

# VISUALIZATION AND DECISION SUPPORT FOR WATERSHED MANAGEMENT

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Commission II, WG II/6

**KEY WORDS:** Terrain Modelling; Decision Support; Landscape Modelling; Visualization; Runoff.

## ABSTRACT:

Flow modelling is an important aspect of environmental protection, and it is frequently necessary to evaluate the consequences of proposed construction, such as roads or dams, on the surface water flow. Ideally, a watershed management decision support systems should be interactive: rapid enough to respond quickly to suggested changes. One requirement is a good terrain model, derived from contours, with plausible slope values. Another is a finite-difference flow model using random Voronoi cells to avoid directional bias. The third is interactive landscape modification using CAD-type operators that allow the extrusion of buildings, bridges, tunnels, etc.

## 1. VISUALISATION AND DECISION SUPPORT

The primary objective of a decision support system (DSS) is to assist the manager or planner to make some decision – people make decisions, not computers. The original computer-based DSS was probably a spreadsheet, and for spatial information it was a traditional static map – on paper or on the screen. However, this state of affairs is changing rapidly. Even in the non-spatial domain graphics are recognized as an important mechanism for the transfer of information, and this is even more true for spatial data. Nevertheless, even now many spatial decisions are made with the aid of only static two-dimensional maps.

Effective decision support is a “what-if” activity. This implies an interaction between the manager and the computer, where the manager proposes some action or “scenario” and the computer provides some visualization or evaluation of the consequences. This interaction must take place within a reasonable time-frame: often the manager has a mental picture of what he would like to try – but this is only a temporary image in short-term memory, and must be reinforced by some response.

In the simplest case this scenario is merely a change of viewer location, as in a “fly-through”, and computer graphics is now frequently able to achieve terrain visualization, for example, at adequate speeds. There is more difficulty, however, when the scenario requires the recalculation of the consequences of the proposed activity – here both recalculation and visualization must be completed in a short time-frame. Examples of this situation include forest harvest planning and route selection. Our particular interest here is in watershed and runoff management.

### 1.1 Runoff Modelling – Terrain Modelling, Skeletons, Slopes

Runoff modelling requires good terrain modelling; in particular, it is very sensitive to the representation of slope. Thus a first priority is to generate terrain models with plausible slope values – unfortunately many traditional interpolation techniques fail in this respect. We are interested in using available contour data, so we demonstrate the slope behaviour of various interpolation

techniques for this kind of data, and select an appropriate method.

## 2. TERRAIN

While the generation of interpolated surfaces from contours has been studied for many years (e.g. Peucker 1978, Gold 1979), the problem remains interesting for a variety of reasons. Firstly, contour data remains the most readily available data source. Secondly, valid theorems for the sampling density along the contour lines have only recently been discovered (Amenta *et al.* 1998, Gold 1999, Gold and Snoeyink, 2001). Thirdly, the same publications provide simple methods for generating the medial axis transform, or skeleton, which definitively solves the “flat triangle” problem (which often occurs when triangulating contour data) by inserting additional points from this skeleton. Fourthly, the problem of assigning elevation values to these additional ridge or valley points can be resolved, using the geometric properties of this skeleton, in ways that may be associated with the geomorphological form of the landscape. In addition, comparisons of the methods used in a variety of weighted-average techniques throw light on the key components of a good weighted-average interpolation method, using three-dimensional visualization tools to identify what should be “good” results – with particular emphasis being placed on reasonable slope values, and slope continuity. This last is often of more importance than the elevation itself, as many issues of runoff, slope stability and vegetation are dependent on slope and aspect – but unfortunately most interpolation methods can not claim satisfactory results for these properties. The techniques developed here are based on the simple point Voronoi diagram and the dual Delaunay triangulation.

