Towards integrating GIS and catchment models

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Abstract

Modeling the impact of non-point source pollution in catchments is a complex problem, and one that has troubled natural resource managers for many years. The development of spatially distributed hydrologic models has led to improved model forecasting at the cost of requiring more detailed spatial information. In addition, the analysis is much more sensitive to errors in the data. Incorporation of catchment models into a Geographical Information System (GIS) has improved matters by streamlining data input and providing better interpretation of model outputs. This paper reviews different strategies for linking a catchment model with GIS. It examines data issues related to the performance of models and how well they match physical landscape conditions. Integration with GIS is shown to be necessary for the efficient and proper operation of models in resource management situations. The paper concludes that tighter integration between generic sub-models for physical landscape processes and GIS is still required. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: GIS; Watershed; Runoff; Decision support; System integration

Software availability

Interested persons should contact the first author. A version will be available in the future where the main components of the model are implemented as operators in a map algebra language.

1. Background

Increased activities in agricultural regions together with higher demand for water supplies have resulted in concerns about water quality. Resource managers are faced with managing this vital resource without adequate time and modeling tools to research the full impacts of their decisions. Best management practices for dealing with many environmental issues are seen as offering workable solutions, especially pressing environmental issues like soil erosion and salinity. But best management practices only provide a set of options, it is still difficult to judge the impact of an option and where to optimally apply it. In cases where the environmental problem is isolated to a point, i.e. point source pollution, the choice of a management option is relatively straightforward. For instance, contaminant leeching from a cattle dip. However in cases where there is no clearly identified pollution source and the degradation is dispersed across the land, it is difficult to determine the best location to contain the problem and judge the impact of remedial actions. For instance, nutrient transport of fertiliser chemicals from agricultural lands into waterways. This is referred to as non-point source pollution because the source of the pollution is diffuse. It varies spatially and temporally across a catchment in response to a combination of land conditions and topographic factors. Even an experienced resource manager finds it difficult to predict the outcome to alternative management options when dealing with non-point pollution and varying conditions.

Environmental models are a possible solution as they provide a means to simulate physical landscape processes over time and give decision makers an indication of the outcome for different options. But all too often predicative models do not examine the problem in a geographical context. This is where a Geographical Information System (GIS) becomes a valuable tool. A GIS is
a tool for the management, query, visualisation and analysis of spatially referenced information (Burrough and McDonnell, 1998). A GIS coupled with an environmental model provides a tool to run a simulation and to interpret the results in a spatial context.

This paper treats key problems in using a hydrological model and its integration into a GIS, and reports on a significant application of GIS and hydrological model integration. Like several other papers (Panuska et al., 1991; Srinivasan and Engel, 1994; Fedra, 1996; Coroza et al., 1997; De Roo, 1998) we report on our experience with integrating a model with GIS, but in this paper we focus on the nature of this coupling. Our contribution is to demonstrate that GIS can: a) be used to preprocess information and validate its use in an environmental model, and b) be tightly coupled to an environmental model to provide an interactive system that allows decision-makers to quickly modify parameters and visualise the results of simulations. This is demonstrated by the development of a prototype system that integrates a GIS with a hydrological model. The prototype performs the mechanical functions to identify appropriate watershed boundaries, prepare the data, run the catchment model, and visualise the results.

2. Outline of paper

The level of system coupling between a model and a GIS has an impact on the reliability and ease of use of the system. Well integrated systems work as a coherent whole and still afford flexibility for modifying the modelling scenario. The paper is organised about the issues of system integration. System integration occurs in three ways: loose coupling, tight coupling and fully integrated (Nyerges, 1991). Loose coupling means the systems are separate and interoperate by the user exchanging information through file exchange. Section 3 reviews two hydrologic models and discusses the issues related to the loose coupling of these models with a GIS. Tight coupling means that one system provides a user interface for viewing and controlling the application, which may be built from several component programs. The GIS typically provides the shared interface to run and exchange data to a separate modeling program. Section 4 reports on a prototype to test the limits of this form of integration, in particular, to test a GIS’s ability to preprocess and validate data so it can be reliably utilized in a hydrological model. Several procedures are described to prepare and condition data input for the proper operation of the model. Fully integrated means the model is embedded as a component in the host GIS application. Given that hydrological models simulate a physical system, then this later case presumes the GIS has dynamic capability to synchronize time dependent behavior. Section 5 speculates on ways to embed models in dynamic GIS and the added benefits of this solution.

