Landform Classification of the Mamaku Plateau using a Digital Elevation Model

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Abstract

The Mamaku Plateau is a large, forest-covered ignimbrite plateau in the North Island of New Zealand. This study was launched to aid inquiries into the evolution of the plateau by classifying its valleys (which constitute Mamaku's main geomorphological feature).

An automatic classification of the valley forms in the Mamaku Plateau was made using a Digital Elevation Model (DEM). A new algorithm was created for the Arc/Info Geographic Information System, to extract the valleys from the DEM.

Preliminary results from this phase of the inquiry indicated that it was difficult to do a computer-aided classification of valleys based only on valley form. Conventional classification of the plateau's valleys had also been done using stereoscopy to assist in the geomorphological interpretation. The results of these classifications were compared, and it was concluded that DEMs are useful in landscape analysis especially if combined with traditional geomorphological analysis.

1. Introduction

The Mamaku Plateau covers an area of approximately 1500 square kilometres. The plateau slopes gently towards the north and towards the west, and ranges in elevation from 700 metres in the south east, to 200 metres along the northern and western margins. The plateau is strongly dissected by valleys draining towards the north and the west.

The main body of the Mamaku Plateau consists of the Mamaku Ignimbrite (rhyolitic flow deposit) originated from the Taupo Volcanic Zone (Shane *et al* 1994; Wilson *et al* 1995). The Mamaku Ignimbrite is dated at 0.22 Ma (Houghton *et al* 1995). The plateau is also covered with more recent thephra and loess deposits of varied thickness and ages (Kennedy 1994; Kimber *et al* 1994).

2. Sampling and Classification

To develop a model of landform evolution, it was necessary to examine the landforms of the Plateau. This required detailed fieldwork, but the size of the study area was too big to cover in a limited period of time. Sampling was undertaken, involving representative areas identified during fieldwork. The classification was based on features known to be associated with landform evolution. A morphometric approach was adopted to aid the classification and sampling, based on the present landform characteristics.

A commonly used method in this type of studies is the interpretation of stereo pairs of airphotos, ie stereoscopy. Regions that have similar morphometric characteristics are grouped together. Many decisions in this type of classification rely on the specialist knowledge and intuition of the geomorphologist. The method is therefore fairly subjective.

To minimise the bias associated with stereoscopic observations, morphometric measurements have also been taken in this study from topographic maps. Commonly used morphometric measurements include total stream length, drainage area, and height differences, to calculate indices such as drainage density, relief ratio, and lemniscate k (Gardiner, 1975). However this method is often very slow and tedious.

The use of computerised Geographic Information Systems (GIS) in modern geomorphological studies is intended to mitigate the chances of bias associated with manual and optical classification techniques. A computerised morphometric classification is also faster than traditional methods, and a number of computer algorithms have been developed for quantitative analyses of surface topography.

Examples of GIS applications in geomorphological studies include Zevenbergen and Thorne (1987) who wrote an algorithm that determines slope, aspect, and curvature in Fortran; Gao (1994) wrote a program to detect slope forms; Tribe (1991, 1992a, 1992b) wrote algorithms to detect valleys from a Digital Elevation Model; Dymond *et al.* (1995) wrote an algorithm for automatic mapping of land components from DEMs.

However, none of these algorithms can be directly applied to the classification of landforms. Also, some programmes used in this type of work are not capable of handling large databases (Gao 1994); others require a topography dominated by valleys and ridges (Dymond *et al.* 1995), whereas the topography of the Mamaku study area consists of a plateau.

2.1 Inquiry Options

Commercial computer packages such as Arc/Info are equipped to process large databases. Arc/Info also incorporates a number of widely used algorithms in geomorphological studies (Jenson and Domingue 1988; Tarboton *et al.* 1991). This made Arc/Info an attractive software for this study. However, it was first necessary to investigate Mamaku's landscapes using conventional methods of sampling and classification.

2.1.1 Map and Airphoto Interpretation

The aim of map-based classification is to group catchment areas that are similar to one another, but noticeably different from other groups. Topographic maps (1:50000) were used for an overview of the drainage patterns, and stereo pairs of airphotos were used to make detailed morphological observations. Certain features proved to be distinctly different in some areas, and it was decided to use these features as criteria in the classification. These features were:

- the maximum size of the valley cross-section (width and depth);
- the morphology of the valley slopes (concave or convex);
- the variation of valley slope morphology within one catchment;
- drainage pattern and drainage density;
- morphology of the plateau surface in between the valleys (flat or sloping).

