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On behalf of the Organising Committee, I am pleased to introduce you to the Proceedings of the 27th Hydrology and Water Resources Symposium, Melbourne 2002.

The Symposium's theme is "The Water Challenge - Balancing the Risks" - how do we achieve a sustainable balance between the hydrological risks associated with competing demands for water resources. The Symposium explores the issues in tackling this challenge through the four sub-themes of:

- *modelling the hydrologic cycle;*
- *sustainable resource management;*
- *protecting people, infrastructure and the environment; and*
- *the new tools.*

Topics covered include salinity management; water allocation; environmental flows; floods, droughts and other hydrological extremes; floodplain management; climate variability and change; remote sensing and other data collection technology; and GIS systems. Papers from invited high calibre keynote speakers cover key aspects of a number of these topics.

Over 120 papers are included in the Proceedings, and we trust that these will provide a lasting record of the Symposium's contribution to the science and practice of hydrology and water resources management and engineering.

All contributing authors should be commended for the technical excellence of their papers and for their willingness to share their knowledge and expertise with fellow professionals and practitioners.

David Sheehan
Organising Committee Chair
27th Hydrology and Water Resources Symposium

AUTOMATION OF WBNM HYDROLOGIC MODELING USING GIS AIDED TOPOGRAPHIC PARAMETERISATION

Chris Ryan [1], Michael Boyd [2]
[1] Hydrologic and Hydraulic Modeller, Patterson Britton & Partners, NSW, Australia
[2] Associate Professor, University of Wollongong, NSW, Australia

Abstract

This paper describes the development of a GIS interface which can be used to construct lumped hydrologic models for flood estimation on natural and urban catchments. The interface is currently being implemented with the runoff routing model WBNM, but is a general procedure and could be used with a range of flood hydrograph and daily flow models.

The GIS interface utilises digital contour and watercourse data to automatically delineate subcatchments, to measure generalised subcatchment attributes, and to allocate lag times to the subcatchments. The key algorithms in the GIS interface are compared with traditional manual map interpretation techniques, and to some currently available GIS procedures.

The GIS interface dramatically reduces the time required to delineate subcatchments and measure their topographic and hydrologic attributes. It also has significant potential to increase the reproducibility and accuracy of streamflow prediction, while reducing the inherent user subjectivity involved in more traditional methods.

Key Words: GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Runoff Routing

Introduction

Hydrologic modelling plays an important role in flood studies in Australia. Disciplines in which flood hydrographs are required range across a broad spectrum from land development applications, to environmental legislation, and floodplain management strategies.

The increasing availability of GIS data-sets is having a marked effect on the development of hydrologic modelling techniques. The information contained within these data-sets allows 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 lag parameters for hydrologic models.

This paper describes development of an automated GIS interface designed to generate topographic and hydrologic attributes for use with the lumped hydrologic model WBNM.

The following sections describe the structure of the GIS interface and the algorithms that have been developed to automate the process. Particular attention is given to those algorithms that incorporate the automated decision structures that allow aggregation of waterway and contour data to produce a comprehensive digital terrain representation.

Current Industry Techniques for Hydrologic Modelling

At the present time, most flood studies use lumped hydrologic models. By their nature, these models require subdivision of the catchment into a large number of subcatchments, which are assumed to consist of relatively homogeneous topographic and hydrologic attributes (Boyd et al, 1996).

These subcatchments are arranged in a flow matrix that represents the stream network on the real catchment. Lag relations are used to allocate lag times to each subcatchment, and to the stream segments connecting the subcatchments.

Rainfall, in the form of design storm temporal patterns or recorded historical storms, are applied to the model to generate flood hydrographs at the outlet of each subcatchment and at the main catchment outlet.

Catchment Delineation

Currently, delineation of catchment boundaries from topographic maps is done by hand in most cases. Catchments and subcatchments are delineated using contour lines to determine watershed boundaries. Division of the catchment into subcatchments is achieved by locating subcatchment outlets at the confluence of major tributaries with the main stream, or at their confluence with a higher order tributary. The procedure is time consuming and to some extent subjective.

