. Indeed, the limiting factor for vegetation growth at Madrid would appear to be precipitation, whereas for Naples it would appear to be incident radiation. These results confirm that simulations of the vegetation response to climate change should be interpreted with caution because interactions between climatic factors and choice of site will affect the predictions of vegetation change.

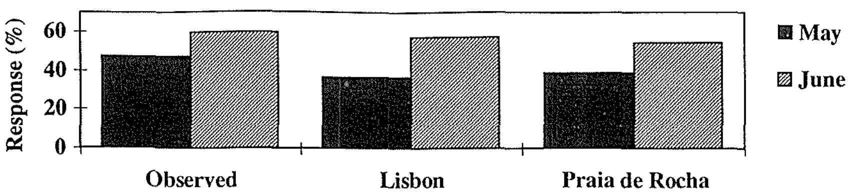

Fig. 2 Increase in daily net photosynthesis (as a percentage) in response to a doubling of CO_2. Observed results are for *Quercus coccifera,* from Reynolds *et al.* (1992).

WATER FLOW ROUTING

Runoff and sediment yield must be routed from the sub-basins to the catchment outlet in the main river network. Discharges must be available at the basin outlet and at any points in the network. The model must be capable of representing flooding and supporting transport modelling.

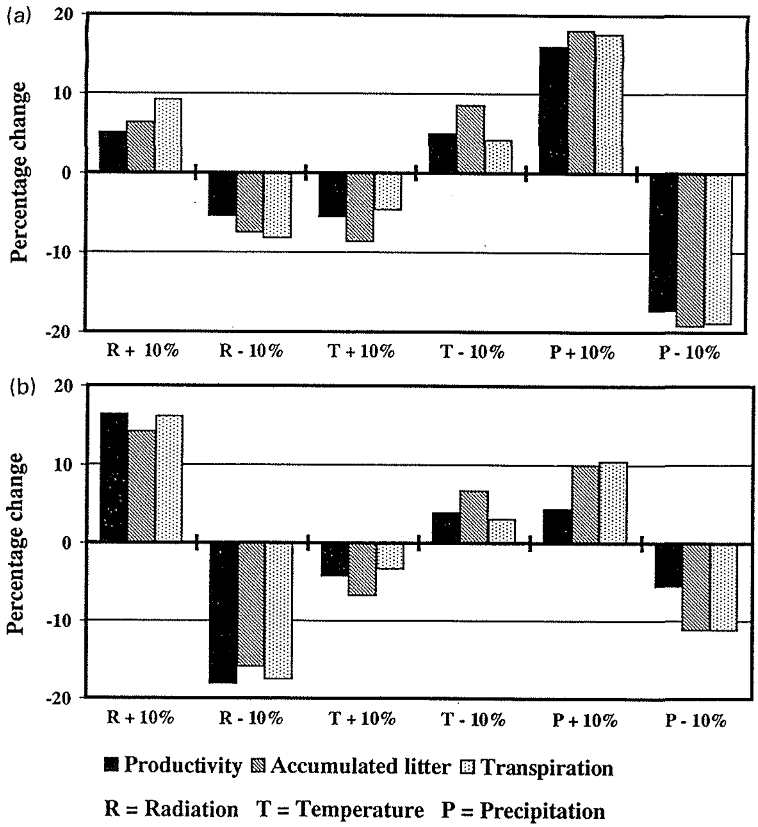

Fig. 3 Percentage response of vegetation characteristics to manipulation of environmental inputs at (a) Madrid and (b) Naples.

A linear transfer function scheme is used for routing water through the channel network. Transfer functions may be calculated from a point to any other downstream point in the network. Two routing modes are possible:

- **cascade routing** from reach to reach providing distributed information across the network; and
- **direct routing** by superposition, which is faster, but provides discharge only at the outlet and does not allow sediment transport modelling.

A linear solution of the convection-diffusion approximation to the Saint-Venant equations is used.

Analytical solutions to impulse inputs to a reach of river can be found for two cases, upstream point input and uniformly distributed lateral input. Integration of these *impulse responses* provides *pulse responses*, equivalent to *transfer functions*, and parameterization has been constrained to retain their linearity.

The routing model was parameterized using node data (easting, northing and elevation) obtained from the digital elevation model and its division into sub-basins. These data were processed into a suitable format and channel reach lengths and transfer functions were calculated. Preliminary tests of the scheme in a cascade routing mode using both single impulse inputs and uniform basin-wide inputs were satisfactory. Example results are shown in Figs 4 and 5.

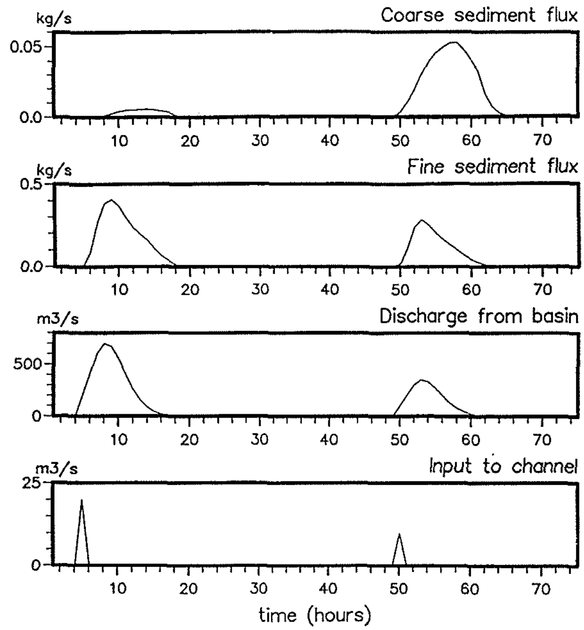

Fig. 4 Response of routing model to synthetic water and sediment input.

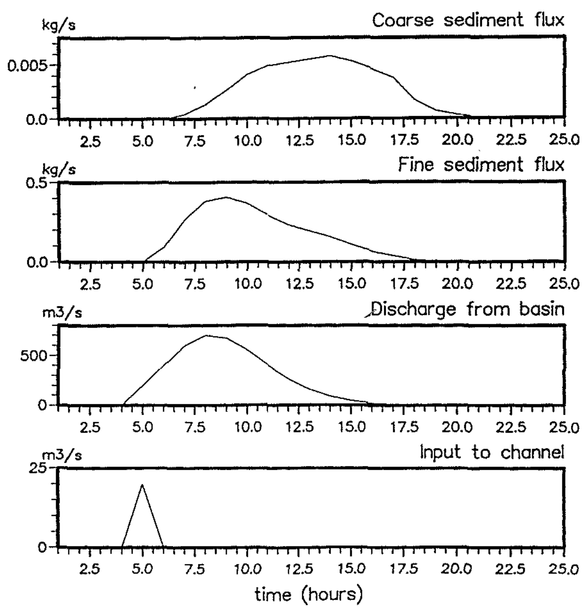

Fig. 5 Response of routing model to computed sub-basin outputs.

