A Practical Approach to Using GIS Data in Lumped Parameter Hydrologic Models

Abstract: The primary goal in modeling hydrologic phenomena is to compute a hydrograph, or graph of stream flow versus time. This hydrograph is computed at a point of interest, or outlet point, for the area of land that flows into a stream, known as a drainage basin. Hydrologists use lumped parameter hydrologic models to compute a hydrograph for each sub-basin in a hydrologic model. Large databanks of Geographic Information System (GIS) data are available for use in developing these lumped parameter hydrologic models. However, tools are just now beginning to emerge that can make use of these hydrologic data for determining important hydrologic modeling parameters. A new hydrologic modeling tool is presented that combines several layers of GIS data and automatically generates the topologic attributes necessary for lumped parameter hydrologic modeling. A unique aspect of this approach is that points, polylines (or arcs), and polygons are combined and connected into a single layer and used to represent drainage features such as outlet points, streams, flow diversions, lakes, and drainage basin boundaries. If changes are made to the point, arc, or polygon data, the hydrologic modeling information is automatically updated reflect the changes. In addition, with this direct link between GIS and hydrologic models, physical parameters such as basin areas and stream lengths are easily computed and stored for hydrologic modeling.

Introduction

The primary goal in modeling hydrologic phenomena is to compute a hydrograph, or graph of stream flow versus time. This hydrograph is computed at a point of interest, or outlet point, for the area of land that flows into a stream, known as a drainage basin.

One approach to modeling hydrologic phenomena is a method called *lumped parameter* hydrologic modeling. Lumped parameter models combine all the data for a sub-basin into a single number, or set of numbers, that define the response of the basin to a storm event.

On the other hand, *spatial, or distributed, models* divide a drainage basin into a set of grid cells. Spatial models take the data for each grid cell and use that data to compute flow from cell to cell for the drainage basin. The combined flow at the outlet cell of the watershed can then be determined.

A Geographic Information System (GIS) is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information. While spatial models are ideally suited for use with a spatial GIS database, lumped parameter models are not. Unfortunately, most hydrologic modeling studies are constrained to the use of industry standard, time proven lumped parameter hydrologic models.

GIS has been around for several years, but the large amounts of geographic data in a GIS are only beginning to be integrated with lumped parameter hydrologic modeling. One of the primary reasons GIS is only beginning to be integrated with hydrologic modeling is because a high level of knowledge is usually required to be able to interact with the GIS data. Also, when a GIS has been combined with hydrologic modeling software, significant user interaction is still required and only one or two hydrologic models are supported (DeVantier and Feldman, 1993). Many hydrologists still find GIS to be more time-consuming than computing the hydrologic modeling parameters by hand, creating an input file, and running a lumped parameter model.

This study focuses on a practical approach to combining GIS data with lumped parameter hydrologic models. The process of combining GIS data with distributed models is discussed elsewhere (Wang and Hjelmfelt, 1998). First, the organization, uses, and limitations of hydrologic data in a GIS were determined. Then, a method was devised to combine this GIS data into a topologic tree format for use in hydrologic modeling. This method uses the data from the GIS and automatically generates and links a lumped parameter topologic tree to the GIS data. The leaves on this tree represent sub-basins and the nodes represent the sub-basin outlet points. One advantage of this *hybrid* approach of linking GIS data with a tree is that the properties computed using the GIS data can be directly assigned to the topologic tree and the hydrologic model.

Previous Research in Watershed Modeling Using GIS

Most of GIS-hydrologic model interfaces require significant user interaction with the GIS, but some do not. DeVantier and Feldman (1993) give an overview of GIS applications in hydrologic modeling. In one of the projects they discuss (Warwick et al., 1991), a popular lumped parameter model called HEC-1 was integrated with a GIS. One problem was that significant user interaction was still required to create a model using this HEC-1/GIS system.