Primary Subcatchment Attributes

Lumped hydrologic models require a range of topographic and hydrologic attributes to be defined for each subcatchment. Primary attributes are those able to measured directly from readily available GIS data. These attributes may be categorised into two groups, those that have a distinct single value for each subcatchment such as area and impervious fraction, and those attributes that can vary over the subcatchment such as roughness, slope, soil and vegetation. In contrast to the assumptions in lumped hydrologic modelling, the attributes in the latter group are unlikely to be entirely homogenous over a subcatchment. Hence, assignment of an attribute to a subcatchment involves development of an average or generalised value.

Generalised attributes are often determined by a 'best-guess' approach, or are based on a small number of measurements made at selected points within the subcatchment. These decisions are often subjective and may be difficult to reproduce with consistency. Accurate calculation of a subcatchment attribute involves processing a large amount of data. Such calculations are usually impractical by hand, but they lend themselves well to automation using GIS based algorithms.

Secondary Subcatchment Attributes

Secondary catchment attributes are those that have a functional relationship to one or more primary attributes. Rainfall-runoff models typically require several secondary attributes to be defined. Specifically, WBNM requires definition of rainfall loss rates and lag parameters.

Rainfall losses are related to soil, vegetation, land-use, antecedent moisture conditions, and may also be related to topographic attributes. Much of this information can be obtained as spatially distributed GIS data-sets.

Lumped hydrologic models also require specification of lag parameters for each subcatchment. These parameter values are used to determine a time lag for flood routing of the hydrograph to the downstream subcatchment. WBNM uses three types of lag parameters: for routing of overland flow in natural catchments; routing runoff from impervious surfaces in urban catchments; and routing of hydrographs in streams. Each of these parameters is dependent on the topographic attributes of the subcatchments.

The dominant influence on lag times is the size of the subcatchment and, for urban catchments, the impervious fraction. Second order influences may include stream slopes, surface roughness and drainage density. GIS algorithms have the potential for rapid measurement of these attributes, allowing the investigation of relationship between them and subcatchment lag times.

Potential Contribution of GIS Integration

While subcatchment delineation, measurement of topographic and hydrologic attributes, and determination of model lag parameters is usually done by hand, all of these tasks are governed by logical rules which have the potential to be translated to computer code. GIS applications have shown some promise in their ability to reproduce catchment delineation and parameterisation techniques. However, in practice we are yet to see a large scale shift from hand calculations to GIS based techniques.

Automation of the tasks associated with setting up a hydrologic model, such as WBNM, produces considerable benefits. Significant time saving is possible and the methods present potential for a tangible increase in the accuracy and reproducibility of results, with a corresponding reduction in user subjectivity.

The GIS interface and the algorithms it employs to substitute these manual techniques are described in the following sections.

Structure of the GIS Interface

The GIS interface can be categorised into four sequential program components. These are:

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 preprocessing of the DEM to make it compatible with hydrologic modelling;

3. Flow routing mechanisms superimposed over the DEM; and,

4. Geo-spatial 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 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 GIS model may find difficult to interpolate directly from the source data.

Source Data

The base GIS data required by the algorithms can be imported from a number of data storage formats compatible with many commercial GIS platforms. Typical data requirements to allow development of a good terrain representation include 3D contour lines and 2D vector maps of known watercourses.

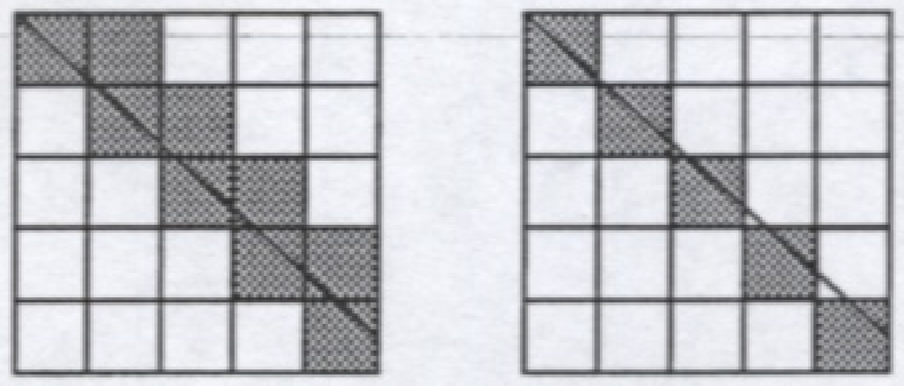
This data is imported into the application and stored in a compressed internal format for use in development of the raster DEM.