SEDIMENT TRANSPORT

The sediment transport scheme runs in step with the water flow code. Each river reach is considered as one element. In view of the generally small channel reach lengths used for the Agri basin (mean around 2 km) and small associated dispersion it was decided that a finite difference scheme was appropriate. An upwind difference scheme was developed operating on the channel reaches in descending order of elevation. An adaptive time weighting has been used, dependent on the Courant number at each reach and time step. This ensures stability, whilst minimizing numerical dispersion, which is already present due to the water flow transfer function method. The scheme allows for two particle sizes, fine and coarse. The fine fraction moves at the water velocity, the coarse fraction more slowly. Transport is limited by a capacity rate; excess sediment falls to the bed, and may be re-suspended if discharge increases. The transport capacities and coarse sediment velocity are pre-computed in order to reduce running time, and held in a look-up table referenced by the channel discharge. Bank erosion is simulated, with coefficients pre-computed and again held in a look-up table referenced by discharge. Infiltration of fine sediments into a bed-store is also allowed, and is controlled by the relative concentrations in suspension and in the store using a simple two parameter equation. A number of channel "types" may be specified and parameterized, allowing for different cross-sections, gradients, roughness and bank erodibility. The scheme has been tested on the Agri network using artificial and model inputs. Sediment pulses are satisfactorily routed, and may be deposited and re-suspended with appropriate discharge inputs. Example results are shown in Figs 4 and 5. The initial testing has used one channel type – this will be extended when more data become available.

CHANNEL EVOLUTION

Over the long simulation periods used for this modelling, river channels may evolve. For example they may widen due to higher discharges or become narrower due to lower flows and sediment deposition. It is planned to address this channel evolution by using the recent history of simulated flood events (last five years or so). The frequency and magnitude of flooding will be used to modify channel dimensions *via* the equations of hydraulic geometry which relate flow velocity, bankfull width and depth to measures of discharge.

FUTURE WORK

MEDRUSH is a new model that will require much testing. A comprehensive programme including sensitivity analysis and numerous parallel runs alongside an existing physically-based distributed hydrological model is in progress.

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Breadth first linear quadtrees for water resource management in Geographical Information Systems

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Abstract A GIS is a valuable tool to provide the information required in managing water reservoirs. When a GIS in raster format is utilized to depict the locations of reservoirs, they may be represented by black pixels in a binary image. A new coding is proposed in this study to construct a linear quadtree. The proposed scheme, a breadth first linear quadtree (BFLQ) coding scheme, emphasizes the reduction of a bit string to encode spatial data. The decomposition discrimination process is designed to have the image data represented in two linear lists. With the usage of both identifier and colour lists, a compact storage is derived to code spatial data on a binary image. Two sets of binary images with various resolution factors are tested in the experiments. A theoretical analysis for the image in the worst case is also derived. Both empirical results and theoretical analysis demonstrate that the proposed BFLQ coding scheme has a better storage space reduction than other methods.

INTRODUCTION

Water resources are closely related to human life, and are also an important factor for environmental quality control and economic development. So research on the management of water resources in geographical information systems (GIS) is an attractive topic. The reservoirs for water resources are generally represented as regional data on a raster-based GIS. The reservoirs may be viewed as objects represented by black pixels in a binary image while the background is represented by white pixels. So a problem arises as to how the regional data in a raster image can be stored in a GIS. A raster-based GIS usually has to overcome a problem that a large volume of storage is required to store the image data. The storage even enlarges the interval of processing time. A quadtree data structure is considered to be a valid method to diminish the amount of storage. The quadtree data structure has already been found to be useful for applications in such fields as image processing, computer vision, pattern recognition or computer animation. However, the most extensive application is probably in geographic information systems (GIS) (Samet *et al.*, 1987; Ganhegan, 1989). The quadtree is a data structure which recursively divides an image into four sub-images until each sub-image contains only one object (uniform intensity). The pointer quadtree (Hunter & Steiglitz, 1979) was the first method used to organize image data. Gargantini (1982) stated that the pointer quadtree wastes too much storage space, and suggested the use of a linear quadtree. The original pointers are removed and a linear array is applied to record related data. Many investigations (Abel, 1985; Hunter & Willis, 1990; Lauzon *et al.*, 1985; Wang, 1991) have attempted to find various linear quadtree coding schemes. Samet (1990a, 1990b) has provided a detailed description of the development of quadtree coding schemes and their applications. Two problems still persist despite the fact that the linear quadtree developed by Gargantini has some merit of storage improvement. Each digit in a quaternary code requires three bits for its representation. A range of eight values can be represented, but only five codes 0, 1, 2, 3 and "X" are used. This implies that there is three-eighths space wastage in data representation. Greater reduction of space could be induced if an appropriate use of that wastage is made. This is the first disadvantage. The coding scheme can be further improved to diminish the requirement for storage space if the data structure is redesigned. This is the second disadvantage we seek to eliminate. Hunter & Willis (1990) provided two labelling methods to overcome the first disadvantage of Gargantini's coding method. They introduced a quaternary code on the 4-postfix technique in which $2n + 4$ bits (n being the image resolution) are used to encode instead of the original $3n$ bits required in Gargantini's method. They further designed the 3-postfix coding scheme in which only $2n + 2$ bits are used. Their method, although being a significant improvement over the original linear quadtree coding method designed by Gargantini, requires a bit length in representation proportional to the resolution of the images. The proportionality can be replaced by a constant bit length that induces a more compact linear quadtree. In this study, a different coding scheme, breadth first linear quadtree coding (BFLQ) is developed for linear quadtrees.

THE BREADTH FIRST LINEAR QUADTREE CODING SCHEME

Given a binary image of resolution $2^n \times 2^n$, n being a resolution factor, the image is recursively decomposed into four sub-images (quadrants) until each quadrant contains only a uniform intensity. A quadrant of merely black pixels denotes an object area while a region of only white pixels is the background area. Following completion of the decomposition, a quadtree is constructed for the input image. The internal nodes on the quadtree represent a case in which four quadrants for a specific decomposition consist of both background and object data; however, all external nodes are of either background or object data. Therefore, three kinds of information represented by a quadtree, are available, i.e. nodes of mixed data, nodes of background data and nodes of object data. Although three kinds of information are available in a quadtree, only two different meanings essentially exist. The internal nodes imply the condition whether or not a further decomposition is required; however, all external nodes are merely of data to be encoded. Therefore, the proposed BFLQ coding scheme applies two data structures for encoding the spatial data. Two linear lists are used to record the linear quaternary codes. The first is the identifier list generated for identification purpose. A zero bit in the identifier list implies that an area of uniform intensity is found at a decomposition; in contrast, a one bit in the identifier list indicates that an area of uniform intensity is not yet met and further decomposition is necessary. The second linear list is the colour list in which a bit of either zero or one is inserted when a zero bit is set in the identifier list. A zero bit in the colour list represents a region of background data while a one bit is used for a region of object data. Based on the application of identification and colour lists, the proposed BFLQ scheme does the coding process in a time proportional to the number of pixels in an image.

The encoding process for the input image was developed on the basis of a Morton sequence and the breadth-first traversal order. The coding process is completed under the constraint that each pixel is accessed only once. The encoding process, beginning from the northwestern corner on the image for each quadrant, maintains the intensity of the first pixel and its Morton number (*FM*). The last Morton number (*LM*) of this quadrant is also computed. The scanning in the Morton sequence continues until a pixel of intensity different from that of the first one is met. The Morton number of this specific pixel is recorded as the Morton number of the transition pixel (*TPM*). With the use of the *TPM* at any level, level r, with TPM_r, as an example, the assignment of binary codes for the four sub-quadrants at the next level, level $r + 1$, is determined by the relationship between FM_{r+1}, LM_{r+1} and TPM_r. Therefore, the necessity of repetitive visiting of all previously accessed pixels can be eliminated. When a decomposition is determined, the four last Morton numbers of its four sub-quadrants can be computed first. The relationship among the *TPM* and these four last Morton numbers of four sub-quadrants provides the entry point for the next scanning. The entry point for the next scanning is in one of the following cases:

(1) If the TPM_r is greater than or equal to the LM_{r+1} of a sub-quadrant (the northwestern sub-quadrant as an example) after a decomposition, it implies that the northwestern sub-quadrant has already been accessed. It must have an intensity either of black or white. A zero bit is placed on the identifier list and a bit of either zero or one can be directly selected for the colour list according to the intensity of the pixel indexed by FM_r. The situation is illustrated in Fig. 1(a).