3. Loose coupled models

This section examines environmental models for catchments, and issues related to their integration with GIS.

3.1. Catchment models

Catchment models deal with watershed areas ranging from a gully system up to a small stream system. The model needs to deal with several components of the water cycle including: rainfall, run-off, overland flow and routing of water in streams. Besides performing hydrological calculations of storm water runoff, it also makes estimates of the sediments and nutrients transported by those processes. Catchment models are suited to inclusion into resource decision-making as the catchment is a natural management area. Model outputs give estimates for the whole catchment and provide information about the processes occurring in different parts of the catchment.

In general, catchment models are distinguished by: a) the precision of the spatial units used in analysis as being lumped or distributed and b) the precision of the events modeled over time as being a single event or continuous time steps (Maidment, 1993).

Lumped or distributed describes the way in which the model spatially handles the data. Lumped models use spatially averaged parameters and perform computations over the whole catchment region. As the within variation for a catchment increases, the model predictions may become less informative and accurate. Distributed models are based upon the discretisation of the landscape into smaller functional land units. Typically a uniform grid is used for computational convenience. Calculations are performed on discrete cells and then accumulated to make predictions over the whole catchment. With advances in computer technology distributed models are gaining popularity. However they require large amounts of data. The advantage of distributed systems is that they are able to better account for local variability in land conditions. This is important for land management decisions which require a better understanding of land processes within a catchment and for applying farm scale management options.

Single event and continuous time step refer to the time frame over which the model runs. Single event models calculate a single rainstorm event and run over a short period that covers the rainfall duration and time for runoff to drain from the watershed. Continuous time step models calculate for longer periods like a year or over the period of a seasonal crop rotation. Both model types are useful and give different types of information. Continuous time step models do not produce accurate estimates for single storms. Similarly, single event models may not necessarily provide accurate long term predic-
tions. An example of a catchment model that implements a single event distributed parameter model is the Agricultural Non-Point Source (AGNPS) pollution model (Young et al., 1989). An example of a catchment model that implements a continuous time step lumped model is the Soil Water Assessment Tool (SWAT) (Arnold et al., 1993). Both models were developed in North America and have been significantly tested. Application outside North America is limited and mainly focused around research applications rather than part of decision support processes.

3.2. Problems with catchment models

The disadvantage of lumped models is that they do not make predictions for specific sites, and therefore may potentially overlook significant environmental problems. Distributed models, on the other hand, are good at detecting local affects and anomalies. However they are very complex in their operation and require large volumes of input data to describe the variation in the landscape. For instance, AGNPS (Young et al., 1989) requires at least twenty-two parameters for each cell. Formatting and input of data is a prohibitively time consuming task using manual methods. Integration with GIS has streamlined this process and resulted in improved data management and analysis ability (Fedra, 1996). But there still exists problems to develop data sets to honor parameter assumptions built into environmental models, and to adequately validate models for local situations. Without proper validation users are not sure of the model outputs and are unlikely to use them for decision-making. Therefore, a tighter integration between GIS and modeling applications needs to additionally provide improved data validity of input and output data. These improvements are discussed in the next section.

4. Tightly coupled model and application

This research integrates Arcview GIS (ESRI, 1996a) with the AGNPS model. Arcview is a windows based desktop GIS designed for running on personal computers. The integration will be discussed later, but first here is a quick discussion of the AGNPS model.