2.1.2 Field Reconnaissance

Finally, this phase of the study was concluded with fieldwork, carried out to determine (visually) the type of landforms, and to assess whether the classification thus far provides an adequate basis for further investigation. The valley slopes were examined with reference to three criteria:

1. slope angle (measured with a clinometer);
2. vertical curvature; and
3. horizontal curvature.

On the plateau surface, the field reconnaissance was conducted on the basis of three other geomorphological criteria:

1. slope angle,
2. roughness of terrain; and
3. the presence of tors.

The field notes also recorded (for each examined location) whether the transition from plateau surface to valley slopes was rounded or sharp, and convex or concave.

Landscape Unit	Landform Type		
West Landscape	W1	W2	W3
North Landscape	N1	N2	N3
Middle Landscape	M1	M2	M3
East Landscape	E1	E2	

Table 1: Classification of Landforms. Note: The terms in this table are explained in section 2.2

2.2 Landscape Classification

The Mamaku Plateau is characterised by four broad landscape types, listed in Table 1:

1. the West Landscape,
2. the North Landscape,
3. the Middle Landscape, and
4. the East Landscape.

The west and north landscapes are dominated by deep valleys. In the north landscape, the valleys tend to be deep, narrow, steep and V-shaped. The valleys of the west landscape are deep, steep but quite wide. The east landscape is characterised by low drainage density; and the middle landscape is characterised by the absence of river valleys. Figure 1 shows a snapshot of a topographic map of the Mamaku Plateau, with the initial boundaries of each landscape type delineated manually.

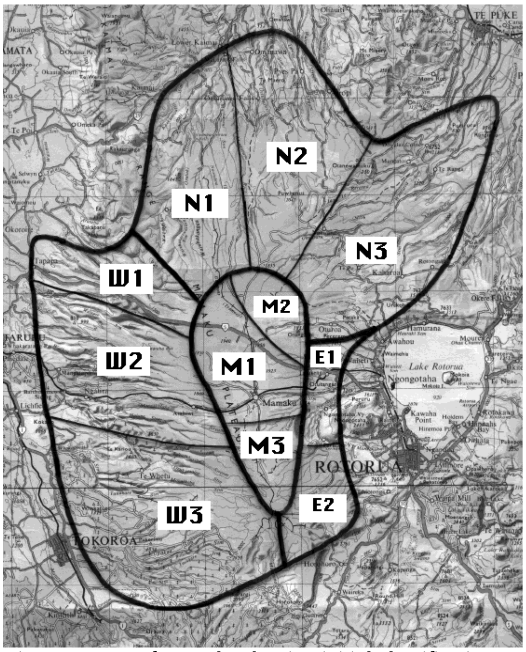

Figure 1: Map of Mamaku showing initial classification

2.2.1 The West Landscape

The West Landscape is characterised by a slightly westwards-dipping plateau surface that is incised by valleys draining westwards in parallel drainage pattern. Close to source, the valleys are steep and V-shaped.

Further downstream, the valleys are wider and deeper, leaving a very dissected plateau surface. Most of the width of the valleys is taken up by fairly flat valley floors. At locations where larger areas of the plateau surface can be seen, shallow dry valleys are present, on top of the plateau surface interfluve.

The West Landscape contains three landform types: W1, W2, and W3. Landform W1 is characterised by a gradual increase in valley width and depth, and contains a slightly lower drainage density. The valleys are less wide and the plateau surface is less dissected. In landform W2 the valleys reach a width of nearly two kilometres in some places. The width of these valleys relates to a long, low-angle, south-facing valley slope.

A special feature on the south-facing slopes is large concave slope segments, elsewhere described as cuspate features (Kennedy, 1994). The valleys in landform W3 are slightly narrower than those in W2, but do have wide valley floors. A special characteristic of these valleys is the presence of numerous rock outcrops, along the valley sides.

2.2.2 The North Landscape

In the North Landscape, the plateau surface dips slightly northwards and is incised by deep narrow valleys, draining northwards in parallel dendritic drainage fashion. The valleys are very narrow and steep, leaving large areas of the plateau surface undissected. On top of the plateau surface, shallow dry valleys, similar to those in the West Landscape, are present.

