AUTOMATED CATCHMENT PARAMETERISATION FOR RUNOFF ROUTING MODELS UTILISING 3D GIS CONTOUR INFORMATION

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Abstract This paper describes the development of a comprehensive subcatchment parameterisation tool and GIS interface for hydrologic modelling. The interface has been tailored to automate the currently predominantly manual process of setting up lumped hydrologic models for flood estimation on natural and urban catchments.

Key outcomes of the research are rapid, reproducible and accurate automated delineation of subcatchments, measurement of generalised topographic attributes and determination of lag parameters. The interface also provides numerous hydrologic and topographical assessment tools to allow users to quickly determine geophysical properties of the subcatchments.

Keywords GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Rainfall Runoff

Introduction

The escalating availability of GIS data-sets is having a significant effect on the development of hydrologic modelling techniques. These databases allow the application of geo-computational algorithms to determine topographic and hydrologic attributes of subcatchments at a scale not practicable by traditional methods. Furthermore, the abundance of extractable geo-statistics provided by these algorithms also reduces the guesswork involved in defining attributes that are not directly measurable from topographic data, such as lag parameters.

This paper describes a GIS based interface for lumped hydrologic models. In its current iteration, the model is tailored for full coupling with the Australian runoff routing model WBNM (Boyd et al. 1996). However, the procedures are compatible with a wide range of hydrologic, hydraulic and water balance models.

Potential Contribution of GIS to Hydrologic Modelling

Most lumped hydrologic models are currently set up using manual delineation of subcatchment boundaries and calculation of contributing areas. Generalised topographic attributes are usually determined by a ‘best guess’ approach or using a limited number of measurements, which are designed to be representative of the subcatchment.

GIS algorithms have the potential to dramatically increase the speed, accuracy and reproducibility of subcatchment parameterisation, with a corresponding reduction in user subjectivity. However, these GIS based approaches have not been widely adopted for use in hydrologic investigations. Three main reasons have been suggested for this trend:
(1) Lack of 3D GIS source data;
(2) Poor compatibility between GIS platforms and established hydrologic models; and,
(3) Fragile, non-flexible and oversimplified GIS algorithms.

This project aims to overcome the latter two of these issues by development of a robust and hydrologically sound set of algorithms that are fully integrated into a user-friendly GIS interface. The program allows full coupling and data exchange with lumped hydrologic models, presently WBNM. In the following sections, the methodologies behind some of the algorithms are described and compared to techniques in commonly available GIS packages. Hyperlinks to additional web-based information have been included where space restrictions have precluded full descriptions of program components.

Program Structure

The GIS interface can be categorised into four sequential program components, specifically:
(1) Development of a Digital Elevation Model (DEM) by importing and conversion of vector GIS data, followed by interpolation of unassigned pixels;
(2) Assessment and pre-processing of the DEM to ensure compatibility with hydrologic modelling;
(3) Flow routing mechanisms superimposed over the DEM; and,
(4) Geo-statistical analysis of the DEM in order to generalise subcatchment attributes and lag parameters for use with WBNM.

Development of Digital Elevation Model

The Digital Elevation Model forms the basis of the GIS interface. It is a raster (grid) structure of square or rectangular pixels, where each pixel can be identified by a row and column number.

The DEM is developed by raster conversion of vector contour and watercourse data, and interpolation of the remaining unassigned pixels. Algorithms are employed to ensure drainage is maintained along observed watercourses, and to aid representation of ridge lines and other topographic features, which the interpolation algorithms may find difficult to interpret directly from the source data.

The source GIS data required by the algorithms can be imported from a number of data storage formats compatible with many commercial GIS databases. Typical data requirements to allow development of a hydrologically sound terrain representation need only be 3D vector contour lines and 2D vector maps of known watercourses (the latter being optional). This data is imported into the application and stored in a compressed internal format for use in development of the raster DEM.

The vector source data is converted to a raster representation by selective elevation assignment of some of the pixels underlying a contour line, in accordance with accepted vector to raster conversion methodology (Van Der Knapp, 1992).

Incorporation of Watercourse Information

Imported vector watercourse data (optional) is interpreted by the program as pixel-paths where elevations should consistently and linearly decrease between intersected contour lines. By utilising a junction resolution and watercourse sequencing algorithm, the stream network
is interpolated into the DEM. Due priority is given to higher order watercourses, which form the local minima that will shape the interpolation of the remaining DEM.

