Modeling hydrological Process with GIS and Finite Element Numerical Simulation, Towards a New paradigm for the sustainable development: SAGESS_Tunisie

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Abstract

Computers have been applied in urban planning almost since their inception, but only recently with the development of graphics, distributed processing, and network communications has software emerged which can now be used routinely and effectively. At the basis of these developments are geographic information systems (GIS) but gradually, these are being adapted to the kind of decision and management functions that lie at the heart of the planning process. A large number of computational techniques are now employed to document, simulate, and evaluate sub-watersheds. These methods are traditionally focused upon modeling existing conditions, and operating in batch-oriented processing modes. When planning for any landscape development is undertaken, attempts are made to modify the initial watershed models for an evaluation of the impact of a proposed change. Each change requires a laborious retooling and/or recomputation to produce 'results'.

Hydrological modeling of natural phenomena is made difficulty by characteristics such as spatial and temporal difficulty, dominating mechanisms that vary with environmental circumstances, uncertain factors, and scale effects. These effects are particularly inherent in distributed land surface. GIS provides representations of the spatial features of the Earth, while hydrologic modeling is concerned with the flow of water and its constituents over the land surface and the subsurface environment. There is obviously a close connection between the two subjects. GIS offers the potential to increase the degree of definition of spatial sub-units, in number and description detail, and GIS-Hydrologic model linkage also offers the potential to address regional or continental scale process whose hydrology has not been modeled previously to any significant extent.

The goal of this paper is to outline a conceptual basis for the link between GIS and finite element simulation in hydrological processes. Its specific objectives are to present a new taxonomy of hydrologic modeling with the finite element method, to understand the kinds of models that are used, to indicate which kinds of models could be incorporated within GISs, and which are best left as independent numerical tools for strategic management of water resources in semiarid areas.

Key Words: GIS, SDSS, hydrological modeling

1.Introduction

A large number of computational techniques are now employed to document, simulates, and evaluates sub-watersheds. These methods are traditionally focused upon modeling existing conditions, and operating in batch-oriented processing modes. Professional literacy in planning and design uses a complex, heuristic and empirical process. The languages and vocabularies needed for the manipulation of spatial form has resulted in approaches favoring dynamic and process-oriented techniques. In conventional planning and design, the media and processes are difficult and elusive even for many expert and institutional decision-makers. This result in planning and design being made almost inaccessible to associated lay groups.

This is critical in the watershed policy and political arenas where research and practice have become more disconnected. In this situation support mechanisms are required to allow a comprehensive dialogue on sub-watershed planning and design issues. Geographic Information Systems are a rapidly evolving technology that can be used for the efficient storage, analysis, and management of spatial information. Environmental or natural resources management decisions usually require the analysis of spatial information. GIS technologies have been used to facilitate decision making in the field of water resources and many other fields of study.

2. Purpose and scope

The goal of this paper is to outline a conceptual basis for the link between GIS and finite element simulation in hydrological processes called SAGESS_Tunisie (figure 1). Its specific objectives are to present a new taxonomy of hydrologic modeling with the finite element method, to understand the kinds of models that are used, to indicate which kinds of models could be incorporated within GISs, and which are best left as independent numerical tools for usually require the analysis of spatial information.

3. GIS and decision making

GIS technologies have been used to facilitate decision making in the field of water resources and many other fields of study. McKinney and Maidment (1993) combine a GIS with Expert System technology to enhance the decision-making process in water resources management. Given existing and projected water supplies and demands combination of the two technologies determines potential water deficits and surpluses

GIS technologies facilitate the decision making process based on their analytical capabilities with spatial information Densham and Armstrong (1994). In addition to this, many of them are equipped with a graphical user interface, which increases the decision-maker's comprehension of the spatial information that is involved in the problem being addressed. Based on these two potential additions to the decision making process, a GIS is often included as a major component in the development of Decision Support Systems (DSS) Densham (1996).

4. Hydrologic Modeling with Geographic Information Systems (GIS)

Understanding the spatio-temporal characteristics of runoff at the catchment scale involves the use of many different types of data, such as field measurements, remote sensing images, digital elevation models, and results from hydrologic simulation. All of these data types have a strong geographic component, so it is natural to consider a geographic information system (GIS) as a primary tool for data organization and analysis. GISs incorporate data models and functionality specially tuned to map making and geographic analysis. Although traditional GISs have excellent georeferencing and image processing capabilities, they cannot easily handle data in more than two dimensions. For applications to catchment scale hydrology, this limitation implies, for instance, that subsurface (3D) processes and multi-temporal satellite images and simulations cannot be effectively visualized. Another drawback of traditional GISs is that they allow the user only limited interaction with the data.