4.1. AGNPS model

AGNPS is a distributed parameter model which runs simulations based on a single rainstorm event to estimate runoff, erosion and nutrient movement within a catchment. The catchment is divided into a matrix of uniform cells and the model carries out simulations across the grid at the cell level. AGNPS calculates runoff for a single rainstorm event. Several integrated modeling components are run in AGNPS, namely: a) a hydrologic component to estimate runoff and flow, b) a sediment transport component to estimate erosion and deposition, and c) a chemical component to estimate nutrient movement and concentrations through the catchment. Hydrologic calculations are based around the United States Department of Agriculture, Soil Conservation Service Curve Number method (USDA, 1992) with runoff calculated for each cell and accumulated for the whole catchment. The sediment transport component uses two models. Upland erosion is predicted using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), and then the detached sediment is routed from cell to cell across the catchment to determine where sediments are deposited. Nutrient transport calculations use the concept of enrichment ratios and extraction coefficients to estimate movement of nitrogen, phosphorus and COD through the catchment.

AGNPS requires twelve model parameters to setup the model run and to describe the rainfall event. Then for each cell, twenty-two input parameters are required to describe cell information, terrain conditions, land cover, management practices, soil, and surface hydrology, fertilizer and pesticide usage, and channel attributes. The cell information may indicate additional input parameters for point source pollution and terrace impoundment. A multitude of other information may also be specified for options and more detailed parameterisation of the model and cell input. The complex relationship between the parameters and the ability for users to obtain accurate input data is a key issue in the model use. Users lose confidence in the model results when there are difficulties with data validity and model calibration.

AGNPS has been tightly integrated with a number of GIS’s including GRASS (Srinivasan and Engel, 1994) and ArcInfo (Panuska et al., 1991). These examples demonstrate that AGNPS is more usable when integrated with GIS, but they are limited to a UNIX workstation environment and do not address issues of data validity. Data validity is defined as ensuring that the data necessary for model building, model evaluation and testing are adequate and correct (Sargent, 1984). The next section describes the integration of AGNPS with a desktop GIS. As in previous examples the GIS handles the parameter loading, but also takes advantage of some of the interactive query capabilities more commonly associated with desktop systems. Following that is a detailed discussion of the data issues when linking systems.

4.2. GIS–AGNPS integration

The intent of integrating AGNPS with a GIS is to produce a field operational system used by technicians to show landowners the impact of alternative land management practices. The GIS is a befitting tool for the management, query, and visualisation of the necessary information. The application is designed to serve as a spatial
decision-support system (Srinivasan and Engel, 1994). Fig. 1 shows the system architecture. The implementation emphasises interactive visual interfaces (Loucks, 1995) and is targeted at laptop computers for use in field situations. Arcview GIS with its raster surface modeling extension is used for the application development. It includes a hydrological toolbox that supports many basic functions, such as interactive selection of a sub-catchment for hydrological analysis. A software library was developed to exchange data between Arcview GIS and AGNPS. The GIS–AGNPS library uses Arcview’s grid input/output C API functions to read and write data files compatible with AGNPS file formats. The library is called from Arcview through its scripting language Avenue (ESRI, 1996b). A customised graphical user interface was built in Arcview. The model is run from a menu selection using data for a sub-catchment selected by the user. The AGNPS executable produces an output file that is subsequently interpreted and displayed in Arcview.

A user selects an area of interest from the map display and the system analyses terrain data to identify the watershed containing the site (Fig. 2). Various options are specified, such as storm intensity, and the model run (Fig. 3). The user edits site specific data, such as the fertilisers or pesticides (Fig. 3). After the model is run the user can select certain results, such as soil loss, and view the information as a graphic overlay in the map display (Fig. 4). The result can be displayed for improved interpretation as a three dimensional perspective (Fig. 5).

The prototype includes a user-friendly interface aimed at technical people with a familiarity of GIS and an understanding of landscape processes. The application is designed to be used in an intuitive way to do analysis on a selected catchment and to assess various alternative management practices. This was always the way AGNPS was intended to be used (Young et al., 1989).

