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CATCHMENTSIM: A NEW GIS TOOL FOR TOPOGRAPHIC GEO-COMPUTATION AND HYDROLOGIC MODELLING

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Abstract: This paper outlines the capabilities of, and describes the algorithms employed within a freely available GIS software package specifically tailored toward hydrologic applications. The algorithms employed within CatchmentSIM are designed to overcome many of the problems associated with the simplified hydrologic algorithms adopted by conventional GIS packages. CatchmentSIM is based on a raster Digital Elevation Model (DEM) which may be interpolated internally from vector contour and stream alignment data, or imported from external applications. A Priority First Search (PFS) breaching algorithm is utilised to remove flats and pits throughout the entire DEM, which avoids the parallel stream problems that plague flat and pit removal in more common techniques. Following this, subcatchments and watercourses may be accurately delineated using a vector flow routing algorithm that has been shown to be superior to the D8 method employed by most conventional GIS applications. The CatchmentSIM software also includes a range of tools that enable topographic analysis on a scale not practicable by hand and conventional map interpretation techniques. In particular, Strahler / Horton geomorphologic analysis has been incorporated, allowing subcatchment bifurcation and drainage density relationships to be accurately determined. These techniques have been demonstrated to be more resistant to grid scale and rotation effects than comparable raster approaches in conventional GIS software packages. Following analysis of a catchment with the software, an internal macro language may be applied to export project parameters to any existing hydrologic modelling software (of a known data format) a user may wish to apply. The adopted algorithms within CatchmentSIM, enable users to build on the increasingly comprehensive information available in today's GIS, while avoiding the traditional pitfalls of conventional raster GIS techniques and maintaining tight coupling with existing 'industry standard' modelling approaches.

Keywords: CatchmentSIM, GIS, Hydrologic Modelling, Digital Elevation Model, DEM, Runoff

1. INTRODUCTION

Hydrologic modelling has an important role in flood and drainage investigations throughout the world. These models are becoming more complex and spatially variable due to their interaction with Geographic Information System (GIS).

The growing availability of large GIS data-sets and relatively powerful low-cost computing systems is allowing the development of detailed topographic analysis software that can determine topographic and hydrologic attributes of subcatchments at a scale not practicable by manual map interpretation methods.

However, It has been observed that the influence of the increasing availability of GIS terrain data sets can be slow to propagate through towards a greater conceptual or quantitative understanding of flood behaviour. The main reasons for this are thought to be:

- Poor compatibility between commercial GIS software and 'industry standard' hydrologic flood modelling computer modelling packages;
- Oversimplified and error-prone geo-spatial algorithms within conventional GIS software for calculation of terrain attributes;
- Disparity between the largely internationally standard GIS techniques, and the highly country-specific approaches to computer flood modelling; and,
- The expense associated with many conventional GIS packages / add-on modules.

Efforts to overcome these fundamental problems have resulted in the development of a standalone GIS software package specifically tailored towards hydrologic modelling, called CatchmentSIM. This free software incorporates algorithms that are more hydrologically realistic than approaches adopted by common commercial GIS packages and provides tight coupling with a range of common hydrologic modelling software packages. Thus the project allows seamless integration of the latest GIS data-sets all the way through to distributed hydrologic modelling with currently available and *'accepted'* modelling techniques.

The following sections describe the algorithms that have been developed within CatchmentSIM to provide the software's functionality and accuracy improvements over traditional commercial GIS based techniques.

2. OVERVIEW OF THE SOFTWARE

CatchmentSIM provides a user-friendly windows interface that provides access to a comprehensive range of algorithms specifically tailored towards GIS aided hydrologic investigation. Raw GIS data can be imported in most common formats and is stored in a compressed internal format. A raster Digital Elevation Model (DEM) can then be interpolated from this data or imported from an external application. Hydrologic pre-processing is applied to remove flat or pits and allow flow routing to be undertaken throughout the catchment.

The main catchment boundary may then be delineated by identification of the catchment outlet. Subcatchments may be delineated by manual designation of their respective outlets or automated break-up of the catchment into subcatchment using one of two internal algorithms. The nodal subcatchment network arrangement, hydrologic stream networks and topographic parameters are automatically calculated. CatchmentSIM also incorporates algorithms to accommodate modelling of urban structures and maintains a database of impervious areas that can be developed internally or imported from external applications. Furthermore, channels, gutters and pipes can be simulated as additional hydraulic controls that over-ride natural flow routing on the DEM. Finally, once sufficient analysis has been undertaken and subcatchment delineation and parameterisation is complete, a macro language provides tight coupling with a range of 3rd party hydrologic models and will automatically develop run-files for a chosen model (*such as WBNM, RAFTS, RORB, URBS or DRAINS in Australia*).

A more detailed description and analysis of the aforementioned algorithms is provided in the following sections.

3. INTERPOLATION OF DIGITAL ELEVATION MODEL (DEM)

As outlined previously, if an existing DEM is not available for a particular catchment, a user may wish to utilise CatchmentSIM's algorithms for interpolation of the DEM from contour and watercourse alignment data. In many cases, the interpolation of DEMs from contours and watercourse data may be preferred for hydrologic applications over other types of DEMs due to several reasons. Firstly, they can be interpolated at any scale appropriate for the catchment under analysis. Secondly, digital contour and watercourse data are widely available in many countries. Finally, contours have often been manually adjusted to better reflect the hydrologic characteristics of the natural surface and hence, are often said to contain more information than simply a string of points of common elevation (Wise, 2000). The interpolation and drainage enforcement algorithms are designed to take advantage of this extra information.

Internally interpolated DEMs are 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.

3.1 Rasterisation of Contour Data

Imported 3D contour data is incorporated into the model by applying the contour elevation to pixels that underlie the contour alignment in accordance with accepted vector to raster conversion methodology outlined by Van Der Knapp in 1992.

3.2 Incorporation of Watercourse Information

If watercourse alignment data is available then this information 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 network of connected watercourse segments is analysed to determine entire streams that are mapped from their uppermost tributaries to their outlet points. Elevations are then applied to pixels underlying these watercourse segments by linear interpolation between intersected contour lines.

The outcome of the drainage enforcement 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 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.