The North Landscape contains three landform types: N1, N2, and N3. The valleys in landform N1 are shallow, and relatively wide near the source. But further downstream, these valleys become deep gorges, the transition being marked by waterfalls. The valleys in landform N2 are also shallow and wide close to the source; a little further downstream they become deep, narrow and V-shaped. The gorges and waterfalls are present in the lower reaches of the catchment. The valleys in landform type N3 are similar to those in landform N2. However the platforms are distinctly different; the valleys in landform N3 have strong meander curves, whereas in N1 and N2 the valleys are generally straight.

2.2.3 The Middle Landscape

This Landscape is characterised by a nearly flat surface, on which isolated 20-metre high rocks outcrops are present. These tor-like features appear mainly in clusters. Very few small streams flow on top of the plateau surface.

The Middle Landscape contains three landform types: M1, M2, and M3. Landform M1 is characteristic of the Middle Landscape. Landform M2 contains, in addition to the tors, a few small, steep narrow ridges. The latter lie in a predominantly southwest-northeast direction. A few lakes and swamps are also part of landform M2. The plateau surface in landform M3 is not flat but consists of low ridges and shallow valleys in all directions. Most of the valleys are dry, and no specific drainage direction is present. However small streams leave the area in the west.

2.2.4 The East Landscape

The plateau surface in the East Landscape dips quite steeply eastwards, towards Lake Rotorua. A few, fairly straight, small, narrow valleys drain eastwards. Close to the lake, there are no valleys, and the streams meander on the plateau surface. Small shallow dry valleys, as described in the Landscapes West and North, are present on top of the plateau surface.

The east Landscape is subdivided into the landform types E1 and E2. Landform E1 has a parallel drainage pattern. In landform E2, however, irregular domes protrude through the plateau surface resulting in a more complex topography, with a dendritic drainage pattern.

2.3 Verification of Airphoto Analysis

Overall there has been a good correspondence between airphoto interpretation and field observations. The discriminating characteristics of the four Landscapes are consistent with those observed in the field classification.

However the northern-most valleys in the West Landscape contain morphological properties that are characteristic of the valleys in the North Landscape: steep, narrow, V-shaped and feature waterfalls. It was therefore decided to include these valleys into the North Landscape, as shown in the revised classification in Figure 2.

The different landform types within the West Landscape were not easy to recognise in the field. Close to source all valleys are steep and V-shaped and it was not possible to determine which landform type these valleys were part of.

In order to make the classification more suitable for further study the West Landscape was reclassed. The landform types W1 and W3 remained the same.

The different landform types in the North Landscape were not easy to recognise in the field either. Due to dense forest cover, overview was restricted, and it was very hard to discriminate between the different landform types based on field observations alone. In other words, there was more variation within the valleys of one landform than between valleys of different landforms. The landform types of the North Landscape have been reclassed into an upstream landform type N1, a half-way landform type N2, and a downstream landform type N3 (Table 1).

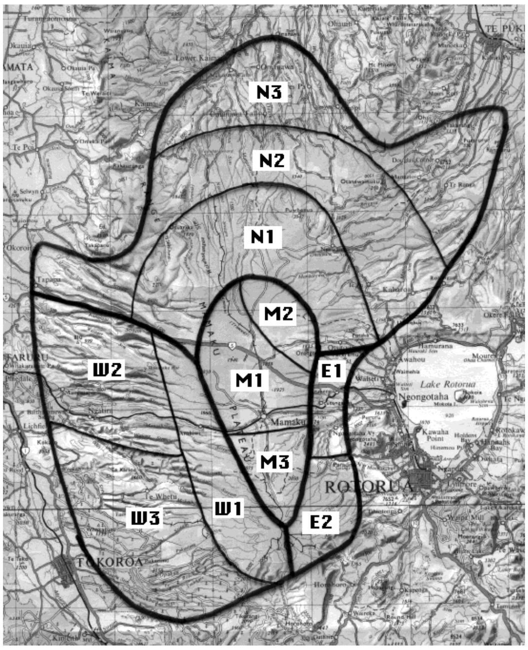

Figure 2: Map of Mamaku showing revised classification

The field observations in the Middle landscape were consistent with the airphoto interpretation. This is probably due to the fact that the main land use in this Landscape is agriculture (rather than dense vegetation), thus providing a good view on the airphotos.

The differentiation of the landforms in the East could not be confirmed in the field. It was not possible to get field access to the landform type E2, so it was difficult to verify the airphoto interpretation for this area.

The revised classification, based on stereoscopy and field observations, gives a good overview of the main Landscape units and landform types on the Mamaku Plateau. However, the reliability of the classification is variable from place to place. Some areas are more easily accessible than others, and as a result field checks could not be undertaken at the same level throughout the whole study area.