### 2.1 Generation of Ridge and Valley Lines

Amenta *et al.* (1998) examined the case where a set of points sampled from a curve, or polygon boundary, were triangulated, and then attempted to reconstruct the curve. They showed that this “crust” was formed from the triangle edges that did not cross the skeleton, and that if the sampling of the curve was less than 0.25 of the distance to the skeleton the crust was guaranteed to be correct. Gold (1999) and Gold and Snoeyink

(2001) simplified their algorithm for extraction of the crust, showing that, in every Delaunay/Voronoi edge pair, either the Delaunay edge could be assigned to the crust or else the dual Voronoi edge could be assigned to the skeleton. The Delaunay edge belongs to crust when there exists a circle through its two vertices that does not contain either of its associated Voronoi vertices; if not then the corresponding Voronoi edge belongs to the skeleton. Skeleton points may be inserted into the original diagram, or not, as needed. In our particular case the data is in the form of contour lines that we assume are sufficiently well sampled – perhaps derived from scanned maps. Despite modern satellite imaging, much of the world's data is still in this form. They are clearly intended to convey information about the perceived form of the surface at a particular scale – and it would be desirable to preserve this, as derived ridges and valleys.

Fig. 1a shows a close-up of the test data set, illustrating a key point of Amenta *et al.*'s work: if crust edges (forming the contour boundary) may not cross the skeleton, then inserting the skeleton points will break up non-crust triangle edges. In particular, if the skeletons between different branch contours are ignored, then insertion of the remaining branch skeleton points will eliminate all “flat triangles” formed from points of the same elevation. Thus ridge and valley lines are readily generated automatically. The same is true in the case of closed summits (Fig. 1b). The challenge is to assign meaningful elevation values to skeleton points.

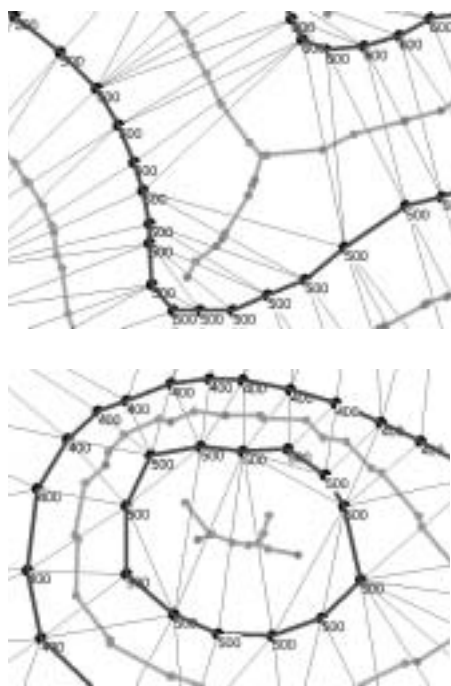


Figure 1. Skeleton and "flat triangles" – a) ridge; b) summit

Two techniques have been developed for this, each with its own physical interpretation. The first, following Thibault and Gold (2000), uses Blum's (1967) concept of height as a function of distance from the curve or polygon boundary, with the highest elevations forming the crest at the skeleton line. This model is based on the idea that all slopes are identical, and thus the radius is proportional to the height of the skeleton point. In the case of a ridge or valley, the circumradius may also be used to estimate skeleton heights based on the hypothesis of equal

slopes. The larger circle, at the junction of the skeleton branches, has a known elevation – half way between the contours – and may be used to estimate the local slope. The elevation of the centre of the smaller circle is thus based on the ratio of the two radii. For more details see Thibault and Gold (2000).

## 2.2 Interpolation

On the basis of a sufficient set of data points, we now wanted to generate a terrain model with satisfactory elevations and slopes, as the basis of a valid rainfall runoff model. Our approach was to interpolate a height grid over the test area, and to view this with an appropriate terrain visualization tool. To obtain perspective views we used Genesis II, available from [www.geomantics.com](http://www.geomantics.com). Vertical views were generated using version 5 of the Manifold GIS, available from [www.Manifold.net](http://www.Manifold.net).

In general, we may ask about three components of a weighted-average interpolation method. Firstly: what is the weighting process used? Secondly: what is the set of neighbours used to obtain the average? Thirdly: what is the elevation function being averaged? (Often it is the data point elevation alone, but sometimes it is a plane through the data point incorporating slope information as well.) In this paper we will only look at the triangulation model and the Sibson (or natural neighbour, or area-stealing) model. For more details see Gold (1989). Fig. 2 shows the result for the triangulation model, including the crust and skeleton draped over the terrain. The flat triangles are readily seen. Fig. 3 shows the improved model when estimated skeleton points are added, and all flat triangles are removed.