4.3. Integration issues

We overcame several problems related to integration, including efficiency, data input validity, and model matching.

4.3.1. Efficiency
Efficient computation is a key consideration in the development, both in terms of storage and in the speed of processing. The underlying database containing the
soil, land cover, land use, and channel information is a regional database. In most cases these GIS layers are represented as polygon features, that is graphics linked to database records. Maintaining the source data in this way is more efficient for data storage and is easier for the user to manipulate. For instance a fertilizer treatment can easily be specified for a field as an attribute of the field feature being analysed. The disadvantage is that the polygon feature data needs to be converted to a raster cell-based representation for processing by AGNPS. Alternatively one could store and maintain the GIS layers in a raster database. We believe maintaining the data in a form easily manipulated by users outweighs the added data conversion processing cost. Users may very easily run different modeling scenarios just by changing database attributes, for instance to assess scenarios for the impact of different land uses on pollutant runoff.

Only the GIS polygon data within the sub-catchment selected by the user is converted to a cell representation. This is done on demand when a model is run. The other efficiency issue is to convert GIS raster data to an input format compatible with AGNPS. This involves transforming twenty-two values for each cell into input parameters for AGNPS. Using a scripting language to do this was found to be very inefficient; this is because scripting is based on a language interpreter rather than an efficient code compiler. A special C library was developed, referred to as the GIS–AGNPS library, to read raster datasets and write directly to data files compatible with AGNPS. This library is called and run from within Arcview.

4.3.2. Data validity

An important part of the AGNPS model is the calculation of sediment and nutrient transport from terrain runoff. The terrain is represented using a raster digital
elevation model (DEM) (Burrough and McDonnell, 1998). If the DEM is not hydrologically sound this causes erroneous results or incorrect functioning of APNPS. To be hydrologically sound requires areas drain to a single outlet and be free of internal drainage. Violation of these situations commonly occurs in flatter terrain or when the terrain data is generalised. Therefore it is necessary to hydrologically condition the digital terrain model for the calculation of flow directions.

Hydrological conditioning the terrain model for AGNPS involves the following steps:

1. Selection of a watershed with a single outlet
2. Removal of sinks
3. Stream enforcement

Arcview provides tools to select a watershed within a larger catchment. The area of interest for analysis is selected by picking a point on the terrain, and the application automatically computes the contributing area that makes up the local watershed. The local watershed is computed by doing multiple sweeps up and down from the selection point. All cells flowing into the watershed are included, and the watershed is grown until no further inflow cells are encountered. This process is controlled by a parameter specifying the minimum acceptable area used for watershed analysis. Besides being a useful way to query a catchment, this procedure also enforces an important constraint, namely the watershed is always defined with a single outlet point. Analysis ensures all water flows to a single low point along the watershed boundary.

Removal of sinks is necessary to create a watershed free of depressions. AGNPS requires continuous flow throughout the watershed. Arcview provides a function to identify and remove sinks by filling in depressions. A sink is identified by a neighborhood of cells that have an inward direction of flow. They can be filled by simple rules, such as to assign a value to maintain direction of steepest descent across neighboring cells. But fixing a sink can sometimes cause sinks to occur in neighboring cells, so the procedure needs to be applied in an iterative process until the DEM is free of all depressions.

Stream enforcement will force defined drainage lines present in the DEM to follow the proper stream channel network. A stream channel network provides an accurate representation of stream routing. A DEM does not always produce valid stream drainage because of data sampling, cell resolution and generalisation. In some cases, particularly at stream junctions or in flat terrain, the DEM will produce a stream routing where drainage lines are cyclic, that is they do not drain out anywhere. Stream enforcement modifies the surface representation of the terrain in the DEM to follow digitized stream lines. Use of a digitized stream network also has the advantage of being able to specify stream channel attributes (ie. roughness coefficients, channel geometry, etc.) which are associated with drainage cells in the AGNPS analysis.