Vector to Raster Conversion

The first stage in the process of forming the DEM is to incorporate the vector contour data and assign the contour elevation value to all pixels underlying the contour line. All pixels underlying the line are assigned this elevation, with the exception of pixels that do not meet the following rule:

If a vector line being converted to a raster representation passes from the last assigned pixel and traverses two of the neighboring 8 pixels then only the pixel containing the longer line segment will be assigned.

This rule is generally recognised to be appropriate for a vector to raster conversions (Van Der Knapp, 1992) to avoid a zero-width line being converted into a two pixel width raster representation as shown in **Figure 1**.



1a) Assigning All Pixels   1b) Applying Rule

Figure 1: Vector to Raster Conversion

Incorporation of Watercourse Information

If known watercourse information has been imported then this data is also incorporated into the DEM. The algorithm interprets known watercourse flow-paths as lines where elevations should consistently and linearly decrease (*in a downstream direction*) between intersected contour lines. The flow-path elevation interpolation algorithm processes watercourse data in accordance with the following rules:

1. The main stream is selected as the known watercourse flow-path beginning at the highest elevation. Elevations of pixels underlying this flow-path are linearly interpolated between intersected contour lines until a DEM boundary is reached.

2. Each of the remaining watercourses are processed sequentially from those starting from the highest elevation to those starting from the lowest elevation. Pixel elevations along each tributary are interpolated linearly until a junction with a previously interpolated flow path is reached.

This algorithm has the capacity to resolve an unlimited number of intersections of three vector watercourse junctions (*a lateral inflow and main-stream line segments above and below its intersection*) and decision structures have been implemented in order for the algorithm to decide which segment to process next in order to continue interpolating in a downstream direction.

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 2.** The green lines (*dashed*) 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 closely follow the same path in almost all cases.

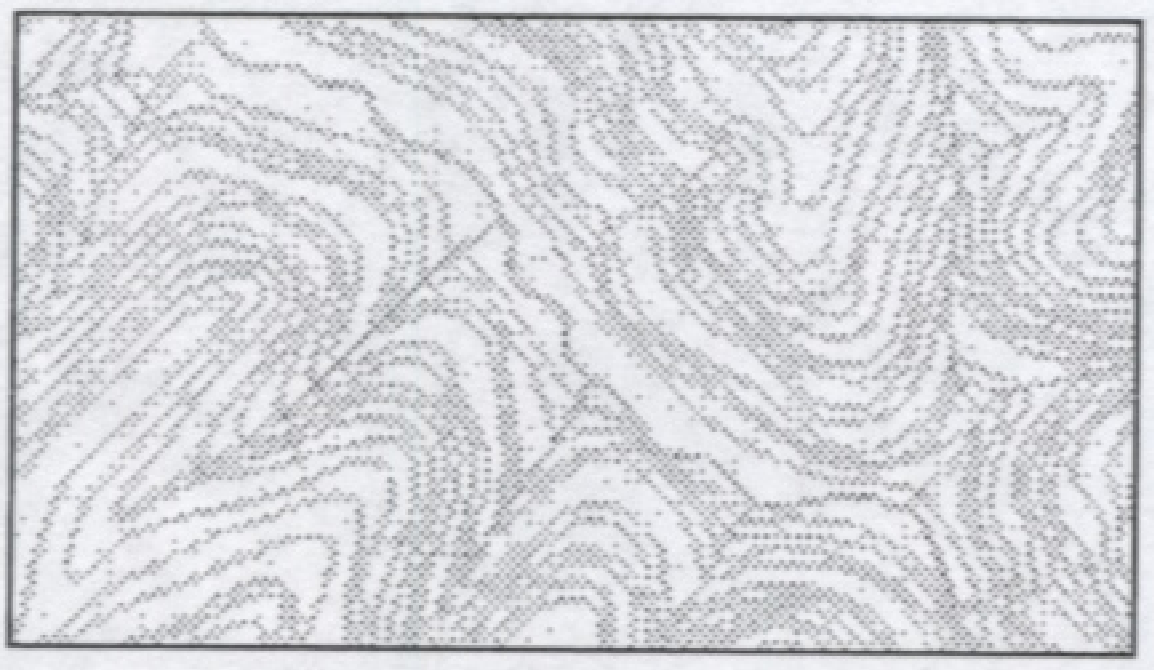


Figure 2: Incorporation of Watercourse Data

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 pixel interpolation algorithm. The level of definition of the interpolation engine is defined by the user, based on the required accuracy and available computational resources.

