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An Object-Orientated Approach to Hydrological Modelling using Triangular Irregular Networks

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Introduction

This paper describes an approach to hydrological modelling with two characteristics: *a)* the terrain is modelled with a *triangular irregular network (TIN)* instead of more commonly used *rasters*; and *b)* an object orientated approach is used, which allows *data* and *process* to be embedded in the same data structure.

Comparisons of TINs and rasters for terrain modelling are well reported in the literature. Data models for environmental modelling are most commonly based on rasters, but some researchers (e.g. Braun and Sambridge, 1997; Tucker *et al.*, 2001) have observed that under certain circumstances, artefacts of the underlying regularity of rasters may manifest themselves in the model output (see Figure 1). This is partly due to the simple method by which flow direction is most commonly approximated in rasters; flow from each cell is routed into the lowest one of its nearest eight neighbours (the 'D8' method, O'Callaghan and Mark, 1984). Other, more sophisticated methods do exist. Deterministic methods include Quinn's (1991) multiple-flow routing algorithm and Lea's (1992) routing according to a local aspect best-fit plane; a disadvantage of the former, is that flow tends to diverge. Methods with a stochastic element include 'Rho8' by Fairfield and Leymarie (1991); a disadvantage of these methods is that different results are obtained with the same input parameters over multiple model runs. A good review of these methods is by Gallant and Wilson (2000). Flowpaths over a TIN surface can be computed using the steepest lines of descent of TIN facets (Jones *et al.*, 1990) in any orientation, rather than being based on 45º direction increments.

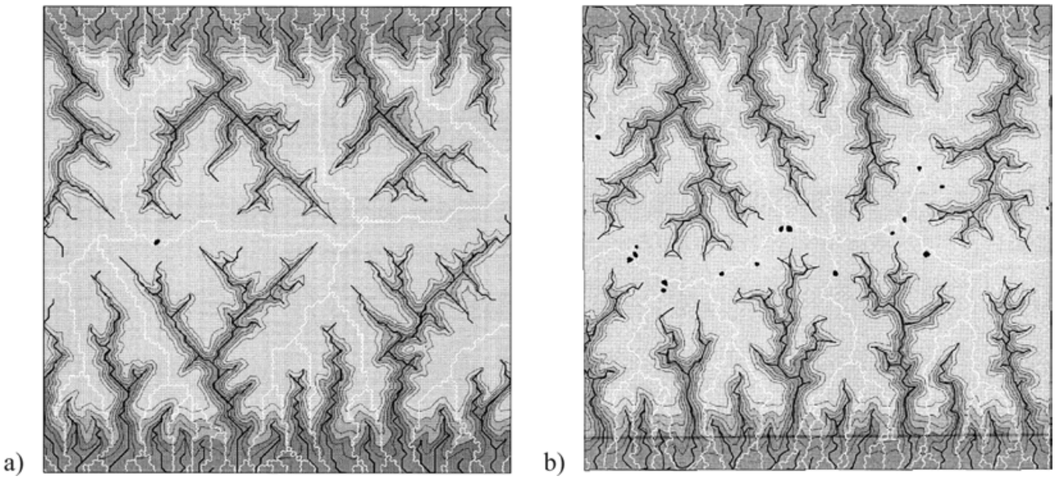

Figure 1: Regular and irregular data models compared. *(a)* Landscape evolution model output, performed on a regular grid. The simulated river channels have a shape strongly controlled by the regular geometry of the grid. *(b)* Output of the same simulation, but performed on an irregular TIN-based structure. Channel networks have a more 'organic' and natural-looking geometry. *Source: Braun and Sambridge (1997).*

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The object-orientated approach models the terrain as a set of interacting TIN elements (nodes, edges and facets). The approach of dealing with 0D, 1D and 2D elements of space in a 2D data model is common. For hydrological modelling purposes, this also allows channel flow (along concave edges) and overland flow (over facet areas) to be modelled separately. Each TIN element is an 'object' which holds data (properties) about itself, and also has the ability (through methods) to build itself, derive spatial relationships with its surrounding TIN elements, and model hydrology upon itself. The set of interacting objects, each responsible for its local operations, forms an 'intelligent landscape' model, into which both *data* and *process* are embedded. The delegation of methods in this localised way greatly simplifies the implementation of the model, in which operations are completed using a piecemeal approach.