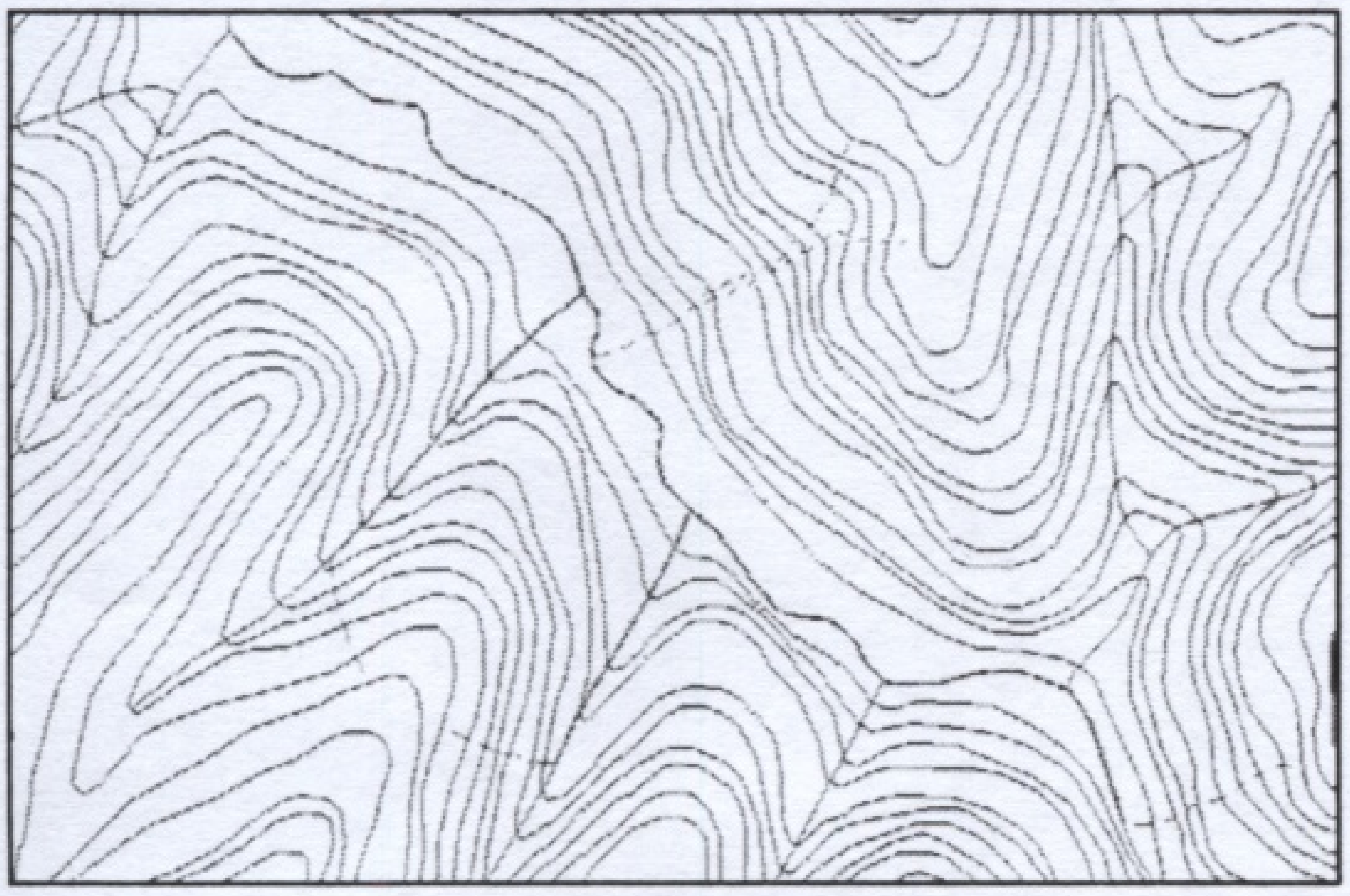

Figure 1: Incorporation of Watercourse Data

3.3 Interpolation of Unassigned Pixels

Following rasterisation of contour data and applications of the drainage enforcement algorithm, CatchmentSIM interpolates elevations for all unassigned DEM pixels. This is achieved by implementing a ray based 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 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.

Some interpolation anomalies may occur in regions of low contour definition. However, internal algorithms 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.

4. HYDROLOGIC PRE-PROCESSING OF DEM

In order for flow routing to be able to be applied to the DEM 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.

Two algorithms are provided for treatment of flat and pit pixels within the DEM. A filling algorithm can be utilised which simply raises pit pixels to the elevation of their nearest neighbour, and then fills all flat pixels by a set increment to allow flow processing. This algorithm is good at treating isolated flat and pit pixels and treating some types of interpolation anomalies that can result from the aforementioned interpolation method (*such as flattened hill crests*). However, a more advanced flat and pit pixel removal method has been incorporated to treat more stubborn arrangements of flat and pit pixels.

4.1 Priority First Search (PFS) Pit Removal

The Priority First Search (PFS) algorithm is an advanced breaching algorithm that can find an outlet for any flat or pit pixel within the DEM provided a pixel with a lower elevation exists at some point within the DEM. The PFS algorithm locates an outlet pixel for each flat or pit pixel and a corresponding drainage path of least resistance between the two points. PFS algorithms are based on well documented weighted-graph theory (Sedgewick, 1988) and determine the optimum drainage path based on a priority function. The CatchmentSIM PFS algorithm has a priority function that forces an optimum drainage path for a flat or pit pixel to go through the path of lowest elevation available. If more than one potential path satisfy this criteria then the path with the largest elevation drop between the original flat or pit pixel and the identified outlet pixel is selected. If these criteria are also equal then the path with the shortest flow distance is selected. Once an optimal drainage path from a flat or pit pixel to its outlet has been found then pixel elevations along that path are lowered by linear interpolation to accommodate the drainage path.