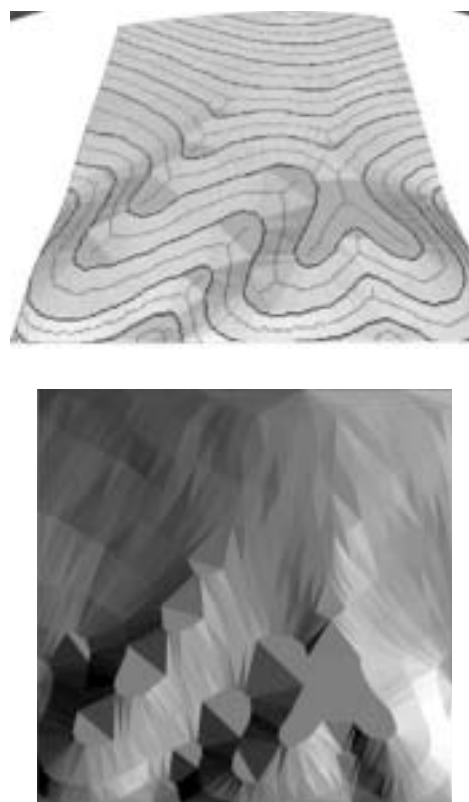


Figure 2. Interpolation from Delaunay triangulation - a) perspective view; b) vertical view

The Sibson method is based on the idea of inserting each grid point temporarily into the Voronoi diagram of the data points, and measuring the area stolen from each of a well-defined set of neighbours. These stolen areas are the weights used for the weighted-average. The method is particularly appropriate for poor data distributions as the number of neighbours used is well defined, but dependent on the data distribution. Fig. 4 shows the results of using Sibson interpolation. The surface behaves well, but is angular at ridges and valleys. Indeed, slopes are discontinuous at all data points (Sibson 1980, 1982).

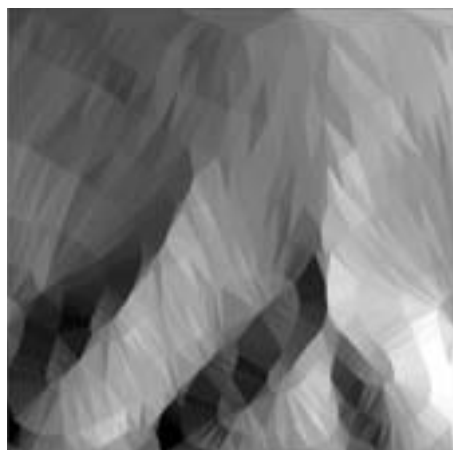
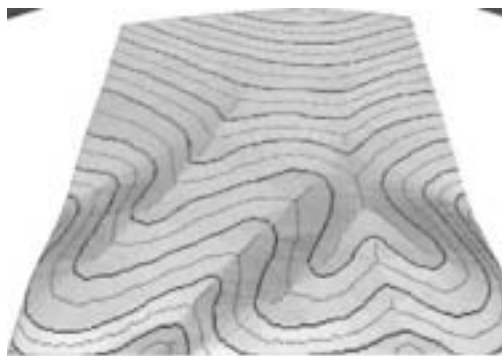


Figure 3. Adding skeleton points to Fig. 2 a) perspective view; b) vertical view

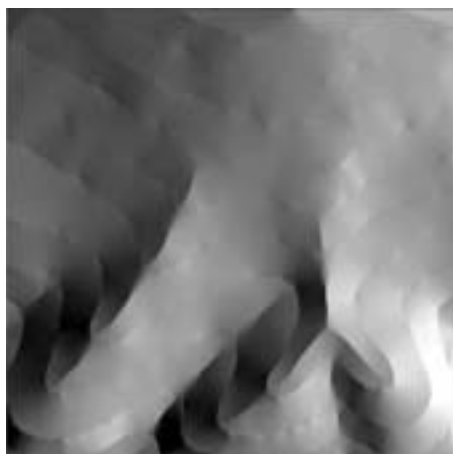


Figure 4. Sibson interpolation - vertical view

One subject is often ignored in selecting a method for terrain modelling – the slope of the generated surface. In real applications, however, accuracy of slope is often more important than accuracy of elevation – for example in runoff modelling. However, in our weighted-average operation we can replace the height of a neighbouring data point by the value of a function defined at that data point – probably a planar function involving the data point height and local slopes. Thus at any grid node location we find the neighbouring points and evaluate their planar functions for the  $(x, y)$  of the grid node. These  $z$  estimates are then weighted and averaged as before.