(2) If the TPM_r is between the FM_{r+1} and LM_{r+1} of a quadrant, taking the northwestern sub-quadrant as an example again, it implies that this northwestern sub-quadrant has not yet been completely accessed. A linear code of one is assigned to the identifier

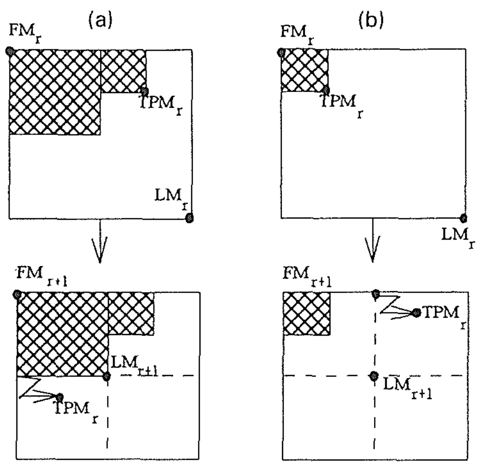

Fig. 1 Image scanning sequence after a decomposition for (a) case 1; and (b) case 2.

list and the encoding process will switch to the neighbouring sub-quadrant. Figure 1(b) depicts this case.

Following the description of the encoding process, a decomposed sample image shown in Fig. 2 is used to demonstrate the encoding result. Figure 2 also contains the identifier and colour lists.

The decoding process is applied to reconstruct precisely the original spatial data. Both identifier and colour lists are used to determine the spatial data on an image. The resolution factor of the original image is also input to determine the range of a processing region in the Morton sequence. Given resolution n, the range of a processing region is determined by 4^{L-1}, $L = n, n - 1, \ldots, 1$. The decoding process has the range of a region derived first, it then reads four bits of data from the identifier list. As a one bit is read, it implies a requirement of a further decomposition; however, a zero bit in the identifier code indicates that the current processing region is of uniform intensity. The region is either of background or else an object depending on the bit data read from the colour list. Therefore, the original spatial data on an image can be completely reconstructed.

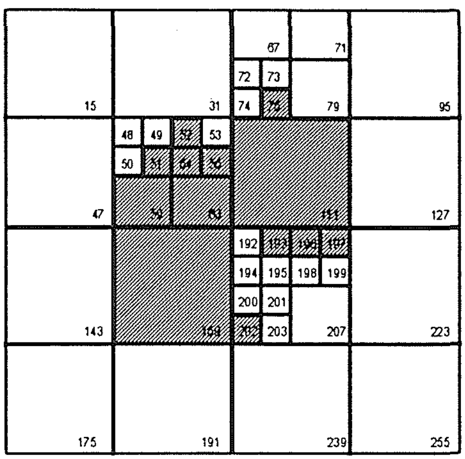

Fig. 2 A decomposed sample image, with the corresponding identifier and colour lists.

EMPIRICAL TESTS AND COMPARISONS

In order to demonstrate the characteristics of the proposed BFLQ coding scheme, the performance of the scheme is analysed and compared in terms of storage complexity and time complexity. Performance is also compared between the proposed BFLQ scheme and the coding method proposed by Gargantini. The comparisons reveal that the proposed BFLQ coding scheme renders storage improvement over the other method. Empirical results and theoretical analysis validate the superiority of the proposed BFLQ coding scheme.

Empirical results

The advantages of the proposed BFLQ coding scheme are illustrated in the following tests. Two binary images of different resolution factors were used in the empirical tests and the results are compared. The first test used the generally applied image of a Florida flood plain map embedded in a 512 × 512 grid; the second image, of resolution 256 × 256, was the agricultural region of Taipei metropolis. These two images are shown in Figs 3 and 4 respectively. All statistical data for comparison are collected in Tables 1 and 2. Table 1 is derived for a tested image of the Florida flood plain map; the encoding results for the second image are listed in Table 2. From the comparisons, the storage required for the proposed BFLQ scheme was significantly less than the result of the Gargantini's method. The capability of storage reduction of the proposed BFLQ is therefore recognizable. The advantage of the proposed BFLQ scheme can be attributed to the following two reasons. First, the proposed BFLQ scheme uses the process of decomposition discrimination to separate internal and external nodes on the quadtree and only one bit is required to encode both internal and external nodes of the quadtree. However, all linear quadtree codes of three other methods require at least two bits to represent a node on a quadtree. The bit length is even longer as generated by Gargantini's method. This is the main feature of the proposed BFLQ coding scheme. Second, the proposed BFLQ coding scheme is developed on the bases of the Morton sequence and the breadth first traversal order, so that a more compact storage requirement for the linear quadtree occurs. All statistics in Tables 1 and 2 clearly demonstrate the advantages of the proposed BFLQ scheme.

Theoretical analysis of performance

The theoretical analyses and comparisons of the proposed BFLQ coding scheme with three other methods were analysed on the basis of an image of size $2^n \times 2^n$, n being the

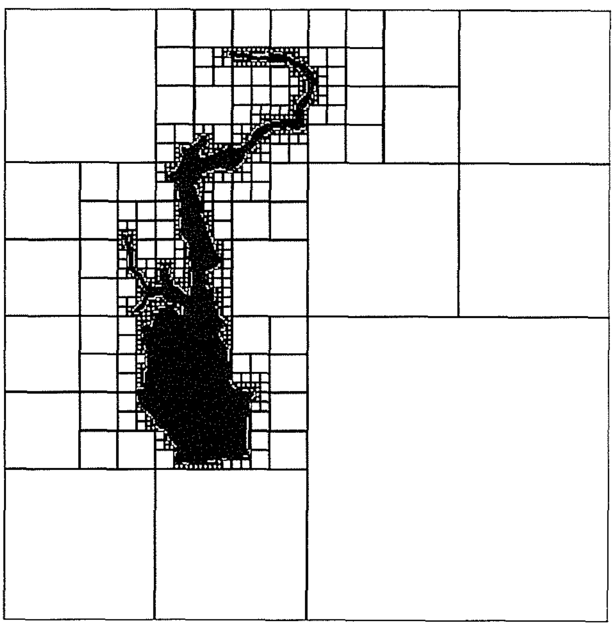

Fig. 3 The decomposed result of the Florida flood plain image with resolution 512 × 512.