The PFS based approach has been shown to have a number of advantages over more common drainage enforcement algorithms (Jones, 2002). The most common of these is the Jenson and Domingue algorithms (J&D

algorithms) introduced in 1989. This algorithm has been adopted in the popular ArcInfo Grid system. The J&D algorithm first fills pits to the elevation of their lowest neighbour and then assigns flow directions at flat pixels towards any neighbouring pixel that has an assigned flow direction (*that is, a non-flat pixel or a previously J&D processed flat pixel*). The major problem with this approach is that it produces areas of parallel flow paths in areas of large flat areas. The PFS approach avoids this problem as once flow paths have defined and pixel elevations along this path have been lowered, then PFS calculated optimal paths from neighbouring pixels will be attracted to this new channel, and the resulting drainage network in large flat areas will be of a fractal nature which is more representative of natural channel systems.

5. FLOW ROUTING

The flow routing algorithm adopted by CatchmentSIM determines a flow direction for each DEM pixel based on the steepest flow direction vector. Flow is considered to originate at the centre of each pixel and flow downslope according to each pixel's drainage angle until the catchment outlet is reached. In this manner, flow is modelled as a vector quantity and the entry and exit points of the flow vector 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.

The flow direction angle for each DEM pixel is based on construction of a steepest descent flow vector composed from the two lowest elevation adjacent non-diagonal neighbouring pixels as illustrated in Figure 2.

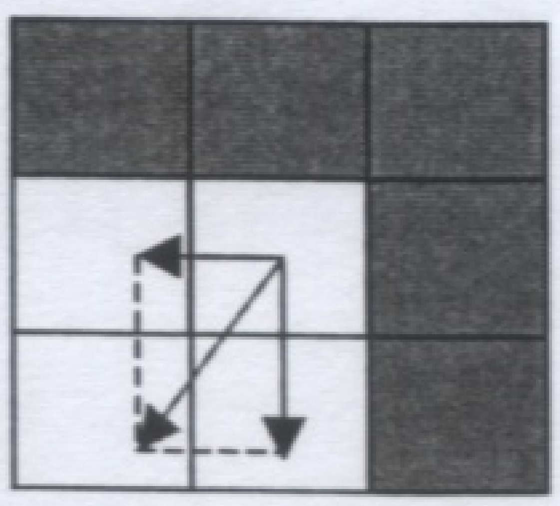

Figure 2: Flow Routing Algorithm

The capability of the flow direction angles in CatchmentSIM to assume any value from 0-360 degrees 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 approximation to 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 3.

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.

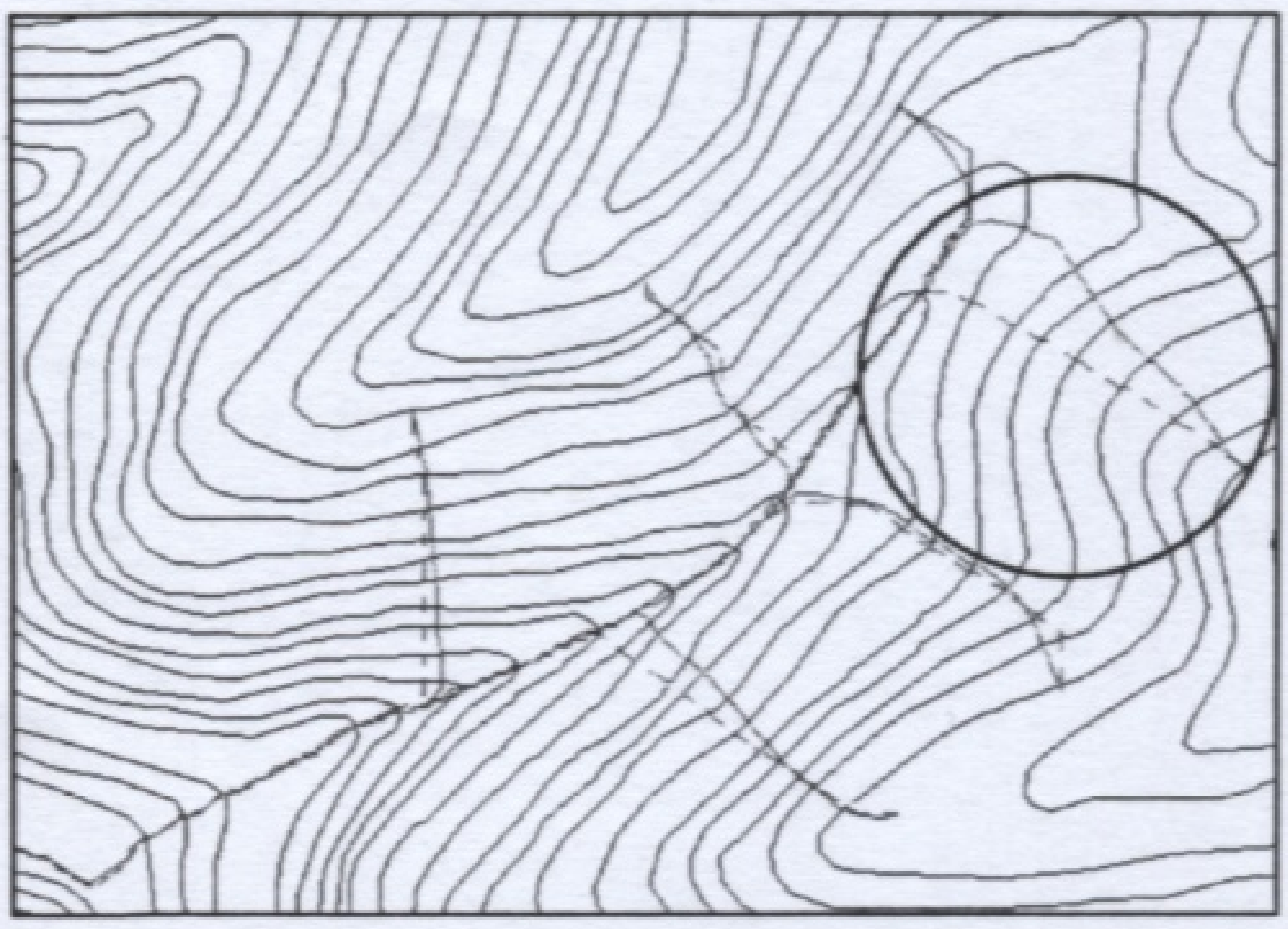

Figure 3: Comparison of D8 Method and CatchmentSIM Flow Routing

5.1 Flow Routing In Urban Areas

Urban structures have a strong influence on flow paths in urban environments but are rarely represented in DEMs or contour and watercourse data. Consequently, these structures need to be either hard-coded into the DEM or simulated as over-riding flow controls. CatchmentSIM provides tools for both of these approaches.