The outcome of the algorithm is preservation of an observed stream network in the DEM. This can be seen by the calculated flow-paths shown in Figure 1. The green (dashed) lines in this image represent the calculated flow-paths originating from targeting the flow routing algorithm on 5 selected points in the DEM. It can seen that in the areas where known watercourses have been incorporated into the model (solid blue lines) the calculated flow-paths will follow observed watercourse in almost all cases. However, occasionally in areas of very low relief, flow-paths may deviate from observed watercourses. A stream burning algorithm (lowering all watercourse pixels by a set elevation) is available to force the drainage patterns in these areas.

Figure 1: Incorporation of Watercourse Data

Interpolation of Unassigned Pixels

Once all imported data is incorporated into the DEM, the program interpolates elevations for all unassigned pixels (ie., those not underlying a contour line or known watercourse). This is achieved by implementing a ray based interpolation algorithm. The interpolation is based on a distance weighted average of a series of linear interpolations along a set number of cross-sections taken through the pixel. For example, the interpolation regime shown in Figure 2 exhibits a 16 ray interpolation sequence. The 180 degree arc is divided into 8 increments and interpolation rays are initiated at the appropriate angles. All rays are paired with a mirror ray which travels in the opposite direction (ie., + 180 degrees).

Figure 2: Ray Based Interpolation Methodology

Once an interpolation ray and its corresponding mirror ray intersect a pixel with an assigned elevation, linear interpolation is applied to determine the approximated pixel elevation for that particular interpolation ray. The final value for the pixel is based on a weighted average of all the cross-section interpolations. The basis for weighting the derived
elevations \((16 \text{ in the current example})\) is the distance between the assigned pixels that form each end of the ray-mirror ray cross-sections.

In order to tailor the DEM interpolation to the user's computational resources and accuracy requirements, the program allows the user to set the number of rays to use in the interpolation. Furthermore, the user may implement interpolation aids that include additional spot heights, ‘heads-up’ digitising of artificial contours and placement of Interpolation Training Lines (ITL). DEMs may also be imported from other interpolation programs \((\text{such as Surfer 7})\) where more advanced interpolation algorithms such as Kriging and surface fitting techniques may be applied.

These procedure have not yet be written into the program since although these techniques have demonstrated some capability to produce good approximations of natural surfaces \((\text{Wise, 2000})\), DEMs produced by these methods can contain undesirable sinks due to local minima of the interpolation surface equations. Furthermore, they could be seen as 'overkill' due to likely accuracy limitations of the source data \((\text{contours})\) and the long computation times required for interpolation of large DEMs with some of these methods. For comparison, the ray based method adopted in this program can interpolate millions of pixels in under 5 minutes.

### Hydrologic Processing of DEM

In order for the Digital Elevation Model to be applied in a flood study it needs to be pre-processed to ensure its suitability for hydrologic modelling. In particular, flows from all pixels within the catchment must be able to be routed downslope until reaching the catchment outlet hence, any flat areas and localised depressions need to be resolved.

The most common flat areas result at hill-crests where the interpolation algorithm will flatten the hill at the final contour since the hill-crest is fully surrounded by a single contour loop \((\text{i.e., all interpolation rays will find the same contour value})\). To resolve these areas the flat and depression pixels are treated by an iterative pixel filling algorithm where depression pixels are raised to the elevation of their lowest neighbour, followed by raising of all flat pixels that have a non-flat neighbour, by a small set increment, until no flat or depression pixels remain. In this manner, flattened hill-crests will be treated from the outside-inward, developing a rounded crest that will realistically distribute pixel flow-paths down all sides of the hill.

### Rainfall Runoff Routing

Routing flow from each pixel downslope to the catchment outlet in a realistic manner is the most important function of the model. The downslope flow angle algorithm utilises an adapted form of the 'rolling ball' flow-path methodology first proposed by Lea \((1992)\) to determine a flow angle for each pixel \((0-360 \text{ degrees})\). Flow-paths are represented by lines and as such are only permitted to enter one of their four immediate neighbours. Diagonal pixels may be accessed by traversing through a side pixel. Consequently, the downslope flow angle algorithm bases its calculation on the four pixels which share a non-zero boundary length \((\text{ie., diagonals pixels are not included})\).