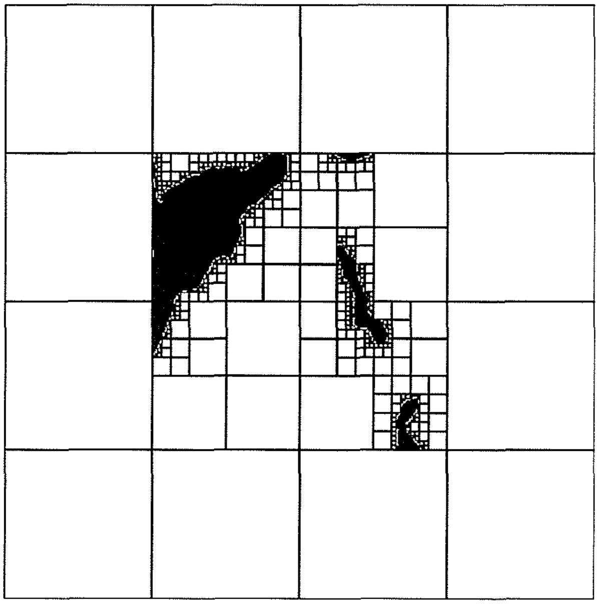

Fig. 4 The decomposed result of the Taipei agricultural area image with resolution 256 × 256.

resolution factor. The image considered was the worst case i.e. a chessboard in which a complete quadtree without any merging of leaf nodes was constructed. The required amount of storage space was approximately computed according to the product of the number of quaternary codes and the bit length of a quaternary code. For Gargantini's coding scheme, each node required $3(n - 1) + 2$ bits to encode and there were $3 \times 4^{n-1}$ nodes. Therefore, a total of $[3(n - 1) + 2](3 \times 4^{n-1})$ bits was required. The total storage was approximately $9n \times 4^{n-1}$ bits. The proposed BFLQ scheme had $(4^1 + 4^2 + \ldots + 4^{n-1})$ bits for all internal nodes and 4^n bits in colour lists for all leaf nodes, so a sum of $(16/3) \times 4^{n-1}$ bits was required for the storage space. According to the analyses of storage requirement for the worst case, the proposed BFLQ clearly had the smaller

Table 1 Comparison of storage space for Florida flood plain.

Coding scheme	BFLQ	Gargantini
Nodes	1 105	1 544
Bits	5 989	40 144

Table 2 Comparison of storage space for Taipei agricultural area.

Coding scheme	BFLQ	Gargantini
Nodes	615	866
Bits	3 374	19 918

Table 3 All requirements for storage of the four coding schemes.

Coding schemes	Theoretical analysis
Gargantini	$9n \times 4^{n-1}$
BFLQ	$(16/3) \times 4^{n-1}$

storage space of the two coding methods. The theoretical analysis also indicated that the proposed BFLQ scheme had an n times reduction of storage requirement relative to the Gargantini coding technique. Table 3 lists all requirement of storage for these four coding schemes.

The complexity of duration is yet another factor for comparison. This complexity, $O(n)$, for the proposed BFLQ scheme, is proportional to the image size as all pixels of the raster image are visited only once during encoding and decoding. The required execution time is the same as that of the Gargantini methods.

CONCLUSIONS AND FUTURE RESEARCH

Water resources have been recognized as an important factor to human life and the management of water resources is therefore considered to be a significant research topic. The management of reservoirs is naturally a part of studies in a GIS. The geographical locations of reservoirs may be represented by a binary raster image in which the reservoirs and the background data are represented by black and white pixels respectively. The raster-based GIS has a basic problem in how the image data can be stored. A new linear quadtree coding scheme, BFLQ, has been proposed in this study for coding image data. The proposed BFLQ scheme was developed on the concept of the order of traversal with breadth first and a Morton sequence. An approach is suggested to use only one bit to represent each node of the image on a quadtree. While a bit of either one or zero in the identifier list is used to indicate whether or not all four sub-quadrants of a decomposition require further decompositions, a bit of either one or zero in the colour list represents the data of a region. The characteristic of the proposed BFLQ coding scheme is in essence to have a different meaning assigned to the bit string in both identifier and colour lists. This is the major reason why the proposed BFLQ scheme has a performance improvement over the previous scheme. Experimental results and theoretical analysis verify the applicability of the proposed BFLQ scheme for linear quadtree construction. The proposed coding scheme will be profitable for applications in GIS. Future research can be directed toward topics of development of extended set operators, construction of multicoloured quadtrees, and extension to octree generations.

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Scale-up of a runoff model using GIS and an object-oriented hydrological modelling system

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Abstract The topographic characteristics of a basin have great influence on runoff processes. If a lumped runoff model that takes into account the topographic characteristics of a basin can simulate runoff processes as exactly as and faster than a distributed runoff model, the former will be very useful. This paper describes a method to lump and scale-up a distributed runoff model taking into account the topographic characteristics and shows the results of its application. In our method, we investigate distributed nature of topographic characteristics in a basin using the Basin Geomorphic Information System (BGIS), and lump slope systems using the cluster analysis technique. We also make a lumped stream network model on the assumption that stream discharge varies linearly along each stream segment at individual moment. To make a total system model, we use the Object-oriented Hydrological Modelling System (OHyMOS), which has been developed in Kyoto University using the object-oriented language C++.

INTRODUCTION

When we analyse the runoff system considering its interaction with the meteorological system, we have to adjust the space and the time scales of those systems. Since spatial scales of runoff systems are usually smaller than those of meteorological systems, it is the spatial scales of runoff systems that have to be scaled up.

In order to simulate runoff processes in a large basin, a lumped runoff model is often used. This is because a distributed runoff model for a large basin is usually very complex and takes much computation time. However, most lumped runoff models are conceptual, and do not make possible a physically-based evaluation of the influences that topographic characteristics of the basin have on runoff processes. Besides, in the runoff-meteorological systems analysis mentioned above, we may require the data about water distribution in the basin. Therefore, in order to avoid the disadvantages of both the distributed model and the lumped model, we develop a method that lumps a runoff model while taking into account the distributed nature of state variables and topographic characteristics in the runoff fields.

BUILDING LUMPED MODELS USING BGIS AND OHyMOS

In most meteorological computer simulations, the meteorological variables are computed at points on the grids placed in the problem area. Under the application of this type of meteorological model, a method was developed in which a runoff model is based on grids. According to this method, a runoff model has the advantage that it can be easily combined with a GIS. We place rectangular grids on the basin with the size conforming to meteorological computation, and investigate the topographic characteristics within each grid area using the BGIS (Basin Geomorphic Information System) (Tachikawa *et al.*, 1994). Taking into account the distributed nature of topographic characteristics, we lump the slope systems and the stream network separately. We use the OHyMOS (Takasao *et al.*, 1995) to make a total system model for a basin.

BGIS

The BGIS is a geomorphic information system in hydrological modelling using a TIN-DEM (Triangulated Irregular Network Digital Elevation Model). In a TIN-DEM, landscapes are modelled as a group of adjoining non-overlapping triangular facets whose vertices are made up of points on the rectangular grids and on stream segments. It is supposed that water flows in the steepest direction on each triangular facet. In order to identify a source area for any segments in a stream network and compute topographic characteristics of slope systems, BGIS subdivides these triangular facets, if needed, so that each of them has only one side through which water flows out.