An example of hard-coding urban structures into a DEM is artificially raising DEM elevations along GIS layers that represent road crown alignments. Following this, the PFS algorithm can be employed to remove any resultant flat or pit pixels. This will cause the imported urban structures to be breached at their low points which results in a hydrologically realistic combination of a natural surface DEM and representation of road alignments. The resulting stream network generated by such a technique is shown in Figure 4, where the black straight lines are road crown alignments and their effect on the generated stream network is clearly illustrated.

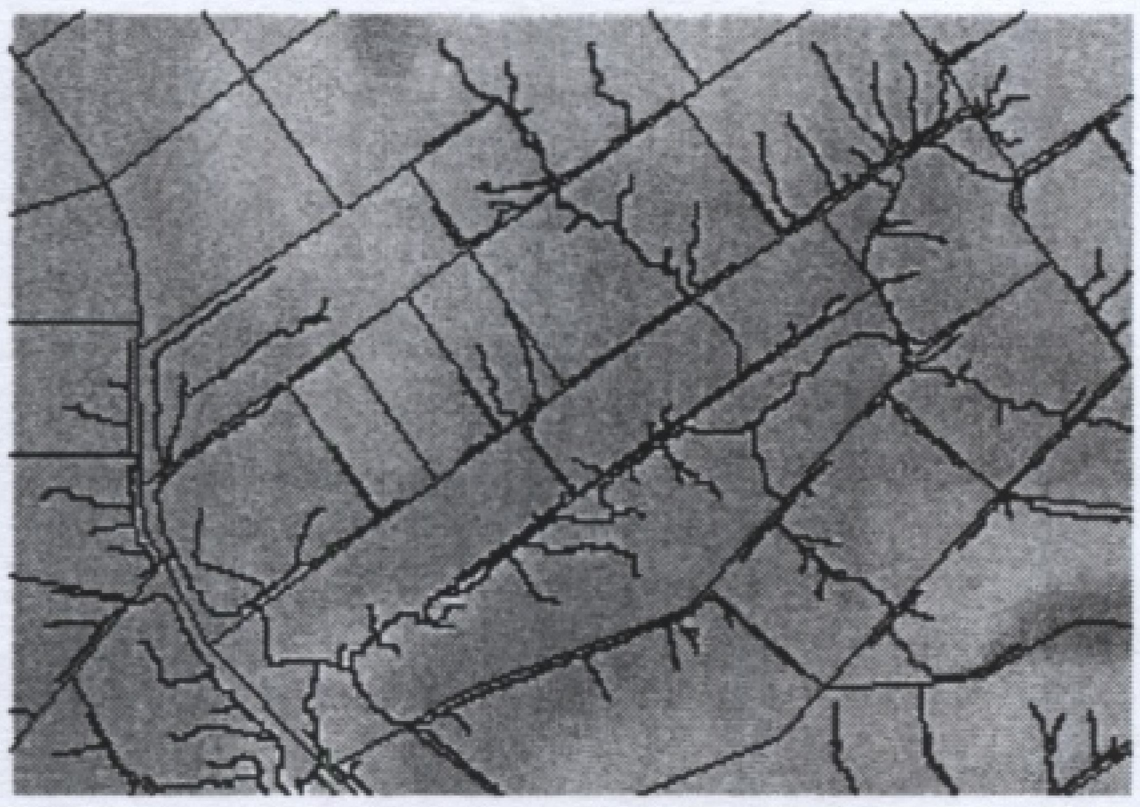

Figure 4: Effect of Roads on Stream Network

However, it is often preferable to simulate urban structures as supplementary flow controls that can be switched on or off for analysis of hydrologic events of different magnitudes, without effecting the underlying DEM. CatchmentSIM allows gutter, channels, and pipe and pit networks to be imported as hydraulic control layers. An example of a gutter hydraulic structure is shown in Figure 5.