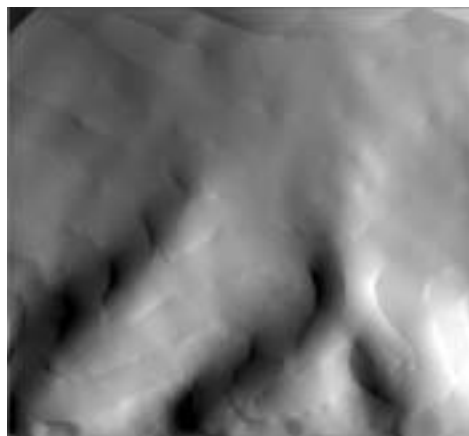


Figure 5. Sibson interpolation using slopes at data points

Fig. 5 shows the result of using Sibson interpolation with data point slopes. The form is good, but slight breaks in slope can be seen at contour lines. When using smoothing and slope information together, the surface is smooth, but has unwanted oscillations. Clearly an improved smoothing function is desirable to eliminate these side-effects. Adding slopes to the simple TIN model (i.e. using the position in the triangle to provide the weights) produced results that were almost as good as the Sibson method when the sample points were closely spaced along the contours. However, the Sibson method is much superior for sparser data, or where the points do not form contour lines. The gravity model does not provide particularly good slope estimates, but even here including the data point slope function produces a significant improvement.

### 3. RUNOFF MODELLING

The second issue concerns the runoff modelling techniques themselves. Finite element techniques are difficult to implement, and many runoff models are based on finite difference methods on a grid. As is well known, this produces a north-south and east-west bias to the simulated flow (or sometimes 45 degrees). We resolve this issue by using a random set of cells based on the Voronoi diagram, and using these for finite-difference modelling. This eliminates the directional bias, and allows us to keep our original data points within the flow model, while adding the random interpolated heights. Our objective at this stage is to produce flow over a relatively smooth surface that behaves reasonably and shows no artefacts due to the data, the interpolation technique or the flow modelling. We demonstrate results that visually satisfy this requirement.

Fig. 6a shows a 3D view of a simple TIN model based on simple contour data and Fig. 6b shows the Voronoi diagram, crust and skeleton. Fig. 6c shows the enriched TIN model with the added ridge and valley lines. Fig. 7a shows the densified terrain model, with interpolation at additional random Voronoi cells. Fig. 7b shows the results of a simple finite-difference flow model on this terrain, after a few time steps, with darker colours representing deeper water.