In a basin topographic model represented by triangular facets, many valley segments exist. If these valley segments do not join a stream network, the stream segment that the triangles contribute to cannot be defined (Fig. 1). To correct this, BGIS traces the path of the steepest descent from the lowest vertex in the discontinuous valley segment, until it reaches a stream network. The discontinuous valley segment and the path to a stream network are newly recognized as stream segments, and we call them "quasi-stream segments" to distinguish them from an original stream network. Therefore, we make

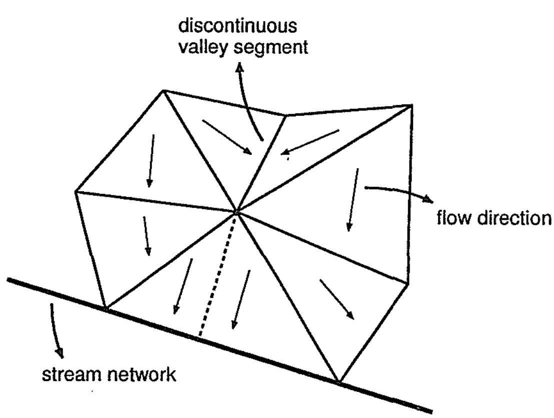

Fig. 1 Schematic representation of a discontinuous valley segment to a stream network.

three lumped models: (1) the lumped slope model; (2) the lumped quasi-stream model; and (3) the lumped kinematic stream network model.

BGIS can also make a runoff simulation based on the basin topographic model which is made by BGIS itself. We verify the performance of our method by comparing the results simulated by three lumped models with those obtained by the BGIS runoff simulation.

OHyMOS

The OHyMOS is a hydrological modelling system that has been developed in Kyoto University, and is designed with the object-oriented analysis technique. In OHyMOS, the basic common functions, such as giving the numerical values to parameters, giving the initial values to state variables, data exchange between element models, and decisions on the computation time steps of element models, are prepared as functions of the abstract base class. If we develop our own element models using "inheritance" from the abstract base model, we need not write those common codes and only have to concentrate on writing the codes that are proper to our own element models. Inheritance is an important concept of the object-oriented language.

Usual data exchanges between element models are done through "ports" where data packed with time are sent and received. Users can define their own data types to be sent through ports. The way of exchanging data through ports is very simple and useful. However, it cannot be used when the dynamic changes of elements depend on one another, because the data flow is restricted to one direction. In such a case, element models can also communicate directly without using ports.

THE LUMPED SLOPE MODEL

As we stated previously, BGIS can identify a source area for any segments in a stream network. Here, a source area for a stream segment is called "a slope element".

We approximate each slope element by a rectangular plane. The width, the length, and the gradient of a slope element are determined by "the projected length of the stream segment adjacent to the current slope element on a horizontal plane", "the slope area divided by the slope width", and "the weighted mean gradient with areas of the triangles that compose the current slope element", respectively.

Since it is considered that the slope length and the slope gradient are dominant topographic characteristics for slope runoff, we lump a number of slopes taking into account the variability of these two variables.

The slope length and the slope gradient should not be investigated separately, because it is unknown whether they are independent of each other. Considering the relationship between those two variables, we use the cluster analysis technique that is one of the multivariate analyses; all slopes are classified into several clusters. The dissimilarity among slope elements is evaluated by the standardized squared Euclidean distance computed from both lengths and gradients of slopes. Clusters are merged by the nearest neighbour method.

In every cluster, the mean slope length and the mean slope gradient are calculated with slope areas as weights. Then, the slope element that has a mean length and a mean gradient is regarded as the representative element for each cluster. Depth of runoff from each representative slope element is simulated using the kinematic wave model that combines interflow with surface flow (Takasao & Shiiba, 1988). The lumped slope model sums up the depths of runoff from all representative slope elements weighted with the area covered by a group of slopes included in each cluster. The output of the lumped slope model, $q_A(t)$, is the total slope runoff divided by the total length of the stream network including the quasi-stream segments.

THE LUMPED QUASI-STREAM MODEL

Most of the quasi-streams have the tree structures composed of several stream segments. However, to simplify the calculation, we neglect the structures and replace them with a single stream segment; that is to say, supposing that the topographic characteristics of a quasi-stream are represented by the length and the gradient of its main stream, we replace a quasi-stream network with a single stream segment whose length and gradient are equal to its main stream length and gradient, respectively. Then we make the lumped quasi-stream model using a cluster analysis technique whose parameters are those two variables, in the same way as the lumped slope model. The quasi-stream element that has a mean length and a mean gradient is regarded as the representative element for each cluster. Depth of runoff from each representative quasi-stream element is simulated by using the kinematic wave model with lateral inflow intensity $q_A(t)$. The output of the quasi-stream model, $q_B(t)$, is calculated as:

$$q_B(t) = \frac{1}{L_B} \sum_{i=1}^{N_c} \sum_{j=1}^{N_i} \frac{\overline{Q}_i(t)}{\overline{L}_i} L_j^i \tag{1}$$

where L_B is the total length of all quasi-stream elements; N_c is the number of clusters; N_i is the number of quasi-stream elements in the ith cluster; $\overline{Q}_i(t)$ is the runoff from the representative quasi-stream element for the ith cluster; $\overline{L}_i$ is the length of the representative quasi-stream element for the ith cluster; L_j^i is the length of the jth quasi-stream element in the ith cluster.

THE LUMPED KINEMATIC STREAM NETWORK MODEL

To simulate the flow in a stream network, we use the lumped kinematic stream network model (Takasao *et al.*, 1994). This model assumes that stream discharge varies linearly along each stream segment at individual moment (Fig. 2). Let $q_0(t)$ be rate of change of discharge in space, which is given by:

$$q_0(t) = \frac{O(t) - \sum_{i=1}^{M} I_i(t)}{\sum_{i=1}^{N} L_i} \tag{2}$$

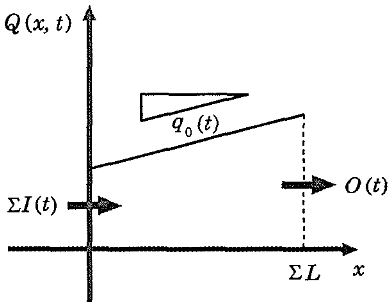

Fig. 2 The assumption that stream discharge varies linearly along each stream segment.

in which $I_i(t)$ is an inflow from an upstream segment, M is the number of upstream segments, L_i is the length of a segment in a stream network, and N is the number of segments in a stream network. Then the discharge of a stream segment at a distance of x from its upper end is given as $Q(x,t) = Q(0,t) + Q_0(t)x$.

Supposing that the relationship between discharge area and discharge such as $A(x,t) = KQ(x,t)^P$ (K,P: kinematic constants) exists, we can express discharge area using $q_0(t)$ as follows:

$$A(x,t) = K\{Q(0,t) + q_0(t)x\}^P \tag{3}$$

The lateral inflow intensity to this model is given by $[q_A(t)L_A + q_B(t)L_B]/L_A$, where:

$$L_A = \sum_{i=1}^{N} L_i \tag{4}$$

At $t = T + \Delta t$, let $S_i(t + \Delta t)$ be storage obtained by integrating $A(x, t + \Delta t)$ along a stream network and $S_c(t + \Delta t)$ be storage obtained from the equation of continuity. We determine a value of $q_0(t + \Delta t)$ that balances $S_i(t + \Delta t)$ with $S_c(t + \Delta t)$ and obtain the outflow from a stream network using the value of $q_0(t + \Delta t)$.

APPLICATION

We applied the method shown here to the Hattori River basin, which is about 95 km^2 in area, and investigated the performance of our models. The BGIS was applied to this basin with the digital elevation data whose grid spacing is 250 m. Then it was found that the Horton-Strahler order of the stream network including quasi-streams is five; the numbers of stream segments, quasi-streams, and slopes are 719, 123, and 1963, respectively.