TINMOD (Slingsby, 2002) is a prototype implementation of a TIN-based 'intelligent landscape' for hydrological modelling. Its design is described and discussed in the context of hydrological modelling.

The Data Model

Figure 2 illustrates the data model. The TIN is composed of three types of TIN elements, modelled by the classes TNode, TEdge and TFacet. These are organised by an instance of the class TTin, which has methods for its building and maintenance and has three lists of pointers to its three types of TIN element, held as properties (state variables). Strictly speaking, only one pointer to one individual TIN element is required, since the TIN can easily be traversed by virtue of the TIN elements' storage and capabilities for deriving its topologies.

Creation and Derivation of Topology

The TNode class stores its position as three integer properties. A pointer to *any one* of the edges attached to it is also stored. This is the starting point of the *GetRadiatingEdges* method which returns a list of pointers to all the edges which are attached to it by using the adjacency information of the edges, and working around the node until the starting edge is reached. When nodes are added to the TIN, new edges and facets are automatically created and added. The triangulation is updated to meet the Delaunay triangulation criterion (this is commonly used for modelling terrains as it maximises the angles, producing 'fat' triangles, improving height interpolation between nodes). A triangulation can be made to conform to the Delaunay criterion by 'swapping' certain edges to their alternative configuration as described by Sloan (1987).

The TEdge class stores pointers to the nodes that define its two end points and to the facets that lie on its left and right (with respect to node1). The TBreakEdge class is inherited from this and instances of it can be treated in exactly the same way as instances of TEdge – the difference is in its behaviour when the *EdgeSwap* method is called. Instances of the TBreakEdge class will not let their configuration be changed. This is an example of the object-orientated concept of *polymorphism*.

The TFacet class stores pointers to the three edges which define it. Its methods *GetNode1*, *GetNode2* and *GetNode3* are used to return its three nodes.

This system ensures that when any node is added to the TIN, methods for updating the Delaunay triangulation and topology are invoked. The local character of the Delaunay criterion facilitates the localised subdivision of tasks. This modular object-orientated approach greatly simplifies the implementation of a potentially complex data model and its operations.