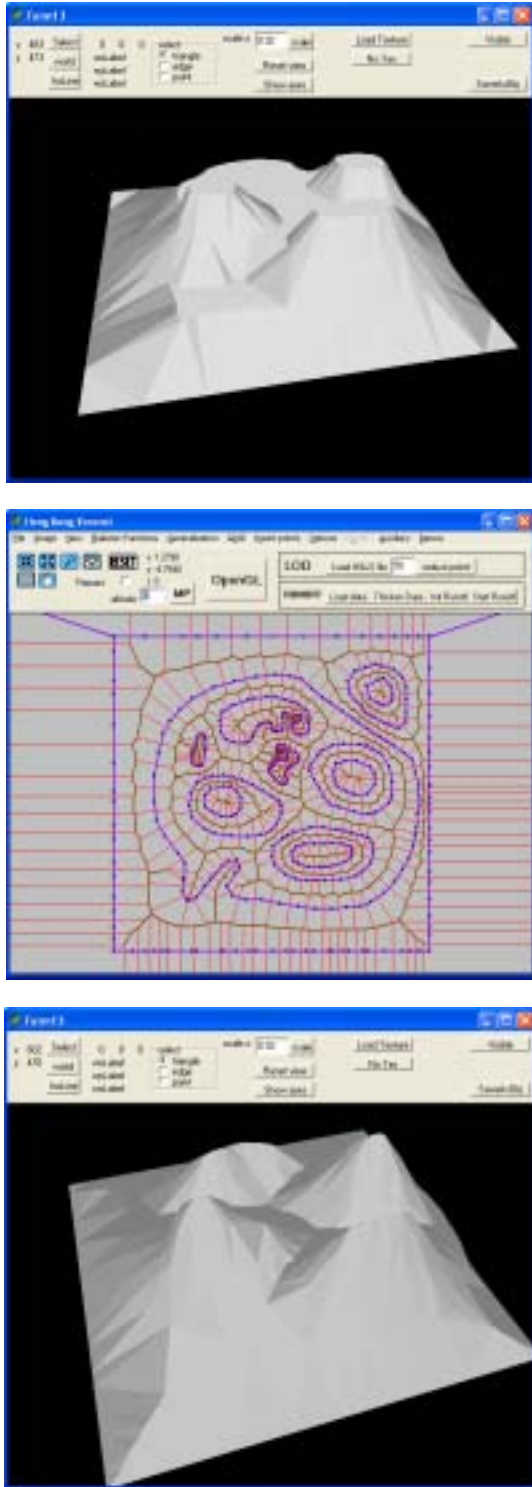


Figure 6. a) Simple TIN; b) Crust, skeleton and Voronoi cells; c) Enriched TIN.

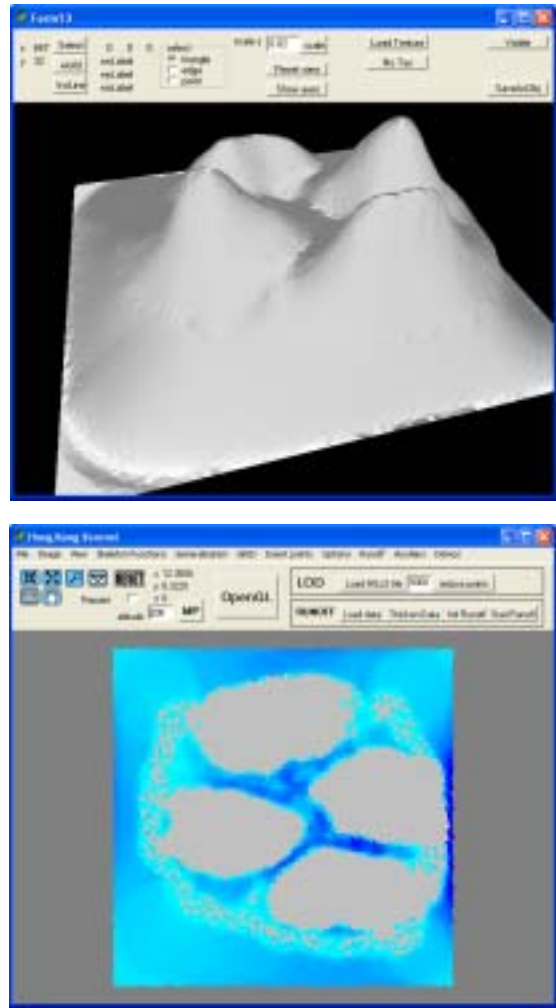


Figure 7. a) Densified model; b) Runoff results

#### 4. WHAT-IF: LANDSCAPE MODIFICATION

A decision support system is intended to assist in making choices. For runoff modelling we wish to examine the behaviour of the surface under various rainfall scenarios, and then modify the landscape with dams, diversions, etc. in order to reduce flooding, increase reservoir capacity, or produce other desirable improvements.

Landscape modification is an awkward problem for decision support. Grid height models suffer from the artefacts mentioned above and lose the link with the original input data, so they must be rebuilt each time. TIN models preserve the input data, but are not usually easy to modify to add the new structures, such as dams, that are required. In particular, 3D visualization techniques usually consist of superimposing buildings and other structures on top of the terrain, without any topological connection, so modification of flow is not possible. We have developed CAD-type operators for the modification of TIN models, including the extrusion of buildings and the construction of bridges and tunnels, that appear to resolve this problem. The terrain is modified in such a way that water can flow between cells and interact with the proposed structures.