Figure 3 shows the structure of a total system model for the basin. We assume that the slope runoff is spatially equal. By using the BGIS runoff simulation, we examine whether this assumption is appropriate or not.

The original runoff simulation by BGIS takes into account the locations of slopes; slope runoff is treated as spatially distributed. If the result of the original BGIS runoff simulation is similar to the one obtained when some representative slope runoff is equally given in space, it is found that we would not have to take into account the spatial distribution of slope runoff.

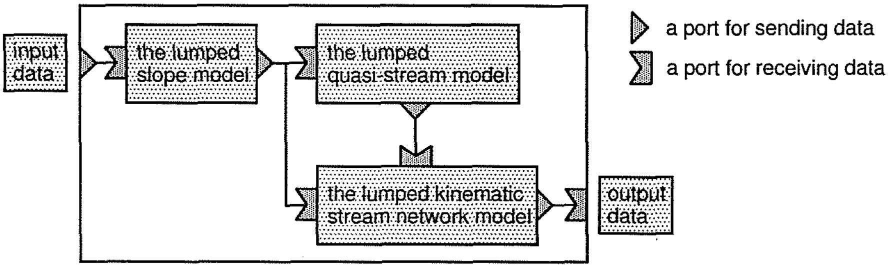

Fig. 3 Schematic representation of the structure of a total system model for the basin in OHyMOS.

Figure 4 shows the distribution of lengths and gradients of slopes. Figure 5 shows the representative slope runoff and the results of BGIS runoff simulation using (a) the representative slope runoff; and (b) spatially distributed slope runoff. The representative slope runoff is given by adding all slope runoff. The values of parameters of the slope runoff model were taken as follows: 0.8 m for the depth of A-layer; 0.015 m s^{-1} for the coefficient of permeability; 0.23 for the porosity; 0.3 s $m^{-1/3}$ for the coefficient of roughness. In both the quasi-stream model and the lumped kinematic stream network model, the value of the coefficient of roughness was 0.05 s $m^{-1/3}$. Since the difference in the results between (a) and (b) in Fig. 5 is little, it is seen that we can neglect the spatial distribution of slope runoff. Now, we discuss the reason why the results shown in Fig. 5 appeared. In Fig. 5, the lag time is about 2 h from the peak of rainfall to that of the representative slope runoff hydrograph; on the other hand, it is about 30 min from the peak of the representative slope runoff hydrograph to that of the outlet discharge hydrograph. The latter is only about a quarter of the former. This implies that the effect of the transformation in the stream network is small and that runoff from any slopes reaches the outlet of the basin with the same short lag time. As a consequence, the spatial distribution of slopes does not contribute much to the shape of the outlet discharge hydrograph in this basin. This also leads to the result that the lumping errors of both the quasi-stream model and the stream network model may be left out of consideration in this basin; it is important to closely approximate the distributed nature of slope characteristics.

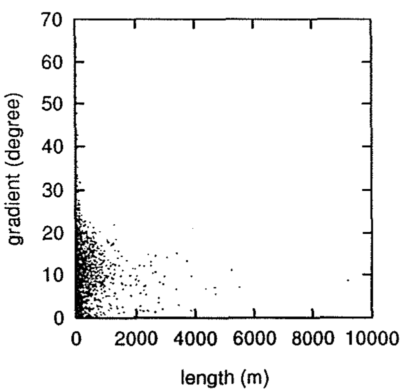

Fig. 4 The distribution of lengths and gradients of slopes in the Hattori River basin.

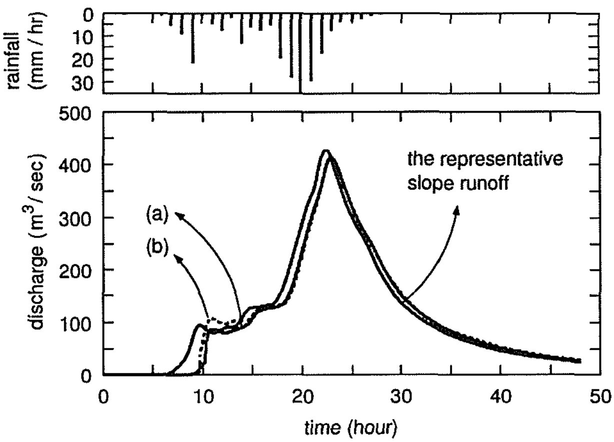

Fig. 5 The representative slope runoff and the results of the BGIS runoff simulation using two types of slope runoff: (a) the representative slope runoff; (b) spatially distributed slope runoff.

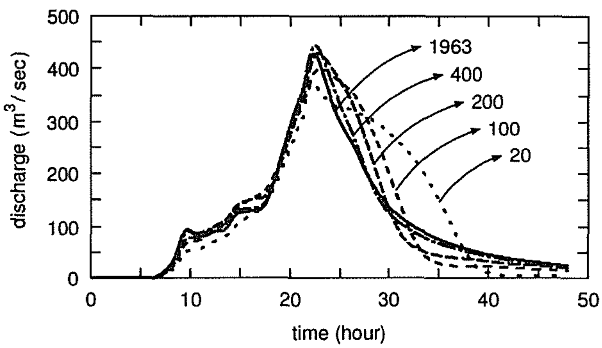

Fig. 6 *Four lumped slope runoff hydrographs and the representative slope runoff* hydrograph. The hydrograph with 1963 is the representative slope runoff hydrograph. The numbers 400, 200, 100 and 20 show the number of clusters.

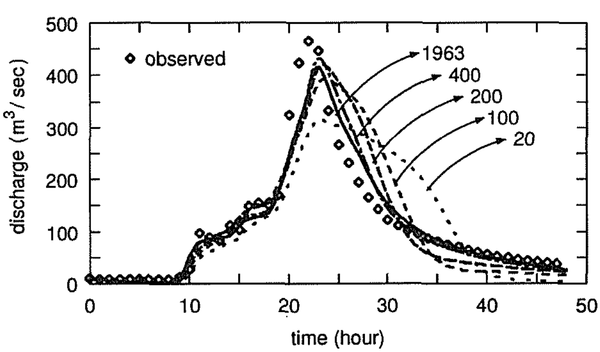

Fig. 7 The outlet discharge hydrographs obtained by using lumped slope runoff shown in Fig. 6 as inputs to the lumped quasi-stream network model and the stream network model.

In the following, we discuss only the lumping error of the slope model. We classified the slopes with different numbers of clusters, such as 20, 100, 200, and 400. As the number of clusters increases, the approximation of the distribution of slope topographic characteristics becomes more accurate. Figure 6 shows four lumped slope runoff hydrographs and the representative slope runoff hydrograph. Figure 7 shows the outlet discharge hydrographs obtained by using the lumped slope runoff shown in Fig. 6.

In Figs 6 and 7, it is seen that the higher the number of clusters becomes, the better the shape of recession part in the hydrograph. These two figures point out that the recession part of the hydrograph in this basin is composed of various types of slope runoff.

CONCLUSION AND FUTURE WORKS

We developed the lumped models of slope, quasi-stream, and stream network taking into account their topographic characteristics. We applied these models to the Hattori River basin and investigated the lumping error of slope model, particularly. It was found that the accuracy of runoff simulation depended on the number of slope clusters in this basin.