The flow direction angle for each pixel is determined from the resultant flow angle vector derived from the steepest descent non-diagonal neighbouring pixel and the steepest of its adjacent non-diagonal pixels \((\text{if any})\), as shown in Figure 3a. Pixel flow-paths are mapped downslope according to each pixel’s drainage angle until the catchment outlet is reached \((\text{refer Figure 3b})\). In this manner, the entry and exit points of flow through all downstream
pixels are modelled. For example, in the lower right pixel of Figure 3b it can be seen that flow-paths from upstream pixels are distributed between both of this pixel's downslope pixels, based on where the flow-paths entered the pixel. This allows for more accurate representation of flow distribution, and calculated drainage-path length / slope statistics.

Figure 3a & b: Flow Routing Algorithm

Flow routing algorithms that map downslope flow-paths are better able to represent flow distribution in raster grids than other single direction GIS flow-routing algorithms (Costa-Cabral and Burges 1994), the most common of these being the D8 method. The D8 method simply allocates flow from a pixel to one of its eight neighbours based on which pixel represents the steepest descent. It has been shown to produce poor results due to its approximation to a cardinal or diagonal direction (Fairfield and Leymarie 1991) and its failure to represent convergent flow. The discrepancy between the D8 method (dashed brown lines) and the described algorithm (solid green lines) is shown with respect to calculated flow-paths in Figure 4a and subcatchment delineation in Figure 4b. These figures illustrate the tendency of the D8 method to 'snap' to cardinal or diagonal angles and the potential for these errors to accumulate in a downslope direction.

Figures 4a & 6b: D8 Method vs Described Flow Routing Algorithm

Generation of Stream Network

During the flow-path mapping, a flow accumulation value for each pixel is assigned and indexed by 1 for each flow-path that passes through the pixel. After processing of the entire DEM, the flow accumulation matrix contains the number of upslope pixels that drain through each pixel in the DEM (i.e., contributing area for each pixel). To automatically generate a stream network, a pixel is defined as a watercourse pixel once its flow accumulation value is greater than a specified value (Stream Area Threshold). The embedded animation (AVI file) is an output tool of the GIS interface and illustrates the effect of reducing the stream area threshold towards 1 pixel (where all pixels will be defined as watercourse pixels), on the stream network image. This can be used as a qualitative tool to assess the differing fractal natures of subcatchments within a lumped hydrologic model.
Geo-Spatial Statistics and Definition of WBNM parameters

In addition to subcatchment topographic parameterisation, lumped hydrologic models such as WBNM require lag relations to be defined. The GIS interface can be used to establish these relations by performing geo-computational analyses on the DEM and flow-routing result database. Measures that can be quickly calculated to derive these relationships include:

- Extraction of subcatchment parameters such as average vectorised slope, impervious proportion, subcatchment area, drainage density, shape coefficient, mainstream slope/length and fractal statistics.
- Development of subcatchment distribution charts including average 'out of stream' flow length distribution and subcatchment drainage density vs stream area threshold.
- Horton characteristics (Horton 1945) such as drainage density (Horton), stream frequency, charting of bifurcation ratio vs stream order and best fit bifurcation ratio.

The GIS interface allows easy comparison of these geo-statistical measures and distribution charts across the subcatchment network, assisting in assigning lag parameters to the model. This is of particular importance for flood investigations where calibration using recorded rainfall and streamflow data is not possible.

Conclusions

The increasing availability of GIS data-sets gives the potential for automation of many of the tasks associated with preparing a lumped hydrologic model.

This paper has described a stand-alone GIS interface for subcatchment parameterisation that is presently fully coupled with the runoff routing model WBNM, yet could be utilised in other hydrology based applications. The algorithms in the interface have been described and comparisons have been made with some simpler but less effective GIS algorithms.

The GIS interface shows considerable potential to increase the accuracy of streamflow prediction by reducing the subjectivity involved in subcatchment parameterisation and lag relationships, particularly in catchments that lack historical hydrologic data.

The GIS interface is freely available with supporting documentation, sample data-sets and tutorials from the project web-site. The hydrologic modelling package WBNM is also available as a free download from its web-site.

References