Stream enforcement modifies the digital terrain surface by “burning in” the stream channel. That is, elevations around streams are lowered proportionally from the stream center to adjoining cells. A heuristic based upon the elevation range of the DEM is used to calculate the amount to lower the elevation of the stream channel. As one moves away from the stream center to adjoining cells these values are proportionally reduced, this buffer distance is user specified. Fig. 6 shows the effect of “burning in” a stream. More advanced methods have been developed to control the smoothing of side slopes to streams and the exaggeration for lowering the stream center (Hellwegar, 1997).

The procedure for hydrological conditioning demonstrates the versatility of GIS, over and above input parameter loading and visualisation of model output, for data preprocessing and data validity for environmental modelling.

4.3.3. Model matching

The hydrological model was developed as an extension, or plug-in, that is loaded into Arcview GIS. The loading procedure includes configuring default settings and matching data sources. That is, it identifies and matches attributes in data sources to the appropriate AGNPS input parameters. There are several options for running AGNPS using default or user defined parameters, such as for soil and fertiliser properties. AGNPS can also include options such as including point pollution sources or landform impoundments in the model computation. The user is guided through the loading process with a wizard to set options and to resolve naming definitions between AGNPS input parameters and the appropriate database table attributes in the GIS.
ing model parameters to the GIS database on syntax alone does not ensure the absence of semantic conflicts between the model and data. Semantic conflicts occur when matched attributes have a different meaning to what is understood by the model. The causes of mismatch include inconsistent units of measurement or incorrect interpretation of parameters. The only way to catch this is through model calibration. That is, it is only through the use of the model that semantic inconsistency and conflicts between the model and the real world situation can be detected and corrected.

The mechanism for resolving syntactic and semantic conflicts in computer science is to define a set of assertions that must be checked. Simple tests can be made for syntactic conflicts, such as testing for mismatch between data types and value ranges. But semantic conflicts are very subtle, and it is doubtful if they can be fully detected without a knowledgeable operator calibrating the model. Calibration is a process where predicted results and observed data are compared, and adjustments are made to the parameters in the model, i.e., climatic erosivity factor or soil erodibility factor used for calculating soil erosion in AGNPS. These adjustments are made by trial and error. This is a common approach for empirically derived models like AGNPS. It is very difficult for the user to understand the underlying model, and almost impossible for an experienced user to modify the model formulae. We believe these difficulties are a consequence of the GIS–AGNPS coupling and a fully integrated system offers a better solution.

5. Fully integrated models

What possibilities do fully integrated systems hold? Building a tightly coupled interface between GIS and AGNPS is a complex and time consuming task. While the GIS–AGNPS application is usable, it still is not easily adapted to different circumstances and to cater for future needs. For instance, it is beyond the capability of most environmental scientists to modify the AGNPS program model. AGNPS, like many other environmental models, is a black box where the mechanics of the model are hidden in thousands of lines of source code. This limits the ability of users to adjust for regional variations or to make improvements to model equations. An example is modification to the soil loss calculations in AGNPS to better represent the erosive effects of rainfall (Kinnell, 1998). Such adjustments to models can not be readily incorporated into the AGNPS program by a user.

One solution is to integrate the hydrological model into a GIS using a high level language that includes domain specific operations for hydrology. A modeling language that uses a vocabulary for representing and manipulating land surfaces would be easier for scientists to express land processes and environmental mechanisms. Most GIS’s have a scripting facility to either customise or add functionality to an application, e.g., Arcview’s Avenue (ESRI, 1996b). Application functionality is exposed through scriptable objects, which can be manipulated using program constructs in the scripting language. Some well-established watershed analysis operations are available in commercial GIS’s, for instance operators to calculate terrain flow accumulation and flow distance to outlets (Gao et al., 1993). This can provide a crude calculation of cumulative overland flow caused by rainfall runoff (Maidment, 1996). Such operators are useful for generating cumulative area maps to show the drainage area contributing to overland flow over time. These time-area maps are related to a stream hydrograph and help to interpret the spatial pattern of water flow.