In our current work we are using the CAD-type b-rep structure and Euler Operators to create a connected TIN model with holes,

e.g. bridges or tunnels (Tse and Gold, 2001). Starting with the well-known TIN model, we have built a set of Euler Operators, which are easy to implement with the Quad-Edge structure of Guibas and Stolfi (1985). All basic TIN modification operations may be performed with Euler Operators. An additional Euler Operator may be used for the insertion and deletion of holes that give the basic forms of bridges and tunnels. Our work consists of four stages:

- Definitions of three levels of operators to achieve our desired system;
- The use of Quad-Edge structures to implement CAD-type Euler Operators;
- The use of Euler Operators to implement basic triangulation functions;
- The extension of our triangulation models to permit bridges and holes.

#### 4.1 TINs and CAD

The examination of CAD modelling techniques does not seem attractive at first sight. The intersection of cubes and tubes, as in Constructive Solid Geometry modelling, hardly applies to terrain models. However, manifold-based “b-rep” CAD models appear to be feasible for our purposes, as the careful specification of Euler-Operators that guarantee the topological validity of the bounding surface seems particularly appropriate. As stated by Mantyla (1981, 1988), “in a “b-rep” model, an object is represented indirectly by a description of its boundary. The boundary is divided into a finite set of faces, which in turn are represented by their bounding edges and vertices.” According to his definition, b-reps are best suited for objects bounded by a compact (i.e. bounded and closed) manifold.

#### 4.2 Simplicity of Implementation – the Quad-Edge Structure

We have used the Quad-Edge structure of Guibas and Stolfi (1985) to implement a set of Euler Operators that have been shown to suffice for the maintenance of surface triangulations. These Euler Operators form the basis of the standard (two-dimensional) incremental triangulation algorithm. In addition, Euler Operators can serve to generate holes within our surfaces, thus permitting the modelling of bridges, overpasses etc. that are so conspicuously lacking in the traditional GIS TIN model. The individual Quad-Edge and Euler Operators take only a few lines of code each. “Make-Edge” and “Splice” are the two simple operations on the Quad-Edge structure, which is formed from four connected “Quad” objects, using the simple implementation of Tse and Gold (2001). The Make Edge operator creates a new independent edge. The Splice operation, which is its own inverse, either splits a face loop and merges two vertex loops or else splits a vertex loop and merges two face loops. This operation suffices to maintain any connected graph on an orientable manifold, such as is the case for CAD b-rep models, and TINs.

#### 4.3 Selection of a Set of Euler Operators

According to Lee (1999), five spanning Euler Operators suffice to specify the six elements in any b-rep model. These elements are: vertices; edges; faces; loops (or rings); holes; and bodies (or shells). However, in TINs there are no loops (holes in individual faces), leaving five elements, so four spanning Euler Operators (and their inverses) suffice for TINs with holes. In the traditional TIN models there are no holes, so three Euler

Operators and their inverses will serve for our initial model: MEVVFS/KEVVFS, MEF/KEF and SEMV/JEKV.

MEVVFS adds an edge, two vertices, one face and one shell to an empty model. Its inverse KEVVFS removes them. One Quad-Edge Operator is used to implement MEVVFS (which is simply “Make-Edge”) to create a single edge. MEF and KEF are used to create (make) an edge and a face, and to delete (kill) them. In MEF we need to give two quads as parameters to make a new face by splitting an old one. In KEF we need to give an edge as a parameter for removing the edge, and one face will be destroyed as this edge is removed. SEMV and JEKV are used to split one edge into two pieces, or merge it by adding or removing a point on an edge. SEMV splits edge “e” into two parts, and two parts are joined by JEKV. For further details see Tse and Gold (2001).

#### 4.4 TIN Modelling Using Euler Operators

In the TIN model we have three main functions, which are: create a first triangle; insert a point; and swap an edge. The Euler Operators are used to implement triangulation functions, which are “Big Triangle”, “Insert Point” and “Swap” with inverse process. The initial frame triangle is created by operators “MEVVFS”, “MEF” and “SEMV”. “Insert point” is implemented using “MEF”, “SEMV” and “MEF”. “Swap” is a procedure for swapping two edges inside the TIN model: “KEF” kills the edge and “MEF” recreates the edge so as to connect the other diagonal of the original triangle pair. These operations are shown in Fig. 8.