We must solve the following problems:

- We must design a criterion for giving the number of clusters. To do this, we use some statistical indexes of the basin topographic characteristics. This approach yields the number of clusters in such a way that the indexes do not change much before and after applying a cluster analysis to the data. Such a number of clusters would be enough to express the distribution of the topographic characteristics in the basin.
- We must discuss the lumping errors of both the quasi-stream model and the stream network model, which are not discussed here and have an important influence on the runoff simulation in a basin where the stream network has large effect of transformation. In particular, we should examine whether or not it is proper to treat a quasi-stream network as a single stream segment by neglecting its tree structure.

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Integrating dynamic environmental models in GIS: the development of a prototype dynamic simulation language

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Abstract A modelling language is presented to run dynamic models in a GIS environment. The focus of the language is on environmental applications. The approach taken was to design and build a GIS which includes a modelling language for the formulation of the dynamic behaviour of environmental systems. The spatial modelling language allows for a component-based modelling approach without the burden of technical implementation of database and algorithm details. Generic components, representing storages and fluxes of mass or energy, can be linked to create hydrological and environmental models.

INTRODUCTION

Current GIS capabilities have become an indispensable tool for feeding spatial models and analysing their results. Especially, the capability to derive spatial attributes from multiple sources, such as remote sensing, sampling, interpolation and digitizing existing maps, and to store these attributes in a geographic database simplifies the collection of input for a model. Analysing model results is helped by the possibility of simultaneous graphic display of multiple spatial attributes.

There are a few approaches to link models to GIS. Relatively simple, static, models can be run in the GIS itself, if all the model operations are part of the GIS functionality. From the database, new data is derived which is added to the database. Dynamic models, with parameters and variables changing over time, are more cumbersome to run in a GIS, because current GISs are focused on querying and maintaining a static database with static phenomena. Current GISs do not explicitly allow for dynamic phenomena to be stored and analysed. A possible solution for the lack of dynamic functionality is to program the dynamic behaviour in scripts or macros, but current practice is to program dynamic models as separate programs and to exchange data between the model and the GIS.

True integration, where a user-defined dynamic model runs entirely in the framework provided by the GIS, is not yet possible. For such an integration a GIS must support all the operations that constitute a dynamic environmental model and have all these operations available in a single modelling language. In this paper we present such a modelling language called DYNAMITE, the associated analytical engine and the spatial database that are all part of the new PCRaster version (Van Deursen, 1995; Van Deursen & Wesseling, 1995).

REQUIREMENTS AND DESIGN ISSUES

Every model is written in some type of language. Whether a model is a FORTRAN program, a sequence of GIS macros or a formula in a spreadsheet, they are all descriptions of a model which is materialized in a particular programming language. Even graphically designed flow charts in which (spatial) operations are chained, (e.g. ERDAS Spatial Modeller or STELLA flow charts) are graphical representations of a programming language. Some of these programming languages are general purpose programming languages while others are specially designed for spatial analysis.

A well-designed programming language is essential in every area of software engineering. Our goal is to develop a special purpose programming language: a modelling language for dynamic models in a GIS environment. The data manipulated by the language is stored in the GIS database. Therefore language design and GIS data model design must be consistent with each other.

Environmental models cover a large variety of applications, ranging from simple erosion risk assessment descriptions based on generalized slope length and soil type characteristics to complex pollution models containing diffusion and advection processes. Thus the language must contain a large set of operators, from which many types of models can be built. However, the set of operators should be chosen carefully, based on a number of conflicting requisites. The set should be as small as possible to keep the language easy to learn and use, but large enough to build all types of dynamic models. The expressive power of an individual operator should enable one to express models as compactly as possible without risking the obscurity which often accompanies compactness. These requisites mainly deal with the needed level of abstraction that hides irrelevant details from the user.

After discussing the structure of the database, this paper will show how the same GIS language is utilized in examples ranging from *ad hoc* analysis to dynamic models.

THE DATABASE

Computer languages are constructed around data types and data models. The language is the means by which the information in the data can be analysed. The question of *how* to store data seems inevitable when discussing GIS and data models, as can be concluded from the everlasting raster versus vector discussion. More important however, is the question *what* is stored in the database, and what the characteristics of the entities stored are.

For a model, the important entities may include soil type maps and land use maps. A cross-tabulation of these entities is possible whether they are stored as rasters or polygons, but a multiplication of soil class numbers with land use numbers will not produce anything useful since both entities are nominal data types. Even a comparison (equality) would be nonsense since the nominal data types represent different entities. To overcome these difficulties, and for a functional support of the operations, type information can be included in the database, and a strong type checking mechanism could be applied to the GIS operations.

The PCRaster database can only hold raster maps and point data. Both data representations have types attached. These types do not only describe the data represen-

tation but also the special properties of the entities modelled. We distinguish the following data types relevant for environmental modelling:
- Boolean;
- nominal, sub-typed by its legend;
- ordinal, sub-typed by its legend;
- scalar field;
- vector field;
- local drain direction (ldd).

Scalar fields are used to describe intensities and potentials of physical fields, such as temperature, population density and precipitation. Vector fields have both a magnitude and direction and can be used to represent (horizontal) fluxes and forces, such as movement of ground water and air.

The local drain direction (ldd) data type is introduced to allow for the definition of the direction of potential flow. It is a data type that maps the major direction of flow of mass for all locations in the database, and can be used in operators that describe lateral flow. In general, this ldd-map is derived from the Digital Elevation Map, and represents the direction of surface flow through this elevation map, but any scalar field can be processed to determine a local drain direction map. For a further discussion on the construction of this data type see Marks *et al.* (1984), Morris & Heerdegen (1988), Jenson & Domingue (1988), Moore *et al.* (1993) and Van Deursen (1995).

Operations on the database entities can only be applied if the maps have the right type for the operator. Such a strong type checking scheme assists error detection and helps the user in conceptualizing his ideas about the entities used. An additional advantage of typing the entities is that more intelligence, such as polymorphic behaviour, can be built into the operators. For example, an interpolation operator can automatically choose the nearest neighbour algorithm for ordinal data and bi-linear interpolation for scalar data.

The dynamic behaviour of the database, needed for dynamic modelling, is modelled by time series indexed on time and location and stacks of map layers representing the status of the model at different time steps.

THE SPATIAL MODELLING LANGUAGE

The DYNAMITE language is an extension of the concept of the Map Algebra and Cartographic Modelling Language proposed by Tomlin and Berry (Berry, 1987; Tomlin, 1990). It follows the same approach in the sense that it provides a limited set of generic functions, which can be used as primitives for the models. However, the language appearances are opposites. Tomlin proposes a natural language that is understandable for a large group of users with no former experience in computer programming. In our case, we think the majority of users consists of the developers of dynamic models, who are expected to be familiar with compact mathematical notations. Therefore, the syntax of the language is based on mathematical equations where each equation assigns the value of an expression to a single output.

As an example, the equation for determining excess rainfall and abstractions from storm rainfall known as the Curve Number approach (SCS, 1972) reads:

$$Pe = (P - 0.2S)^2/(P + 0.8S) \qquad (1)$$

with Pe = excess precipitation or direct runoff (inches); P = precipitation (inches); and S = potential maximum retention (inches).

This equation can be applied to find excess precipitation from a 5.0 inch rainstorm on the raster map *RetentionMap* using the DYNAMITE command:

$$Pe\_map = sqr(5.0 - 0.2\,RetentionMap)/(5.0 + 0.8\,RetentionMap)$$

which yields a map *Pe_map* with the excess precipitation distribution.