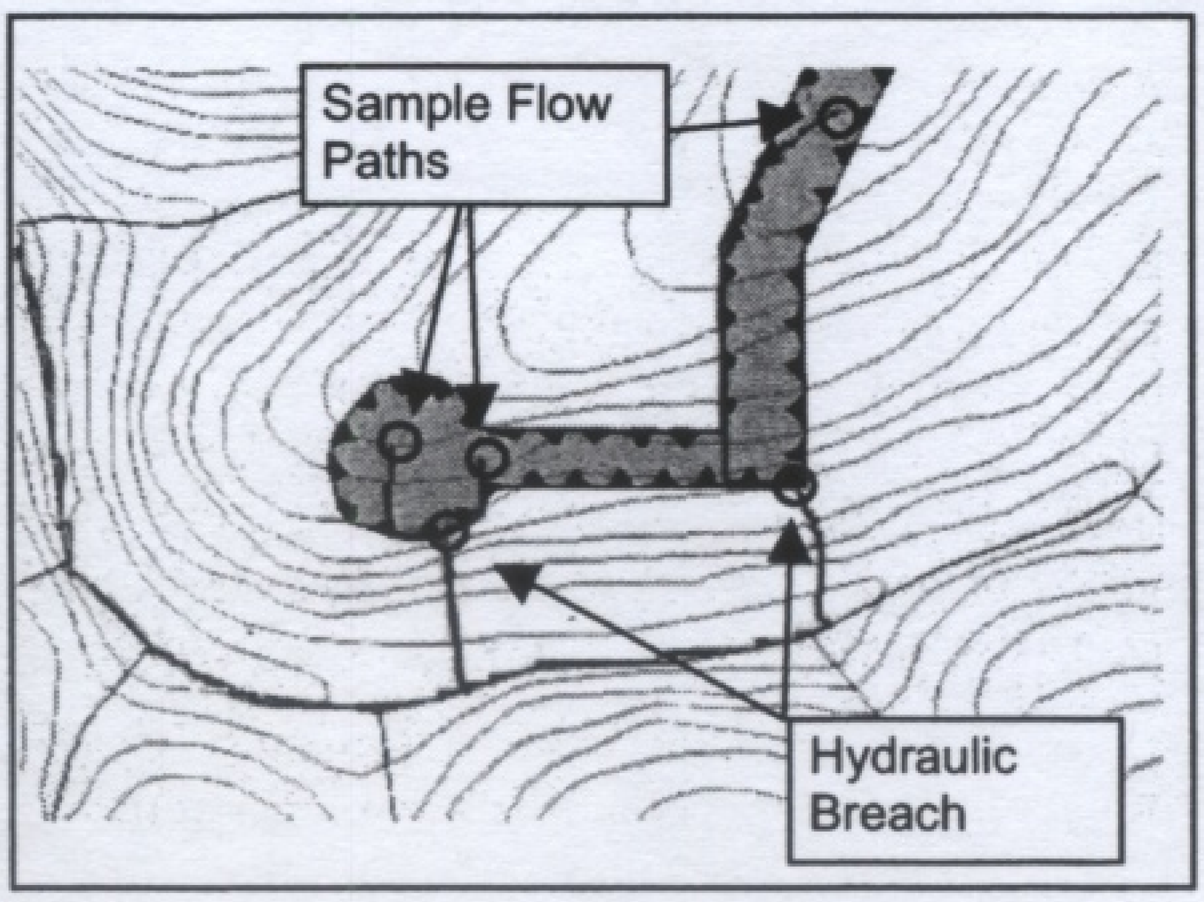

Figure 5: Effect of Gutters on Flow Paths

Calculated flow paths will follow the DEM until they intersect with a hydraulic control. In the above example of a gutter three sample flow paths have been generated. Flow will follow the gutter in whichever direction represents the steepest downslope direction. If there is no available downslope direction that follows the gutter then the algorithm will search within a distance or elevation tolerance for a pixel along the gutter with a lower elevation. This phenomenon accounts for ponding behind a gutter which effectively fills a pixel elevation and may provide a potential downslope flow path. However, if a downslope pixel along the gutter is not found within the specified tolerance then the algorithm allows for the hydraulic structure to be breached as indicated in Figure 5.

5.2 Impervious Areas Database

Many hydrologic and hydraulic models require accurate representation of impervious area proportions for each subcatchment. CatchmentSIM accommodates this requirement by maintaining a GIS database of impervious areas and allowing simple manipulation of these parameters as shown in Figure 6.

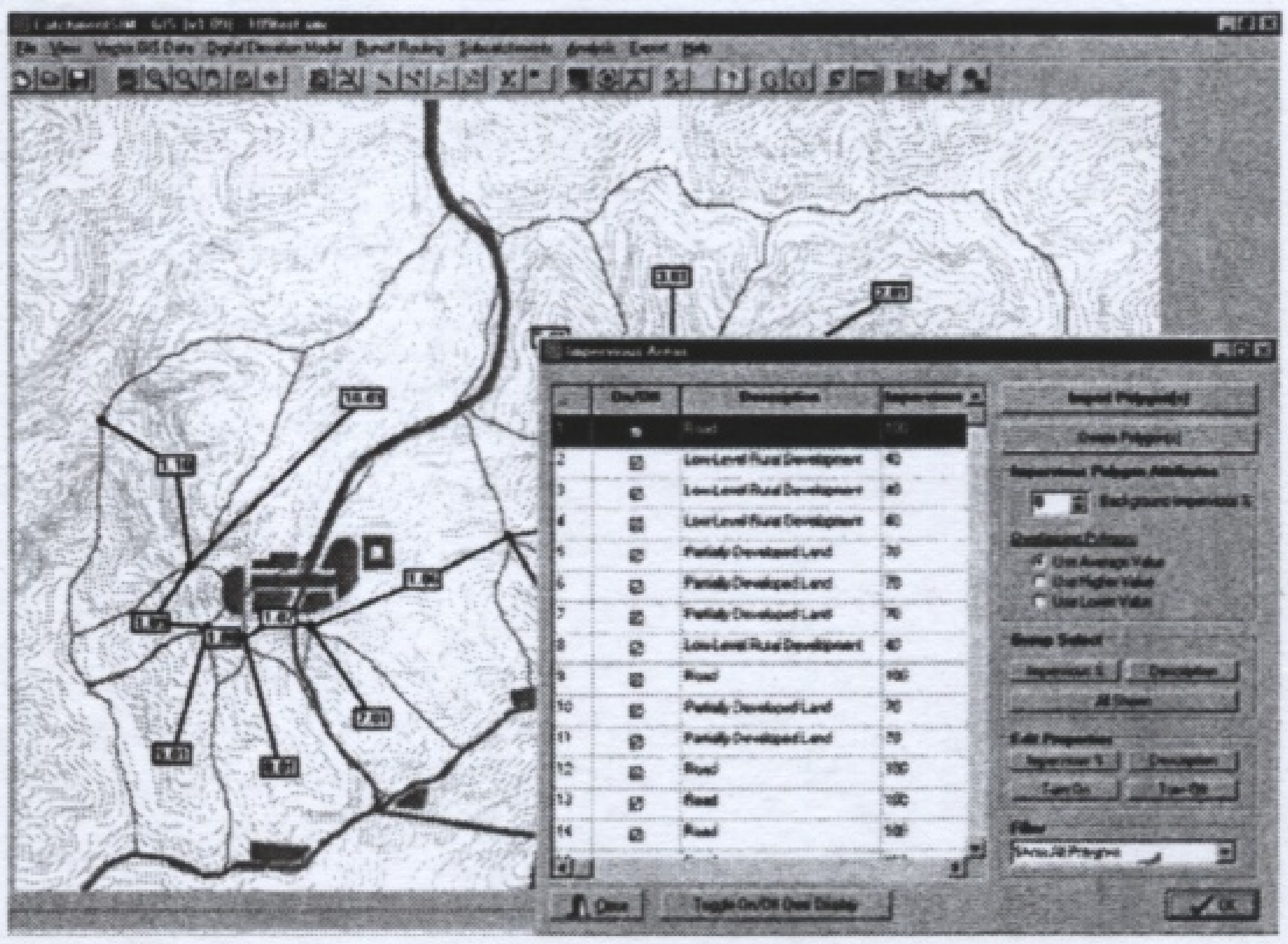

Figure 6: Impervious Areas Database

The algorithm applied to rasterise impervious polygons is able to handle complex polygons such as concave and convex polygons as well as multi-region or island polygons (*as shown in Figure 7*). DEM Pixels are determined to be within or outside of individual impervious polygons by defining a one-direction horizontal line originating from the pixel centroid and calculating the number of intersections with the polygon boundaries. Pixels with an odd number of intersections are determined to be within the polygon whereas an even number of intersections indicates a pixel outside of the polygon boundary or within an island region.