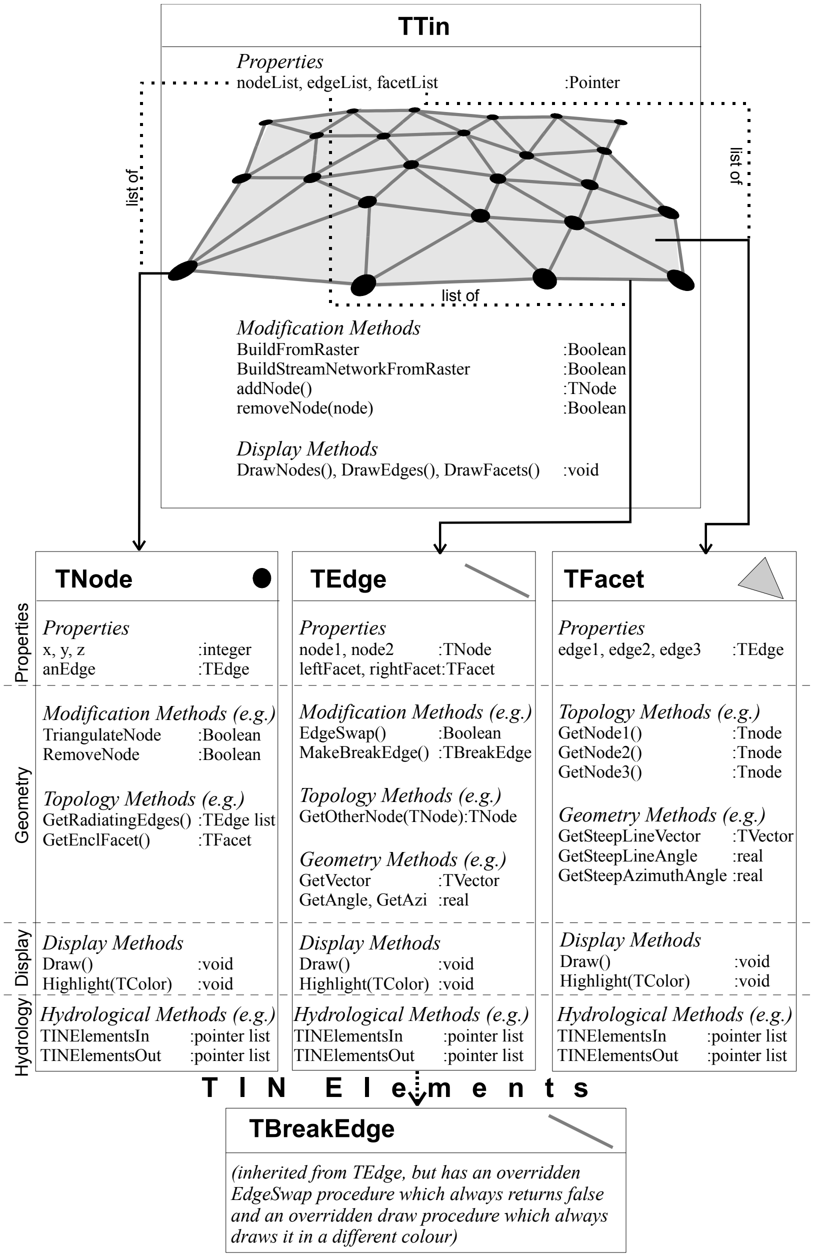


Figure 2: The TINMOD data model. The class TTin holds a list of pointers to its TIN elements and has methods for its building and maintenance. TIN elements are the objects that make up the TIN, defined by the classes TNode, TEdge and TFacet. Each holds properties relating to itself, and methods for manipulating itself, deriving its topology, displaying itself on-screen, and modelling hydrology upon itself. The TBreakEdge class models edges whose configuration is prescribed (to coincide with a linear feature such as a channel or ridgeline). It is inherited from TEdge and behaves like the latter, except that it will not allow its configuration to be changed and it will draw itself in a different colour.

Display

All the TIN elements have a *Draw* method for drawing themselves on-screen. TTin has methods for drawing all instances of each TIN element in its pointer lists. The *Highlight* method allows a display colour to be specified. These methods produced the outputs seen in Figure 5.