The command above is a point operation, where a new value for each location, a grid cell, is derived from different attribute values on that same location. Non-point operations, where a new value for each location is derived from attribute values on (possible) different locations, are also modelled as mathematical functions.

Additional to the traditionally available functions for buffer zone creation and the moving windows functions, DYNAMITE incorporates several functions to determine lateral transport over the ldd map. The most simple functions allow for the instantaneous transportation of all the surface water to be accumulated at the outlet point of the catchment (accu-function). More advanced functions allow for the definition of losses and maximum transport capacities along the drainage pattern, including the most general functions for lateral transport: the route functions. They simulate flow through a network, starting with an initial distribution in the network and returning the new distribution (state) and the conveyance of material through the network (flux). The amount that is conveyed is determined by a flux equation. The syntax of these functions is:

$$ResultMap = routestate\ (LddMap,\ FluxEquation,\ InitialMap)$$

and

$$FlowMap = routeflux\ (LddMap,\ FluxEquation,\ InitialMap)$$

Since both functions operate on the same input maps, they can be combined into one statement:

$$StateMap, FlowMap = routestate, routeflux(LddMap, S\hat{}0.3, S = IniMap)$$

Any legal operation resulting in a scalar map can be used to describe the flux equations, and the route functions will evaluate the distribution of the material based on the initial distribution and these transport equations.

The previous examples show a single step in the analysis. Entering one or more of these statements on the command line is usually sufficient for answering *ad hoc* queries. Dynamic models are usually more complex, and are programmed by writing scripts containing series of statements. In addition to the statements used in static scripts and simple one-step analysis, dynamic modelling requires functionality to create and access time series and to define blocks of statements that should be executed iteratively. The time input functions allow for accessing the appropriate data in the input time series database for each individual time step, while the report function allows for the creation and updating of the resultant time series. The language has no explicit structures for iteration, but the script includes a timer section which defines model start time, end time and time step. In the script specialized sections (the dynamic sections) defining the iterative behaviour of the model are controlled by the definition of the timer. The next example shows a simplified surface runoff model.

```
# timer: start end increment
timer 1 100 1;

initial
# initial status of surface water
SurfaceWater = InitSurfaceWaterMap;
# coverage of meteorological station for the whole area
RainId = RainStationsAreaMap;

dynamic
# add rainfall to surface water
SurfaceWater += timeinputscalar (RainTable, RainId);
# distribute surface water according to drainage pattern
# and return both the state and flux
SurfaceWater, Runoff = routestate, routeflux (Ldd, S^0.3, S = SurfaceWater);
# output runoff at each time step for
# selected locations
report SampleTable = timeoutput (SamplePlaces, Runoff);
```

The initial section is executed once to initialize the model run. The dynamic section is run repeatedly for the number of time steps stated in the timer section. In this example, rainfall is the dynamic input, read from the table *RainTable*, which lists the precipitation measured at several meteorological stations. *RainId* does not represent the location of the stations, but the area of pixels for which the measurement at that station is the best estimation of the actual precipitation at each pixel. The *RainId* map denotes for each pixel the column number in the time table. At each time step, *timeinputscalar* reads the row associated with the current time step from the time series file *RainTable*, and returns a map containing the column values as defined by *RainId*. The last statement of the example creates a time table sampling certain locations in the *Runoff* map. These locations are identified by the *SamplePlaces* map. Each non zero value in the *SamplePlaces* map is responsible for creating and maintaining a column in the time table *SampleTable*. Note that the current time step is an implicit argument to all dynamic functions, such as *timeinputscalar* and *timeoutput*.

In the dynamic section, the route functions are used to define lateral flow of *SurfaceWater* through the area. At each step the flux function is evaluated that uses the *SurfaceWater* values computed in this time step as initial state. For each time step, first the new amount of *SurfaceWater* is computed by adding rainfall to *SurfaceWater*, and with this amount of *SurfaceWater* distribution of the water within the flow network is determined.

COMPONENT-BASED MODELLING

When multiple layers where material can be stored are involved, the sequential approach of the dynamic section becomes cumbersome. A better structure for these models is to define components, link them together and describe the characteristics of each individual component that make up a dynamic system separately. Therefore DYNAMITE offers a component-based syntax to define the components, storages and their connections, called transports. The spatial modelling language that results is based on the systems dynamics approach of Forrester (1968) and is a spatial extension of an approach similar to the STELLA modelling environment.

In the next example two storages, *Surface* and *Groundwater* are defined. These storages are linked through a connecting transport *Infiltration*. *SurfaceWater* is fed by *Rainfall*, which is also modelled as a transport, connecting an unlimited supply with the storage *SurfaceWater*. *SurfaceWater* is redistributed through the network using the approach described above. The component-based script for this model reads:

```
timer 1 100 1;

initial
 InfiltrationRate = lookupscalar (InfiltRateTable, SoilTypes);

dynamic
 report SurfaceSample = timeoutput (SamplePlaces, Surface);
 report GroundWaterSample = timeoutput (SamplePlaces, GroundWater);

storage Surface:
 initial Surface = InitSurface;
 routing route (Ldd, S^0.3, S = Surface);

storage GroundWater:
 initial GroundWater = InitGroundWater;

transport Rain to Surface:
 Rain = timeinputscalar (RainTable, RainId);

transport Infiltration from Surface to GroundWater:
 Infiltration = InfiltrationRate * Surface;
```

Each component definition encapsulates the relevant model code for that component. A storage definition consists of an initialization and an optional routing function. A transport can be a function of any component in the model and can be used for input (e.g. the definition of the transport *Rain*) and output of an open system. Note that the component-based description of the model does not define the sequence of execution. The execution order is determined by the interdependencies of the storages and transports.

The component-based approach offers a structured method to develop environmental models from scratch, test them, and modify them if necessary. The approach yields a structured, high level simulation language that can be used to implement environmental models in GIS without having to code database access and numerical algorithms to solve process equations.

DISCUSSION AND CONCLUSIONS

In this paper we have presented DYNAMITE, a modelling language for dynamic modelling in a GIS environment. Key features are the ability to process dynamic data and a strong type checking mechanism that reveal possible errors in the model.

It is important to mention that the language is not a macro language. A DYNAMITE script is not a list of actions that is sent to separate autonomous modules of the GIS. Instead, a single program (CALC) reads a script entirely, checks it for errors and then executes it. This approach yields better error detection facilities and faster execution of the model than macro languages. A disadvantage, compared to macro languages, is that it does not allow a user to add lacking functionality. Therefore, provisions must be made that enable a user to extend the set of functions recognized by the CALC program.

The language discussed here has been developed at the University of Utrecht over a period of five years. In this period, early prototypes of the language were used for numerous environmental models. Published examples are LISEM, a physically-based hydrological and soil erosion model on catchment scale (De Roo *et al.*, 1994), RHINEFLOW, a water balance model for the river Rhine (Van Deursen & Kwadijk, 1993) and Calluna, an ecological model for heath land dynamics (Van Deursen & Heil, 1993). Most of the current applications put a strong emphasis on environmental modelling and especially hydrological surface routing. Therefore, the evolution of the language has resulted in a rich set of global functions involving drainage networks. Demonstrations of the use of vector fields and associated processes, such as diffusion and advection, are not yet available. Further research and development must prove if DYNAMITE is effective in areas such as groundwater modelling, where such processes are used extensively. A demonstration version of the software will be released in 1996 as an invitation to the GIS community for further discussion on GIS and dynamic modelling.

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