Innovative System Developers, Inc. have developed a GIS application in Arc/Info that, given the sub-basin outlet points, can be used to locate sub-basin boundaries (1995). Geometric parameters can be computed, the time of concentration can be determined from a selected point in the sub-basin, and a TR-20 hydrologic input file can be generated from the GIS data.

One of the best and most complete papers linking GIS data and a hydrologic model is the discussion by Hellweger and Maidment (1998).

In Hellweger and Maidment's method of defining hydrologic elements using geographic data, two data layers are required: a line, or arc, layer of streams, and a polygon layer of sub-basins. Six steps are required to develop a hydrologic model using Hellweger and Maidment's method:

1. The stream and sub-basin layers are generated from digital elevation data.
2. The stream and sub-basin layers are intersected, creating a new layer containing only those streams inside the watershed.
3. Arcs representing the primary stream and surrounding reservoirs in each sub-basin are determined.
4. Each node in the model is identified as one of ten different types of nodes. Each node can be classified as a source node, sink node, reservoir node, and so forth based on the type and direction of arcs surrounding the node.
5. A schematic diagram of the watershed is automatically generated. This schematic diagram contains nodes that represent diversions, junctions, reservoirs, sinks, sources, and sub-basins. It also contains arcs defining the sub-basin boundaries, channels, and basin-outlet links. In this model, sub-basin outlet points are treated as junctions.
6. The basin-node connectivity and locations are written out to a “Basin File”—a file that can be read into a hydrologic modeling program called HEC-HMS.

All the methods discussed above use the GIS as the mechanism to perform hydrologic modeling. It is extremely convenient to perform all your hydrologic modeling in a GIS. However, there are also advantages of using your GIS as a data storage mechanism and importing your GIS data into software specifically designed for hydrologic modeling. In this study, the organization, uses, and limitations of GIS data in hydrologic modeling were first determined. Then, a procedure to link this GIS data directly to a topologic tree for use in hydrologic modeling was determined.

Organization of Hydrologic Data in a GIS

GIS Data Structures

A vector-based GIS consists of five basic elements: Nodes, vertices, points, arcs, and polygons (Figure 1). Each arc has a direction and consists of two nodes…one “from” node and one “to” node. Vertices along the arc determine the arc’s geometry. Points are not connected to an arc. Points and nodes may contain attributes, but vertices cannot have any attributes. Sets of closed arcs form polygons. The points, nodes, arcs, and polygons in a GIS can all have attributes assigned to them. These attributes can be computed values such as length and area, or hydrologic parameters such as soil imperviousness or land use.