Adding generic operators to geographic analysis languages has great potential for developing fully integrated systems. The raster cell representation is supported in many commercial GIS, and these systems are able to calculate some land surface interactions that incorporate modifications of model processes to respond to varying land conditions. The main limitation in current GIS is that they do not explicitly handle the calculation of movement across land surfaces. AGNPS routes detached sediments and dissolved nutrients from cell to cell based upon flow propagation. The flow accumulation algorithm, found in Arcview and several other raster GIS packages, is able to compute flow paths for terrain but cannot explicitly deal with transmission of water across the terrain. To simulate overland flow requires a solution to simultaneously model the transmission and storage of runoff across the terrain (Bedient and Huber, 1988). No commercial GIS has these dynamic capabilities.

Development of terrain and environmental flux operators is an area of research that merits further investigation (Burrough, 1998). Instead of simply computing cost distance values along flow paths, operations to compute the accumulated flux between cells could be developed. Environmental adective-diffusion models can be described using a small number of scripting statements (Pullar, 2000). Such scripts describe an environmental model succinctly and can easily be modified to suit specific land conditions. The way a model works is easily understood instead of being hidden in complex low level source code. This line of research is being pursued by the authors to develop fully integrated solutions.

6. Conclusion

Development of catchment models has primarily been driven by scientific development. Consideration of widespread use of such models in planning and natural resource decision-making is often an after thought. As a result, hydrologic models are generally complex, involve
tedious data entry, and require an expert level of knowledge to run and interpret results. Integration with GIS offers some improvement by streamlining data input from GIS map layers and visualising model outputs, but until recently the majority of integrated systems occurred on high powered machines that also required specialist knowledge. We believe integration into desktop GIS provides a better interface and visualisation capability in a user-friendly environment.

This paper has reviewed different strategies for coupling a hydrological model and a GIS. Hydrologic models can estimate changes in pollution loads and predict impacts of land management change over time and across space. The only practical way to handle distributed models with large data requirements is with an integrated GIS solution. The GIS is beneficial for visualising and interpreting the results of runoff simulations and understanding the impacts of pollution. We have tested linking AGNPS and a GIS using both loose (Awadhwal, 1998) and tight (Springer, 1997) coupling strategies. A tight coupling strategy proved to be superior with respect to doing model analysis and to perform data calibration. The prototype described in this was used to evaluate different management options for a catchment, and to do sensitivity analysis on different model parameters to assess various impacts of management options. This required making systematic changes to landuse and agricultural activity within a catchment, running a model and tabulating the results. For practical reasons it requires a tightly integrated system to do this. The prototype was also used in an agricultural region to predict areas of land causing soil erosion within a large catchment. Again there is a need to run multiple simulations in an expedite fashion.

The other major benefit of integrating a model with a GIS is validating data input and in model calibration. Hydrological models depend upon inherent physical properties, such as the way water flows across a landscape, to work properly. The GIS has tools to assist in selecting a well defined watershed for analysis, for removing depressions within this watershed and for enforcing drainage patterns so that the model operates properly.

Despite these benefits it still requires specialist knowledge to modify the way AGNPS operates from a GIS. AGNPS has very exacting data requirements that are difficult to understand and comply with. Due to the complexity of the model it was only through experimentation that we could discover inconsistencies in matching model parameters. It is difficult to intuitively understand the way AGNPS performs calculations, and it is impossible to make any enhancements to the algorithms. We believe a better solution is to break hydrological models down into smaller operations, some of which are germane to other hydrological models. To incorporate more generic data models for land-surface interactions into GIS requires that GIS provide support for dynamic modeling. Research to develop generic advective–diffusive operators is occurring and promises a better solution.

References