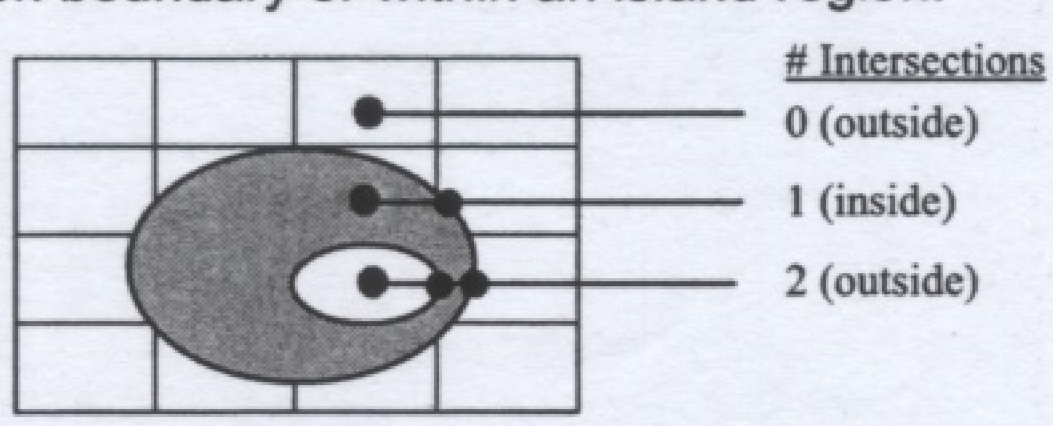

Figure 7: Algorithm for Rasterisation of Impervious Area Polygons

5.3 Generation of Stream Network

Generation of stream networks is an important component of flow routing and hydrologic analysis. CatchmentSIM allows development of both raster and vector stream networks. Following calculation of the flow direction angles for each pixel, it is possible to develop a stream network from the DEM. 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.

The raster stream network is simply defined by pixels whose flow accumulation value exceeds a designated Stream Area Threshold (SAT). That is, once a pixel drains more than a specified area (*number of pixels * pixel area*) it is designated a stream pixel.

5.4 Horton Stream Ordering

CatchmentSIM also includes a more complex and hydrologically realistic algorithm for representation of a vector calculated stream network. Vector representations of stream networks are preferred to raster types because they are more scale independent and enable calculation of meaningful parameters such as drainage density and shape which are based on stream lengths which are themselves vector quantities. In addition to lengths, the vector algorithm also calculates stream order values in accordance with Strahler's 1957 revision of Horton's original work (Horton, 1945) on quantitative geomorphology and stream network fractal scale-similarity. That is, the CatchmentSIM algorithm derives a set of connected polylines with calculated length values and Horton / Strahler order characteristics, enabling calculation of bifurcation and channel maintenance parameters. This is illustrated in Figure 8 where a vector stream network has been calculated for a catchment (*higher order streams have a darker line colour*) and a resulting bifurcation chart has been generated below.