The methodology behind the interpolation algorithm 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 3** 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*).

Once an interpolation ray and its corresponding mirror ray each intersect a pixel with an assigned elevation, linear interpolation is applied to determine the approximated pixel elevation for that particular interpolation and mirror ray combination. 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 in the current example*) is the distance between the assigned pixels that form each end of the linear cross-sections.

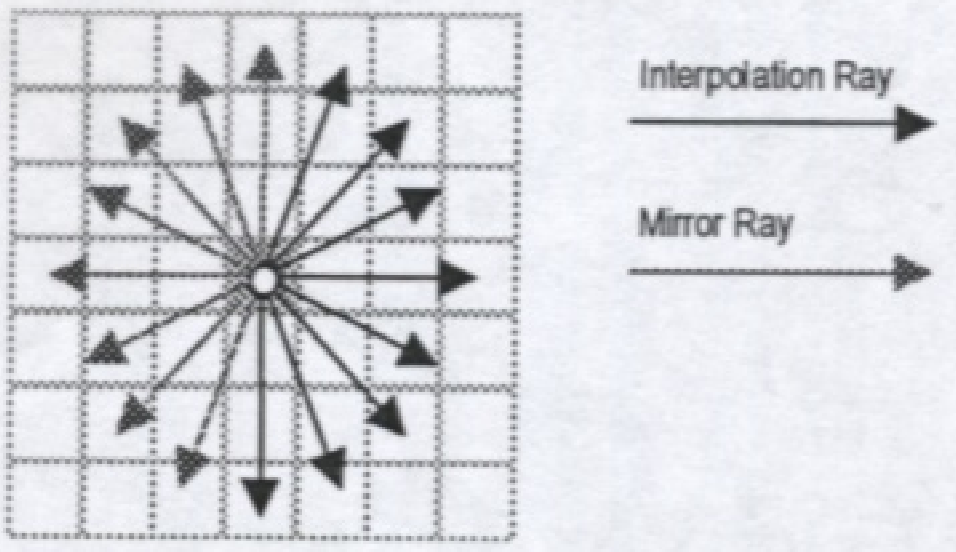


Figure 3: Ray Based Interpolation Methodology

The program allows the user to designate the number of interpolation rays (*and mirror rays*) that are used to interpolate the pixel elevation. This study has found that increasing the definition of the algorithm largely improves the DEM interpolation result with a relatively small cost in computational time.

This technique does have shortcomings, namely, it can have difficulty representing hill peaks and ridge lines unless additional data are incorporated. This may be seen in **Figure 4** which depicts a cross-section generated from a DEM interpolated using the ray based algorithm. The cross section alignment is shown in red and the flattened crest may be seen in the highlighted section of the corresponding cross-sectional plot.