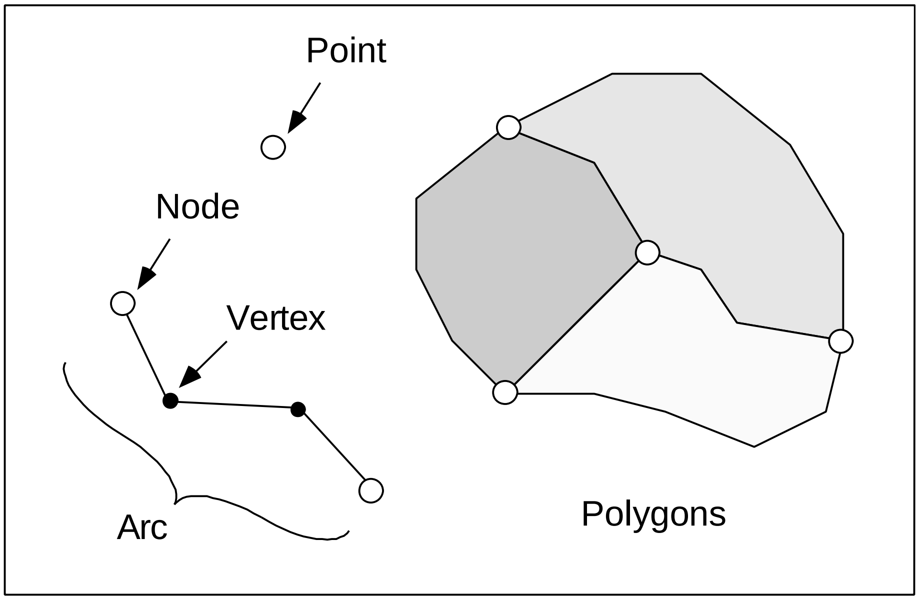

Figure 1: GIS Data Types

Hydrologic Data Development Using GIS

When developing a hydrologic model using GIS, two coverages, or layers, of data are required. You must first have a polygon coverage of the watershed and its sub-basin boundaries. You must also have an arc coverage of all the streams in the watershed. Other useful layers include a land use layer, a soil type layer, and an elevation layer. Given a boundary polygon coverage and a stream arc coverage, a coverage containing each sub-basin's outlet point can be derived from the intersection of the boundary polygon coverage and the stream arc coverage. For each sub-basin of your watershed model, you can compute the average basin slope, the maximum flow distance, the maximum stream flow distance, the sub-basin centroid, and several other geometric parameters. These parameters may then be used as input parameters to your watershed model. Elevation-based parameters such as the percent north and south facing area in each sub-basin could be computed using background elevation data. Watershed rainfall runoff coefficients can be computed using land use and soil type data. Then, using the method described by Hellweger and Maidment (1998), you could derive a schematic of the watershed and save the schematic in a format that watershed modeling software can use.

Limitations of Hydrologic Modeling in a GIS

Although a GIS is the best way to store and retrieve spatial data, it is difficult to use a GIS for modeling using this spatial data. There are three factors that make it difficult to use a GIS for modeling:

- When modeling using a GIS, your model is usually customized for a single model, county, or other municipality.
- If an interface to a watershed model is constructed for a GIS, it requires a GIS to run.
- A GIS is a generic tool, making it difficult to use a GIS to solve specific modeling problems.

Customized for a single model, county, or other municipality

A GIS us usually customized for a single model, such as HEC-1, or for a single county. This makes it difficult to share GIS data for different areas of the country or even within a state. Also, a single GIS system cannot be the solution for different watershed modeling projects around the country.

The interface is built on top of GIS and requires a GIS to run

In a GIS-based interface to a watershed model, the interface is built using the GIS. This means that the company or municipality using the GIS requires the GIS to run it. Many times, GIS licensing may be expensive or the municipality may already be using other GIS software and may not want to change the GIS they are using to accommodate a watershed model.

GIS is a generic tool, therefore it is difficult to solve specific modeling problems

A GIS is inherently a generic tool. It is extremely flexible and is good for creating maps and analyzing geographic properties, but is poor for performing modeling tasks. It is difficult to represent time-dependent data in a GIS. It is also difficult to work with a GIS to perform basic watershed modeling tasks.

Time

Many computations in watershed modeling are based on time-dependent processes. The amount of rainfall in a watershed, the change in soil moisture, and the level of a reservoir in a watershed are all dependent on time. Unfortunately, there are no easy ways to represent these time-dependent values in a GIS.

User interaction

Often, a GIS requires a significant amount of user interaction for basic modeling tasks.

Organization of Hydrologic Data in Hydrologic Modeling Software

Two classes of software exist for performing hydrologic modeling. Lumped parameter models take all the data for a sub-basin and combine it into a single number, or set of numbers, that define the response of the basin to a storm event. On the other hand, Spatial, or distributed, models take the data for each grid cell inside the watershed and use the data to compute flow from cell to cell. While spatial models are ideally suited for use with a spatial GIS database, lumped parameter models are not.

Despite the huge developments in GIS technology in recent years, most hydrologic modeling studies are still performed using the industry standard, time proven, lumped parameter hydrologic models such as HEC-1 and TR-20.