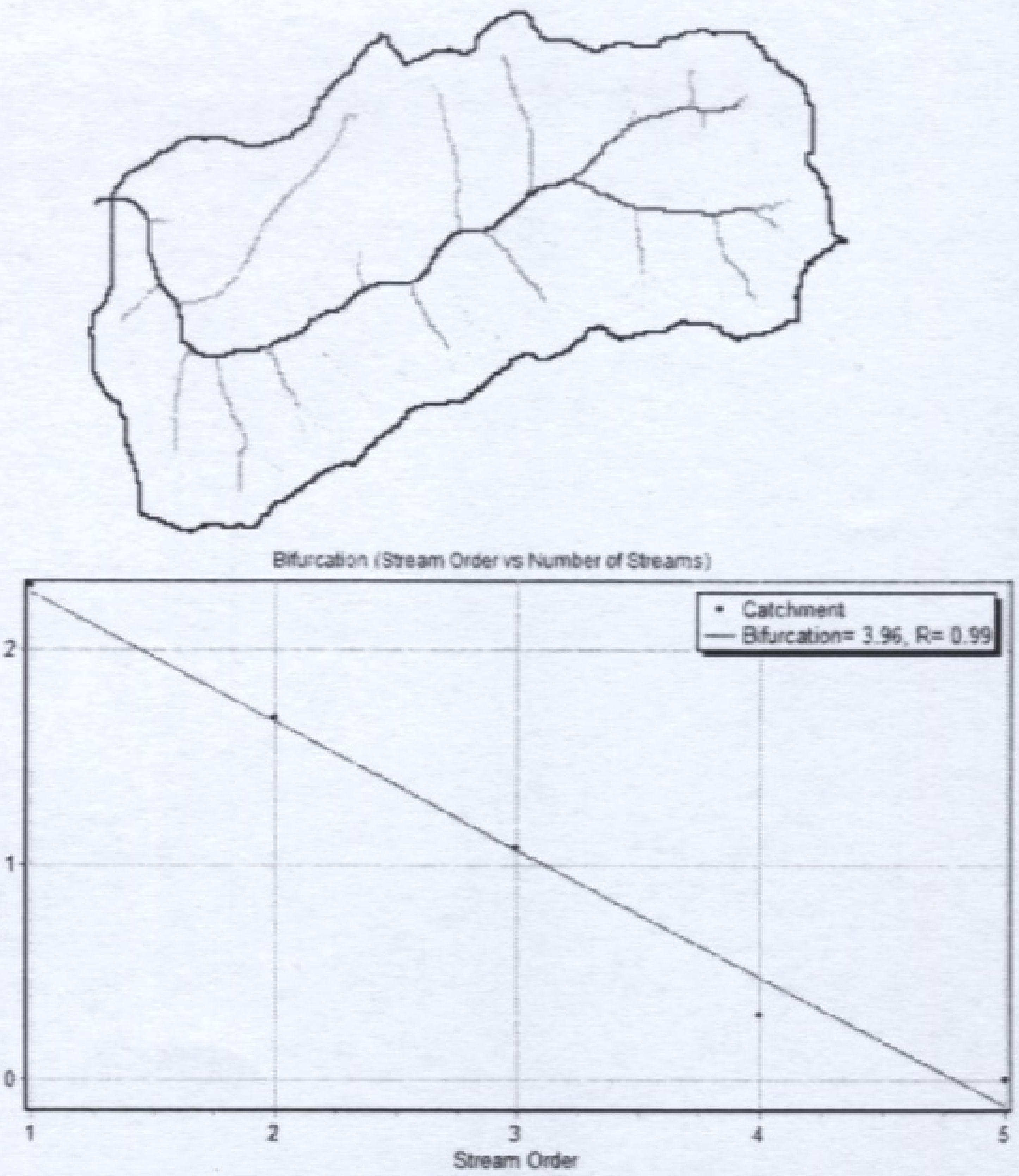

Figure 8: Vector Stream Network / Bifurcation

Interestingly, research on a number of catchments with vector stream networks derived with a different SAT values have been found to have bifurcation ratios that are scale independent and seem to concentrate around values of 4-5. This is very similar to results found by Strahler (1952 & 1957) whose work was based on manual calculation of stream lengths illustrated on maps. These similarities add weight to the argument that automated vector stream generation based on flow routing over a DEM can closely represent the fractal nature of natural stream networks, provided hydrologically accurate methods of DEM interpolation and pre-processing are applied.

Although bifurcation and stream length frequency distribution analysis have been found to be relatively constant over different catchments in various countries and climates, slight variations may be seen over subcatchments within a single CatchmentSIM project. Further research will be necessary to investigate this issue but these variations could provide evidence for differences in subcatchment rainfall response and consequently, they could provide the basis for determination of the less physically based parameters required by common hydrological modelling packages, such as subcatchment lag and routing parameters.

6. SUBCATCHMENT BREAK-UP

An important component in the development of a lumped hydrologic model is the identification of subcatchments. However, deciding how many subcatchments to use in a lumped hydrologic model and where they should be located can be a subjective decision. Two algorithms have been incorporated into CatchmentSIM to help engineers and scientists with these decisions. The first of these algorithms automatically breaks a catchment into a set number of subcatchments (*designated by the user*) based on locating subcatchment outlets at the largest jumps in the flow accumulation matrix, which represents the confluence of significant tributaries.

This algorithm can reduce the uncertainty in locating subcatchment outlets. However, the user still needs to decide on a target number of subcatchments. The number of subcatchments chosen can have a significant effect on generated hydrographs. The availability of Horton ordering allows a more quantitative basis for catchment break-up by identifying all subcatchments as a result of intersection of stream of various Horton order values. Hence, by adoption of a realistic SAT value for the particular catchment based on soil type and climate factors, the catchment break-up may be based on the more objective criteria of the stream network fractal relationship. This is shown in Figure 9 where basins of 2nd and 3rd orders have been automatically delineated.