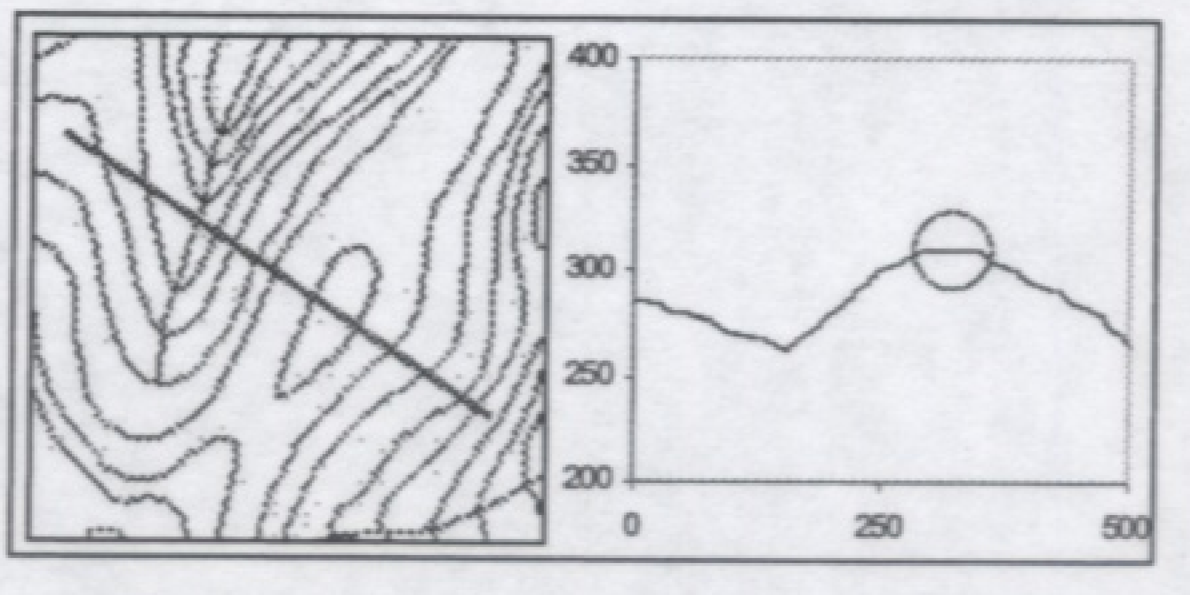


Figure 4: Anomalies in DEM Interpolation

The program allows for the implementation of additional spot heights, 'heads-up' digitising of artificial contours and placement of Interpolation Training Lines (ITL) to overcome these problems and generally improve the resulting DEM.

There is potential to incorporate other algorithms utilising more advanced mathematics to improve the DEM interpolation. Kriging and surface fitting techniques have demonstrated some capability to produce good approximations of natural surfaces (Wise, 2000). However, since these methods are not constrained by the closest contours, they are often prone to creating artificial holes and peaks which have a detrimental effect on rainfall-runoff simulation.

Furthermore, these methods can require unfeasible computation times for the interpolation algorithms whereas the ray based method adopted in this study can be applied to a DEM containing millions of pixels in a matter of minutes.

Hydrologic Preprocessing 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, flat areas and localised depressions must be treated to ensure flow from each pixel can be routed downslope until ultimately leaving the DEM boundaries.

The program currently treats flat and depression phenomena by raising pixel elevations until they are greater than their lowest neighbour. This technique would seem to be appropriate in most cases where flat areas or single pixel depressions are likely to be due to inaccuracy in DEM interpolation or lack of definition in the source data. However, scope exists for the introduction of breaching algorithms for treatment of more complex drainage anomalies.

Rainfall Runoff Routing

The flow routing algorithm embedded in the program involves a single direction 360 degree flow direction formula based on the steepest flow direction vector. Flow is considered to originate at the center of a pixel and flow downslope according to each pixel's drainage angle until the catchment outlet is reached. In this manner, the entry and exit points of flow through all downstream pixel are modelled, and an accurate representation of distance to outlet, overland drainage path length and average flow-path slope can be ascertained.

As flow is represented by a line, it is only permitted to enter one of its four immediate neighbours. Diagonal pixels may be accessed by traversing through a side pixel. Consequently, the algorithm bases its calculation on the four pixels which share a non-zero boundary length (*ie., diagonal pixels are not included*).

The flow direction angle is calculated according to the following rules and as shown in **Figure 5:**

1. The neighbouring pixel with the steepest downward slope is identified out of the four adjacent pixels. The magnitude and direction of this slope is assigned as the primary slope vector.

2. The neighbouring pixel on either side of the steepest downward slope pixel (*diagonal pixels are not included*) are tested to ascertain whether they are also downhill. If one or both of these pixels are downhill then the steepest of these is assigned as the secondary slope vector and the resultant flow angle is calculated by the hypotenuse of the primary and secondary slope vectors. Alternately, if neither of these are downhill then the flow vector is assigned immediately into the steepest slope pixel (*ie., 0, 90, 180 or 270 degrees*).