The weaknesses that are inherent in a traditional GIS are the very strengths of a data flow visualization system. The idea behind data visualization is simple: a computer graphical display of a (usually large) set of data values can facilitate the discernment of patterns and trends in the data that might otherwise be laborious to detect (Jankowski *et al.* 1997). This can be accomplished in many different ways, and a variety of different types of visualization systems have been created. In general purpose, or data flow visualization systems, visualization is broken down into discrete modules, each of which performs a specialized task. The modules can be categorized as data sources (which read in the data), data filters (which transform, select, or refine the data), mappers (which construct an abstract geometrical representation of the data), and renders (which generate an image). The modules are assembled together into a data flow network, the output of which is an image plus widgets to control the various processing parameters. This process is extremely flexible as users can add their own specialized modules and create any visualization they desire.

Because of the complementary nature of GIS and data flow visualization systems on problems found in many of the environmental sciences, there has been much discussion over the last few years about how to bring visualization concepts and techniques into GISs, and vice versa. The reality today, however, is that the systems are separate. This is not necessarily a disadvantage, as one can capitalize on the unique strengths of each as building blocks for the desired research system. We will discuss the pros and cons of both approaches, and give an overview of current research in this area.

As a case study, we have considered the merger of GIS and data flow visualization techniques in an application involving remote sensing and hydrologic simulation, which requires both georeferencing and 3D-volume visualization (Fedra 1997). The application includes the development of techniques to simulate numerically run-off of watershed, and the validation of these techniques using ground truth measurement and hydrologic simulation over a range of scales (field, sub-catchment, and catchment). The implementation is based as much as possible on off-the-shelf components, with a minimum of custom software development. The GIS and visualization software used in the study consists of ARC/INFO, and MEFL3D.

4.1 Topological aspect between GIS tools and finite-elements method (FEM)

The finite-element method allows two-dimensional space to be subdivided (discretized) into a mesh with variably sized elements (Chu and Marble, 1995), (Drolet 1997) (Kuniansky and Lowther 1993). Some generalizations can be made in considering the design of a mesh for a specific problem. These considerations vary with the partial differential equation or equations being solved for hydrological processes, such as two-dimensional flow. Where both velocity and water surface elevation are unknowns, smaller elements are necessary, where there are sharp gradients in velocity, in depth of bed, and in the water surface. These conditions are common in and around the stream channel.

For all finite-element problems, the size and the shape of the elements affect the solution given by the numerical model (Chu and Marble, 1995). Theoretically, as the size of the elements approaches the vicinity of zero, the solution approaches the true solution of the equation. Nowadays, there is an increase in runoff error as the number of equations solved infinity and the element size decreases.

The shape of element affects the solution quality, because the finite-element method uses interpolation functions, also called shape functions or basis functions, which are derived from the co-ordinates of the nodes for each element (Chu and Marble, 1995), (Kuniansky and Lowther 1993). In the finite element model, each triangular element is a polygon defined by three vertices (called nodes of the finite element). For the water surface flow, the mass balance of the water is computed algebraically by summing the flow at nodes, which may be connected to several elements.

One the most important keys to develop finite-element mesh using GIS software lies the ability of the GIS to perform the following functions: (1) to build triangles that will satisfy the numerical aspects of the mathematical problem; and, (2) to use the topological relationships provides by the GIS software to create the node co-ordinate and element connection data required for finite-element model, this kind of file called *.ele and *.cor (Kuniansky and Lowther 1993), (Chu and Marble, 1995). To do this, we have developed an algorithm called TIN3D-FEM, which transform the data and topology extracted from the TIN to be used by the numerical model (figure 2).

4.2 Finite element formulation

A Galerkin finite element formulation was used to reduce the partial differential equation (PDEs) governing the process to a system of ordinary differential equations in time. This method requires that the weighting functions be the same as the shape functions in the residual minimization. The PDEs governing overland flow are the conservation of mass and momentum. The simplified form is applicable to most practical hydrology conditions

The simulation of surface water flow requires an array of the principal slope and Manning roughness coefficients for each node. The distribution of rainfall intensities were assumed spatially invariant and thus lumped for watershed. Thus, the infiltration is integrated through the numerical model by the Horton infiltration law (1964)

5 CONCLUSION

At present, the mathematical model and its implementation in Arc/Info-TIN have been developed, and it is planned to test it with runoff data of the Merguelil's sub-watershed called Msilah, (figure 3 and figure 4)

The model presented in this article gives a good representation of the flow processes in a watershed. Different phenomena, such as water losses due to evaporation can be considered, and the fact that water particles flow at different rates are considered in the model, allowing the user for more modeling flexibility at the expense of more model parameters.