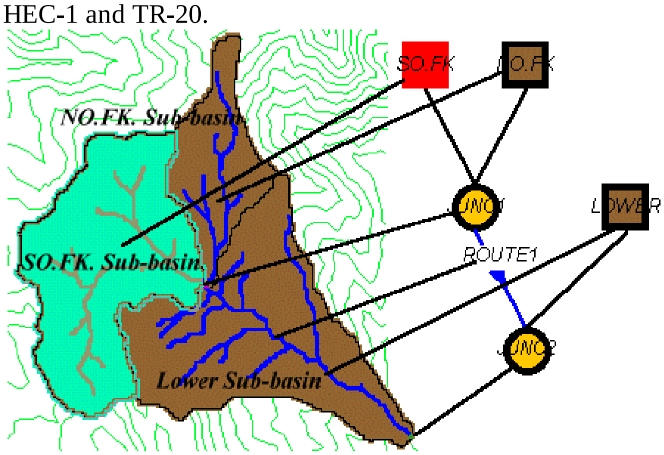

Figure 2: Correlation between a GIS watershed model and a lumped parameter watershed model

When using a lumped parameter model, it is useful to draw a schematic diagram of the watershed you are modeling. Many times, the schematic diagram of a watershed can be constructed using a tree diagram. In this tree diagram, the leaves on the tree represent sub-basins. The leaf stems show which outlet each basin drains to. The tree nodes represent sub-basin outlet points and the connections between nodes represent main channels (Figure 2).

Limitations of Hydrologic Modeling using Topologic Tree Based Software

When working with GIS data, a hydrologist's task is to convert the spatial GIS data into this tree structure for use in watershed modeling. Converting this GIS data into this tree structure can be difficult, especially if the hydrologist is modeling a large watershed. Also, determining all the parameters from the GIS data to input into a hydrologic model can be time consuming.

The Derivation and Linkage of a Tree to GIS Data: A Hybrid GIS-Tree Approach

Because of the difficulties involved in going from a GIS-based representation of a watershed model to a tree-based representation of a watershed model, a method of directly linking the GIS data to a tree-based representation was devised. In this method, modifications made to the watershed model cause the tree to be automatically updated and hydrologic modeling parameters are computed directly from the GIS data. This method of linking the GIS data to a hydrologic modeling tree was implemented in watershed modeling software independent of any GIS. The software is called the Watershed Modeling System (WMS).

Before performing any of these automatic operations, however, a layer of streams and a layer of sub-basin boundaries must be combined into a single layer. In this layer, the streams and sub-basin boundaries must intersect at the sub-basin outlet locations. Furthermore, since stream arcs in a GIS have a direction, the stream arcs must be ordered from downstream to upstream. In other words, to automatically generate a topologic tree from the GIS data, all the topologic attributes must be assigned correctly in the GIS data. These topologically correct GIS attributes may either be created in a GIS and imported into WMS or be created directly in WMS. The coverage in which the streams, sub-basin boundaries, and sub-basin outlet locations are topologically linked is known as a drainage coverage.

Two steps are involved in automatically linking and updating a hydrologic modeling tree from GIS data. First, all the stream and lake arcs are must be looked at to determine which sub-basin they are in. Second, all the boundary polygons must be checked to assign sub-basins to each of the polygons.

Assigning sub-basins to stream and lake arcs

In the first step, all the arcs in the drainage coverage are visited. If an arc is not a stream or lake arc, it is checked to see if an outlet is assigned at either end of the arc. If an outlet is assigned at an end and there are no stream arcs attached at that end, the outlet is deleted and all the sub-basins assigned to that outlet are deleted.