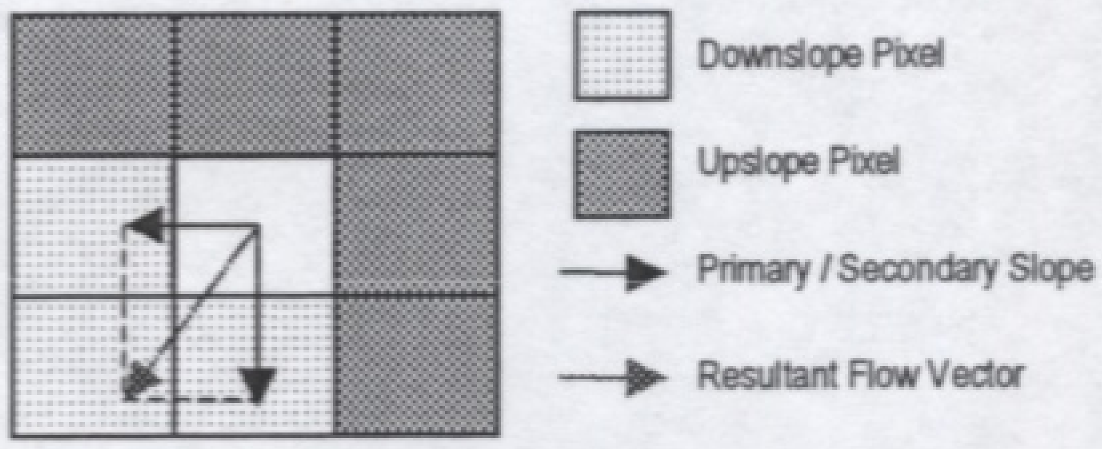


Figure 5: Flow Routing Algorithm

The capability of the flow direction angle to assume any value from 0-360 degrees as allowed in this study is a distinct advantage over the flow routing algorithms used by many GIS applications. Often these programs simply allocate flow from a pixel to one of its eight neighbours by calculation of the steepest descent path. This method, known as the D8 method, has been shown to produce poor results due to its approximation to the nearest 45 degrees (*in a square grid*) and its failure to represent convergent flow (Turcotte et al, 2001). Errors generated by the D8 method also have a tendency to propagate and increase down a hillslope. To illustrate this, downslope flow paths generated for 6 selected DEM pixels by the algorithm used in this study, and by the traditional D8 method are contrasted in **Figure 6**.

The D8 generated flow-paths are shown in brown (*dashed line*) while the results produced by the algorithm in this study are shown in green (*solid line*). It can be seen that the algorithm employed in the program produces flow-paths that are more natural and are better able to intersect contour lines (*source data*) at right angles. Moreover, the propagation of errors using the D8 method is clearly shown in the highlighted area.