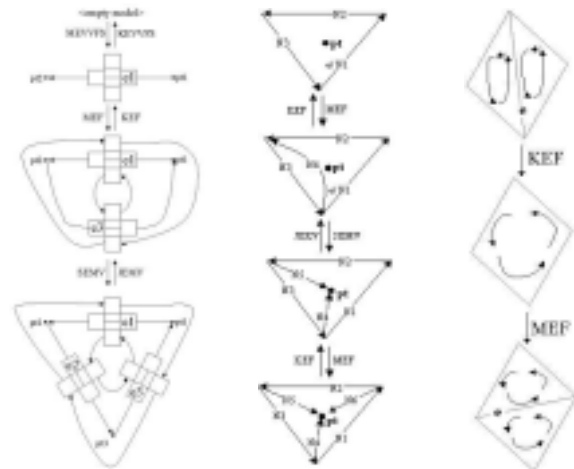


Figure 8. “Big Triangle”, “Insert Point” and “Swap”

#### 4.5 Extension to Bridges and Tunnels

So far we have merely re-formulated the traditional incremental algorithm, but with this background existing Euler Operators are used to modify the TIN surface in other ways, e.g. by the insertion and deletion of holes. The operator “Make Edge Hole Kill Face” (MEHKF) consists of exactly the same code as MEF, but instead of taking two Quad-Edges that are part of the same face loops as parameters, it takes Quad-Edges that are parts of separate face loops. The two triangles concerned are deleted, an edge is formed between the two triangles, and a new face is formed that loops through each of the deleted triangles and both sides of the new edge.

Fig. 9a shows the result of the first step MEHKF, and Fig. 9b shows the result after MEF – one new edge and face is made. Fig. 9c shows the result of the final MEF – again, one new edge and face are created. There are now three faces inside the hole, but the connectivity is preserved and you can walk through the hole while remaining on the outside of the object. Three more MEFs are used to split the faces inside the hole into triangles. Fig. 10 shows a simple terrain, with a bridge and a tunnel added. We can use the same idea to create a building and other complex structures. A triangle is selected on a TIN model and gives a specified height to extrude a building.

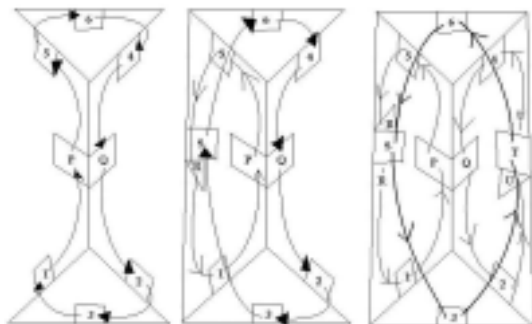


Figure 9. Creating a hole using MEHKF, MEF and MEF

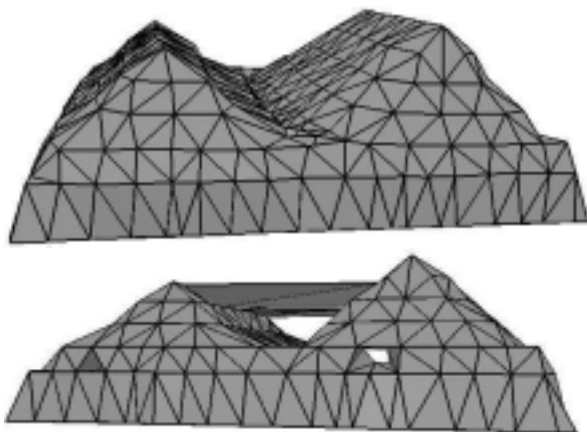


Figure 10. Upper: Top view of TIN model. Lower: A Hole and a bridge on the TIN

## 5. CONCLUSIONS – DECISION SUPPORT FOR INTERACTIVE RUNOFF MODELLING

The main components of a watershed management decision support system have been described: terrain modelling with valid slopes, runoff modelling without directional bias, and interactive terrain modification tools. All of these components may be programmed directly using Quad-Edges, Euler Operators and Voronoi diagrams, and thus could be incorporated within other, more general-purpose, systems.

While all these components for the visualizing and decision support system for runoff modelling have already been developed, they are not yet integrated into a production system. However, they have been individually demonstrated, have a variety of advantages, and appear to have a significant potential

for the rapid evaluation of watershed management scenarios, leading to effective decision making. We hope to continue with the integration and development of these methods, so that they may easily be used for full-scale environmental planning.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the partial support of this research by Research Grants Council, Hong Kong SAR, project B-Q488.

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