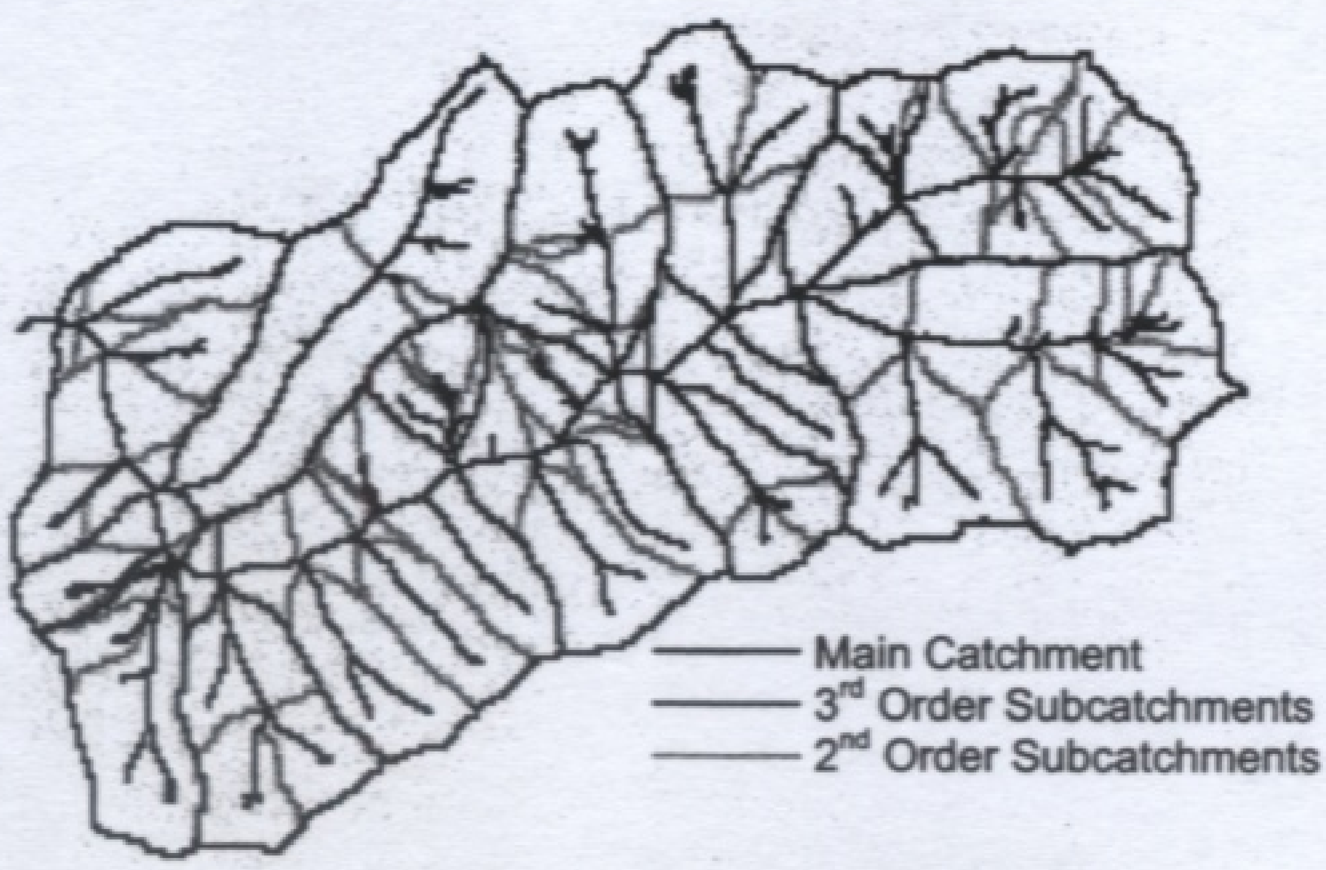

Figure 9: Automated Catchment Break-up Using Horton Stream Orders

These methods of automated catchment break-up reduce the uncertainty associated with identification of subcatchment outlets and also vastly increase the speed of catchment break-up. This increase in model setup time provides the potential for a sensitivity analysis of a hydrologic model to number of subcatchments and basis for catchment break-up, an important step which is rarely undertaken in flood and drainage investigations.

7. TOPOGRAPHIC PARAMETERISATION AND GEO-SPATIAL STATISTICS

An important aspect when using lumped hydrologic models is the assignment of lag times and associated parameters to the subcatchments. These 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.

Algorithms have been included with CatchmentSIM to accommodate calculation of these parameters and will automatically calculate parameters including average vectored slope, Horton drainage density, bifurcation and many others. A range of graphs can also be produced including overland / in-stream flow distance frequency distributions, bifurcation plots, hypsometric curves and others.

8. COUPLING WITH 3RD PARTY HYDROLOGIC MODELS

CatchmentSIM integrates directly with a wide range of Australian and international hydrologic models. Figure 10 illustrates the software's ability to integrate with some of the most prominent Australian hydrologic modelling packages for natural and urban catchments. Supported international models include HEC-HMS and ArcGIS. CatchmentSIM tightly couples with these 3rd party models by automatically creating run-files or import files that can be directly opened with the coupling software.

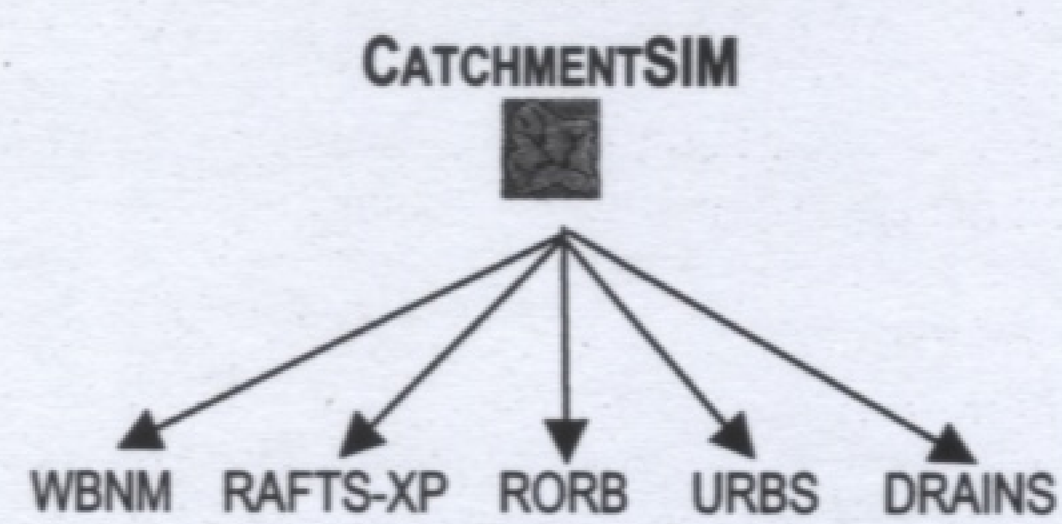

Figure 10: Supported Australian Hydrologic Models

The ease of integration of CatchmentSIM with a range of hydrologic modelling packages that are recommended for a particular region enables a sensitivity analysis to be easily undertaken using multiple hydrologic models with an identical subcatchment arrangement and associated topographic parameters. This is also an important type of sensitivity analysis rarely undertaken in flood and drainage studies.

9. CONCLUSIONS

The increasing availability of accurate GIS datasets within Australia and around the world has opened the door to automation of many of the tasks associated with preparing hydrologic and hydraulic models. However, the algorithms included in many commercial GIS software packages to undertake these tasks are overly simplistic and are too generic to be applied with confidence in complex hydrologic and hydraulic problems.

This paper has described a suite of algorithms that are embodied with the CatchmentSIM software, and their capability to aid engineers and scientists with development of hydrologic models.

CatchmentSIM has shown considerable potential in both natural and urban catchments. The ability of the software to automatically interpolate DEMs, delineate catchments, subcatchments and predicated stream networks and tightly integrate with a comprehensive range of 'industry standard' hydrologically modelling packages should enable faster and less subjective setup of the topographic components of hydrologic models. The bonus is that this will allow users to focus their efforts on other phases of the work where expert human input is irreplaceable.

10. FUTURE RESEARCH

CatchmentSIM is currently being applied in natural and semi-urban projects in Australia and around the world. Scope exists for further work in highly urban environments, particularly in the further development of CatchmentSIM's modelling of pipe and pit networks.

Development of CatchmentSIM is set to continue and the focus of the research 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 hydrologic and hydraulic modelling.

11. SOFTWARE AVAILABILITY

CatchmentSIM and tutorials can be freely downloaded from the project web-site (http://www.catchmentsim.com). Users can also freely register as a site member in order to be notified of updates.

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