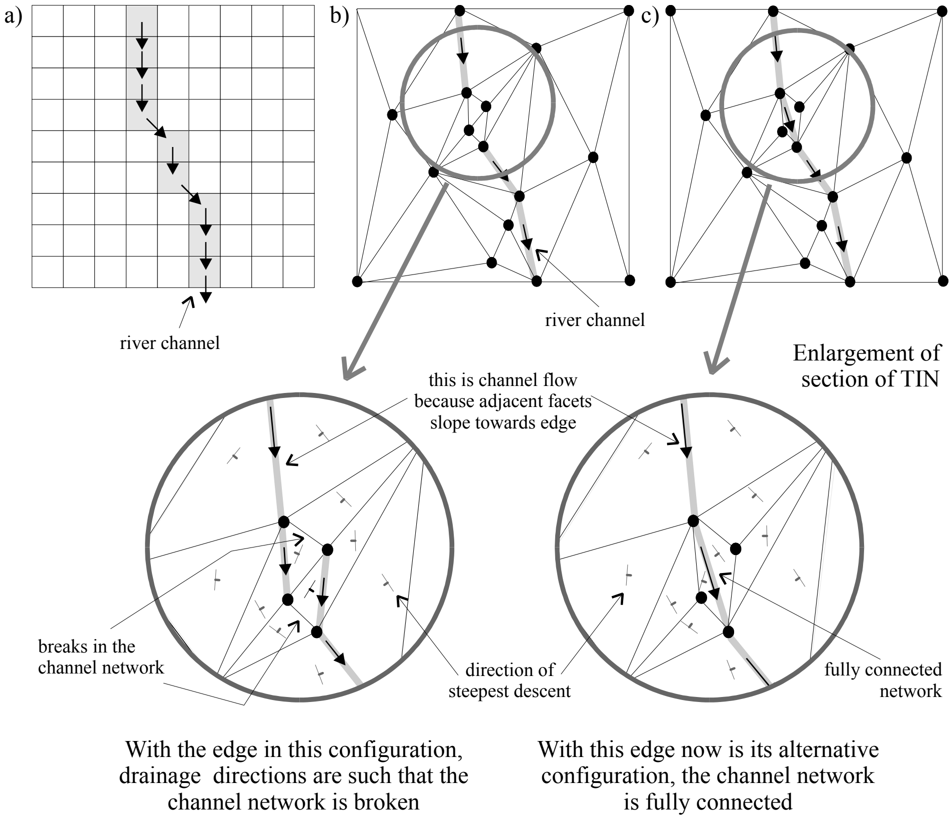
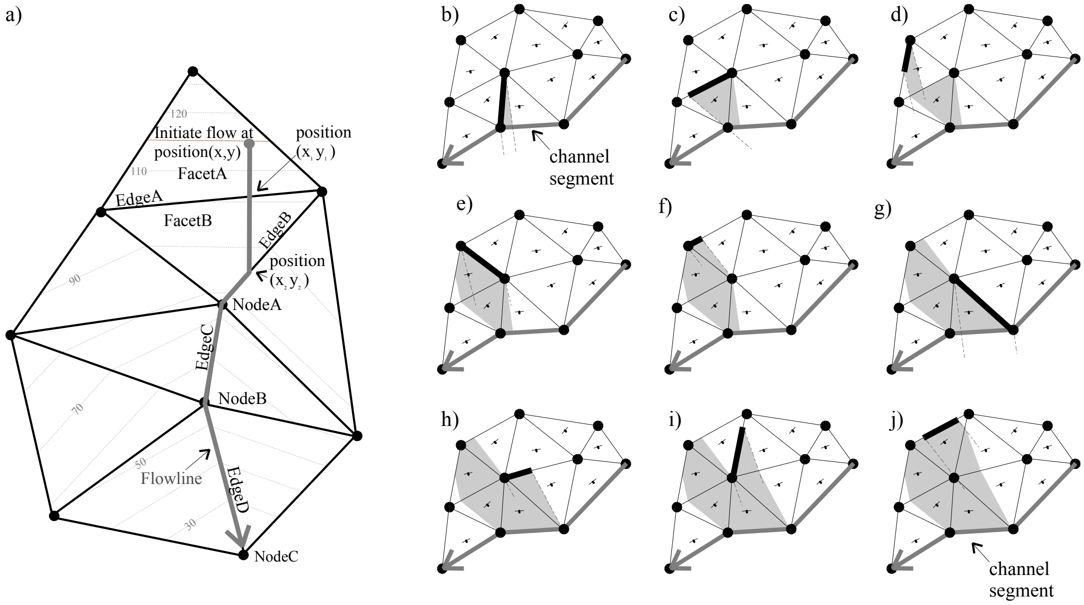


Figure 3: Rivers and drainage directions on rasters and TINs. *(a)* an example of a river represented on a raster. *(b)* an example of the same river represented on a TIN. Strict Delaunay triangulation has caused a break in the network. The enlarged section shows the reason for this. The steepest descent directions of the facets are such that *channel flow* (flow along edges) *cannot* proceed pass this point. Flow as *overland flow* (across facet surfaces) *can* proceed through. *(c)* The edge has been constrained (forced into this configuration) to coincide with the river, relaxing the Delaunay criterion for this edge. The drainage directions are now such that a fully connected channel network exists.