The idea of GIS empowering communities to participate in decision making about community pertinent problems has stimulated a number of interesting research issues. One of them is how groups of people, comprised of the diverse community members, can collaborate outside the confines of the traditional public meeting environment to better understand and consequently propose feasible solution alternatives to a land use zoning problem. The prototype provides tools for communication among group members, database access, problem exploration, spatial modeling, and the evaluation of proposed solution alternatives. The effectiveness of the prototype design will be tested and assessed in the course of the experiment.

6. References

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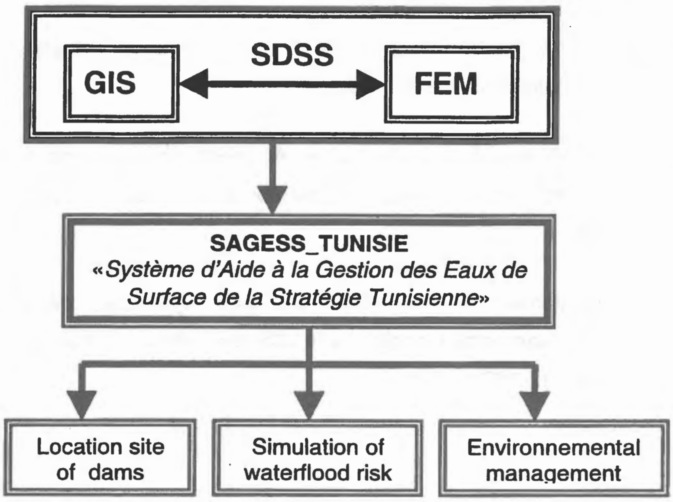

Figure1 Principal of SAGESS tools

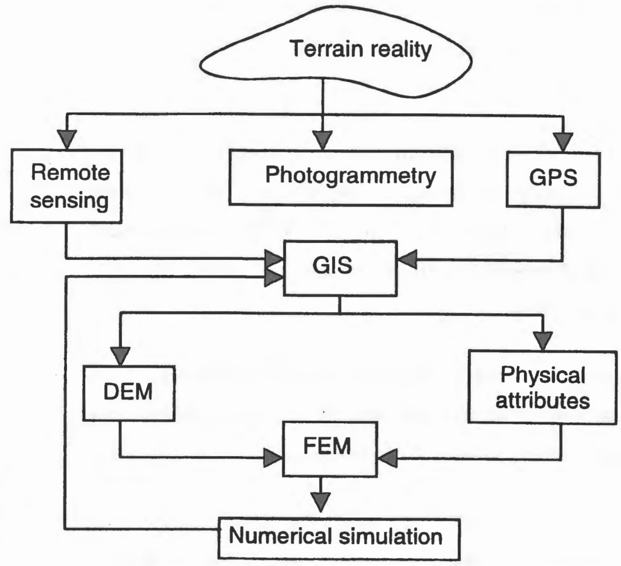

Figure 2 Linkage between GIS and FEM

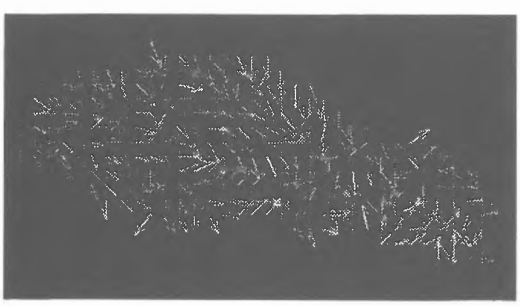

Figure 3 Automated mesh with FEM and GIS
Velocity flow

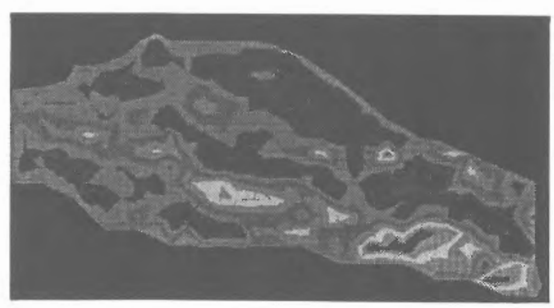

Figure 4 Numerical simulation of the watershed :
Tools for SDSS