If an arc is a stream or lake arc, the arc is followed downstream until a sub-basin outlet location is found. If a sub-basin outlet location is found, an outlet on the topologic tree is assigned to this location. If it is a new outlet location, the new outlet is linked into the topologic tree. Then, if no sub-basin is assigned to the arc immediately upstream from this outlet point, a sub-basin is added to the topologic tree at this outlet point and this sub-basin is assigned to all the upstream arcs from this outlet point. Also, if the sub-basin on the arc immediately upstream from the outlet point is the same as the sub-basin on the arc immediately downstream from the outlet point, a new sub-basin is assigned to the topologic tree at the outlet point and the sub-basin is assigned to all upstream arcs from the outlet point.

Assigning sub-basins to sub-basin boundary polygons

In the second step, all the boundary polygons in the drainage coverage are visited. For each boundary polygon, all the nodes surrounding the polygon are visited. These nodes are visited until a boundary node that is the most downstream outlet point in the polygon is found. Once a boundary node that is the most downstream outlet point in the polygon is found, the drainage unit assigned to the arc upstream from this outlet point is assigned to the polygon. If no arc is assigned to the arc upstream from this outlet point, a new sub-basin is created and linked into the hydrologic modeling tree.

If no outlet point in the polygon is found, a stream arc intersecting the sub-basin boundary at a node is found. The sub-basin assigned to this stream arc is assigned to the polygon.

Sometimes, the stream arc may not actually intersect the polygon boundary at a node. If this is the case, a stream arc inside the polygon is found. The outlet point for this arc is found. Then, the sub-basin assigned to the arc directly upstream from the outlet point is assigned to the polygon.

Advantages of the GIS-Tree Linkage

Using the algorithm described above, the GIS drainage coverage can be directly linked to a hydrologic modeling tree. If streams or outlet points are deleted or added to the GIS data, the hydrologic modeling tree can be automatically updated. Furthermore, hydrologic data such as sub-basin areas can be directly computed and assigned to the tree from the GIS data. These computed hydrologic parameters can then be used to run any lumped parameter watershed model (see). In this approach to watershed modeling, the GIS is used to process what it can. Then, a separate interface is created (like the WMS) that is customized to perform watershed modeling tasks.

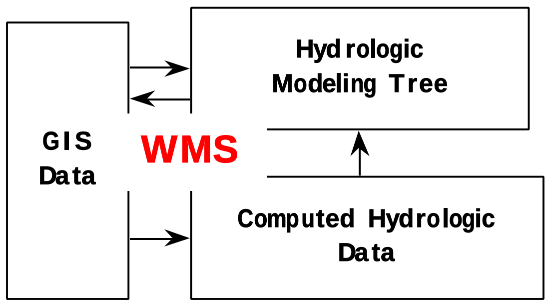

Figure 3: The GIS-Tree link in WMS

Let the GIS process what it can

A GIS is a perfect environment for storing and analyzing watershed data. In the approach to watershed modeling presented here, the GIS can be used to store and process whatever watershed data it can. Then the GIS data can be imported into the WMS.

Customize the interface to do specific tasks

Since the WMS is designed to perform watershed modeling, is easier to work with than a GIS, has a direct link between the GIS drainage coverage and the hydrologic modeling tree, and has interfaces to several different hydrologic models, it is ideally suited to perform watershed modeling.

Application: The Aspen Grover Watershed near Provo, Utah

This section is not yet done.

Conclusions

Previously, all attempts to linked lumped parameter hydrologic models with a GIS were constructed in the GIS itself. The problem with this approach is that a GIS is not very user-friendly and is difficult to customize for use in watershed modeling.

This study presented a new hydrologic modeling tool that combines several layers of GIS data and automatically generates the topologic attributes necessary for lumped parameter hydrologic modeling. Using this method, points, polylines (or arcs), and polygons can be combined and connected into a single layer and used to represent drainage features such as outlet points, streams, flow diversions, lakes, and drainage basin boundaries. If changes are made to the point, arc, or polygon data, the hydrologic modeling information is automatically updated reflect the changes. In addition, with this direct link between GIS and hydrologic models, physical parameters such as basin areas and stream lengths are easily computed and stored for hydrologic modeling.