The Representation of Terrain

A TIN is created from an irregular sample of point data. One method of generating this is to run an algorithm on a raster landscape model to generate the set of nodes required to build a TIN terrain model whose surface does not deviate outside a user-defined threshold from the original (raster) terrain model. The Hierarchy Method (de Floriani *et al* 1984, *cit* Lee, 1991) performed well (Slingsby, 2002). This iterative technique builds a TIN node-by-node by *a)* comparing the intermediate TIN as it is built, with the original (raster) terrain representation, *b)* generating the node which would make the intermediate TIN most like the original terrain, *c)* adding this to the TIN, *d)* repeating until the TIN represents the original terrain within a user-defined tolerance. Since the adding of each node invokes all the necessary triangulation and topology-building methods, the triangulation is always up to date. This adaptive nature ensures that the TIN can be compared at each iteration.

Delaunay triangulation produces the most satisfactory triangulation for modelling surfaces. However, if certain linear features need to be represented in a TIN, the TIN must be constrained to ensure that edges are coincident with linear features, whether or not they meet the Delaunay triangulation criterion. Since TINMOD defines channels as concave edges (whose two adjacent facets slope towards the edge), it is essential that the river channel networks are fully represented and fully connected. Figure 3 shows how a pure Delaunay triangulation *may* result in a broken



a: Delineating flowlines

b-j: Delineating basins

Figure 4: The piecemeal approach. *(a)* Delineating flowlines. Flow is initiated at the position x,y. FacetA can ascertain that the exit TIN element is *EdgeA* at *position* x_1,y_1. EdgeA can ascertain that is it concave (thus a channel) and flow will leave through NodeA… and so on. In some cases, there may be more than one channel downslope from a node (stream divergence). *(b-j)* Delineating a basin. In this simplified example, the area that flows into the segment marked as "channel segment" is delineated (the area from one side only). This channel segment is the sole output of the facet above. This facet has two input edges that contribute to its sole output. In *b* the leftmost edge is taken (marked in black) and the area of the facet through which flow flows is marked (in grey), bounded by the line of steepest descent. In *c*, the facet above the previous edge has only one *partial* input edge (marked in black) from the facet above. The facet area to which this contributes is again marked. This process continues until the whole area that flows into the "channel segment" is delineated. For whole basins, this process starts from the lowest node of the basin, and works upwards to the watershed.

channel network. Tucker *et al* (2001) considered that modelling channel in this way was not robust enough (since it is too much dependent on the edge configuration of the TIN). Instead, all flow is modelled as one flow-type, routing *all* flow over Voronoi polygons, rather modelling flow over facets (overland flow) and along edges (channel flow) separately. The Voronoi method can be used for long term geomorphological models. It is less suited to hydrological modelling, because channel flow (governed by different physics than overland flow) is not modelled. TINMOD creates a suitable constrained TIN by extracting channel- and ridge-line data from the original raster, and adding them as a series of breaklines, before the rest of the TIN is built with the Hierarchy Method.

In the future, it also may be possible to constrain TINs with additional information such as land parcel data, where parcels may have different hydrological properties based on the land use.

Hydrological Methods

Each TIN element can ascertain its geometry (with methods such as TFacet's *GetSteepestLineVector* method) and which TIN elements are both upslope and downslope from it. Thus an edge 'knows' that if it is a 'channel', flow will *leave* the edge through its lowest node and that flow may *enter* it from its highest node and from the facets on either side as overland flow. If the edge is not a 'channel', flow may also leave by the adjacent facets which slope away from it. A facet 'knows' that flow will always move along its path of steepest descent/ascent. From this, it also 'knows' through which edge(s) or node(s) flow will leave or