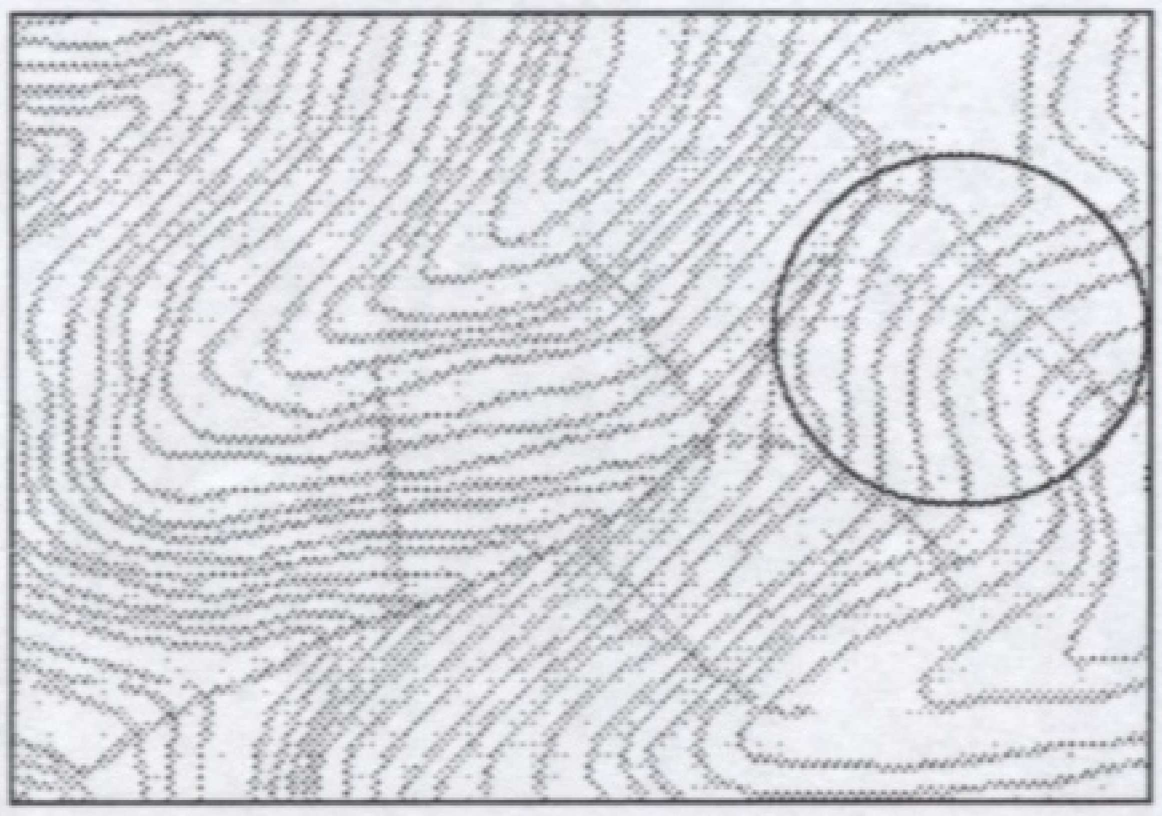


Figure 6: D8 Method vs Flow Routing Algorithm

There is still room to improve the flow direction algorithm and remove its dependency on the simplifying (*and incorrect*) assumption that flow originates from one point in each pixel and flows in a single direction (Costa-Cabral & Burges, 1994). Algorithms that can overcome these difficulties are classed as multiple direction algorithms and distribute a proportion of flow from each pixel to two or more of the neighboring downslope pixels. These algorithms are better able to represent divergent flow however, their computational efficiency and robustness are yet to be adequately demonstrated.

Generation of Stream Network

Once the flow direction angles for each pixel have been formulated it is possible to develop a stream network from the DEM. The network information is stored in a flow accumulation matrix. Each pixel is routed downslope until it exits the DEM, and the flow accumulation matrix value is indexed for each pixel that the flow-path travels through. After completion of this flow routing, the flow accumulation matrix contains the number of upslope pixels that drain through each pixel in the DEM. This enables automated delineation of the contributing subcatchment for any pixel within the DEM.

Streams are designated by a threshold area value. That is, once a pixel drains more than a specified area (*number of pixels * pixel area*) it is designated a stream pixel. The embedded animation (*refer link below*) illustrates the effect on the stream network of reducing the threshold area towards 1 – for which case all pixels will be stream pixels.

Stream Network Animation

Geo-Spatial Statistics and Definition of WBNM parameters

An important aspect in the application of lumped hydrologic models is the assignment of lag times to the subcatchments. Lag times are related to the subcatchment topographic attributes and are determined in the models from equations derived from observed hydrographs and measured subcatchment attributes. Thus both the development of lag relations using observed hydrographs, and the application of these relations to allocate lag times within the model, require extensive measurement and geo-statistical analysis of the subcatchment attributes. GIS interfaces are eminently suitable for this analysis.

Although this component of the program is yet to be finalised, it is envisaged that a relationship could be derived between the WBNM lag parameter and certain geo-statistical parameters that can be extracted using the GIS interface after analysis of all pixels within a particular subcatchment. Data analysis studies will need to be conducted to determine these relationships, however some topographic measures that have been suggested to play a role the hydrologic response of a subcatchment include:

- Average distance to subcatchment outlet for each pixel;
- Average overland flow distance for each pixel;
- Average in-stream distance for each pixel;
- Average slope;
- Drainage density and,
- Stream bifurcation ratio.

Conclusions

Simulation of rainfall runoff phenomena by lumped hydrologic models is an important component of quantitative streamflow analysis in Australia. The increasing availability of GIS datasets gives the potential for automation of many of the tasks associated with preparing a lumped hydrologic model.

This paper has presented the beginnings of a freely available stand-alone GIS interface for the lumped hydrologic model WBNM. The algorithms used in the interface have been described. 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 assigning catchment parameters and subcatchment lag relationships, particularly in catchments that lack historical hydrologic data.

Future Research

This research project was initiated in March 2001 and software development has only been underway for a few months, consequently, the WBNM GIS interface is still in the development phase. However, It is anticipated that by the time of the conference, the final program components will be completed and ready for application in flooding investigations.

Development of the application will continue and the focus will remain on building a robust industry tool rather than a purely research orientated application. The goals will remain: automation, reproducibility and accuracy enhancement of currently accepted techniques for rainfall-runoff analysis.

Software Availability

A free to download version of the current program with a short tutorial is available on the project website. Future versions of the software and relevant documentation will be added as soon as possible. Users can also register for a mailing list that is also available should you wish to be notified of updates.

The hydrologic modelling package WBNM is also available as a free download from its web-site.

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