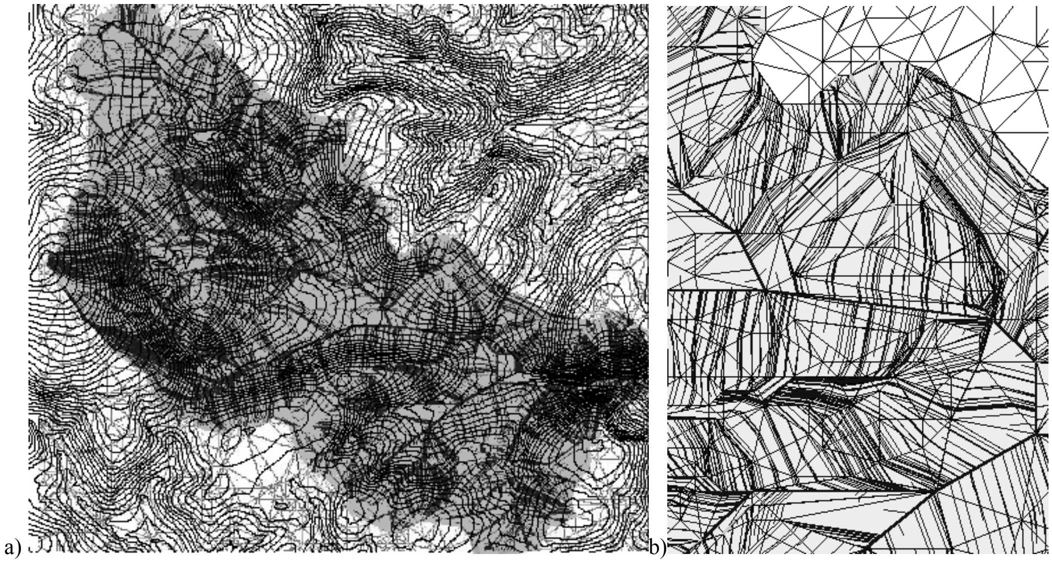


Figure 5: *(a)* Example output from TINMOD, overlain by contours (the TIN can be seen in grey). The shaded area is a basin as delineated by TINMOD from the basin outlet. Within the basin, the dark lines are the traces of flowpaths across the TIN surface, initiated from the centres of each facet area. Note that the flowlines run perpendicular to the contours. *(b)* Detail of flowpaths on the TIN surface. Flowlines on common facets are parallel.

enter. Edges can then derive at which point upon them flow entered or left, by the angle of the input or output facet. Nodes can likewise do this; within a channel network they may be the points at which flow diverges upstream or downstream. Flowpaths can thus be defined as a whole using this piecemeal approach. See Figure 4*a*.

Basins can be delineated by finding all the edges and areas of facet which flow into the basin output (a single node), and then repeating this for all the edges and areas of facet which flow into these. Since facets have either one input edge and two outputs edges, or two input edges and one output edge, and since input edges may contribute to more than one output edge, dynamic segmentation of edges is used to identify sub-areas of facets. See Figure 4*b-j*.

Conclusion

This paper has briefly outlined an object-orientated TIN approach to hydrological modelling. The use of the TIN aims to free the model of some of the common constraints imposed by rasters. The model relies on the existence of a fully connected channel network, and does this by constraining the TIN, based on channel information extracted from the original raster. Two types of flow are modelled, overland flow (on facets) and channel flow (along concave edges). For basin delineation, facets can be dealt with at a sub-facet level.

The object-oriented approach models the system as a set of interacting objects, each with relatively simple behaviours. This approach simplifies the data structure by allocating tasks (methods) to localised structural elements of the TIN (nodes, edges and facets), invoking these methods to reflect dynamic change and providing a unified modelling framework in which the terrain and hydrological processes can be modelled in a piecemeal fashion.

Figure 5 shows some output examples from TINMOD. The implementation and some initial tests (although the latter are not discussed here) of the prototype TINMOD, have shown that this approach is both technically feasible and valid (Slingsby, 2002).

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