Once in the field, it was difficult to get an overview of the landform characteristics in densely forested areas. Therefore, these areas also received modest attention during the airphoto interpretation, as dense forest cover prohibits detailed survey of the microtopography.

To correct for the uneven nature of the reconnaissance discussed above, an additional method of investigation was sought that would be sufficiently unbiased and would give equal importance to all parts of the study area.

3 The GIS classification

3.1 Introduction

In order to make measurements of the morphology of Mamaku using Geographic Information Systems, the topographic data need to be converted into a DEM, representing a three-dimensional model of the landscape. The next step is to select the key areas of interest for the morphological measurements (in this case, the valleys). This is followed by the actual morphometric analysis in which the DEM provides the data for the investigation.

3.2 Digital Elevation Model

The digital elevation data for the Mamaku Plateau were purchased from the Department of Survey and Land Information (DOSLI). The data set consisted of contour lines spaced at 20 metre intervals, for the entire study area. The topographic data were initially converted into a TIN (Triangulated Irregular Network) DEM. The triangulation procedures used in constructing a TIN consists of joining elevation points (spot heights) on the contour lines, to form triangles satisfying the 'Delaunay criterion'. According to the latter, the density of a TIN can vary from one place to another, but should not vary from one area to another within one DEM.

A pilot study was carried out to assess the optimal point density for this topography. In this study the accuracy of four different point densities was assessed using visual checks and quantitative methods recommended by Wood and Fisher (1993). When the tolerance distance is very small between the elevation points used in a DEM, the slope values may become exaggerated in places, because many redundant 'flat triangles' are formed. The resulting DEM would have a step-like appearance. On the other hand, low-density triangulation (with only a small number of elevation points) may result in some steep areas (within a relatively flat surface) being missed in the final DEM.

Because the valleys constitute the primary focus of this research, it was necessary to use a fairly high-density dataset to represent the steep valleys adequately.

3.3 Selection of the valleys

3.3.1 Options within Arc/Info

The TIN-based DEM mentioned in the previous section was converted into a grid (raster) elevation dataset to enable cell-based morphometry of the data.

Arc/Info has three grid-based functions that could be used in this type of geomorphological studies:

- the watershed function,
- the flow accumulation function, and
- the basin function.

The watershed function joins up the neighbouring cells that drain into a designated 'pour-point' cell within a raster matrix. All cells that drain into that specific pour-point belong to the same watershed. However, because the watershed function is cumulative and will include *all* cells that flow into a pour-point, any grid cells situated on the plateau (but within the same matrix) would be bundled indiscriminately with those from the adjacent valleys. In other words, the watershed function in Arc/Info could not be used in the delineation of valleys in this research.

The flow accumulation function calculates for each cell the number of cells that drain into it, thus creating a grid with high and low flow accumulation areas. The high flow accumulation areas can be flagged as valleys. However, a large number of slightly-elevated cells that are part of a valley would appear to have a low flow accumulation and would not be recognised by this function as valleys. In other words, the flow accumulation function in Arc/Info would delineate streams rather than valleys.

The basin function in Arc/Info was also not used, because it produced meaningless results that could not be verified.

It was, therefore, concluded that the current hydrological modelling functions in Arc/Info could not alone be used to identify valleys (rather than streams, basins or ridges). As a consequence, a new algorithm had to be developed for the 'automatic' delineation of valleys from the surface data of the Mamaku Plateau.

3.3.2 A New Algorithm

The Mamaku Plateau has two features that complicate the selection of valleys from the DEM data:

1. The plateau dips at different angles to the north and the west, and consequently the valley floors near the centre of the plateau have a higher elevation than the plateau surface near the north-western margins.
2. There are four rhyolitic domes in the study area that rise above the plateau surface.

To facilitate the selection of valleys, and taking into account these topographic complications, a new algorithm was devised, based on a combination of the following assumptions:

- the valleys will *generally* be steeper than the plateau surface;
- the valleys will *generally* be of lower elevation than the plateau surface;
- the valleys will have a certain *minimum* size.

The first assumption was necessary to separate the steeper valley sides from the nearly flat plateau surface, and a threshold slope angle of 12 degrees was chosen. All cells with a higher slope angle were assumed to be part of a valley system, and cells with slope angles lower than this threshold gradient were assumed to be *plateau* (ie not *valley*).

However, because of the topographic complications mentioned above, it was not possible to find an elevation above which *all* cells would be classified as plateau, and below which *all* cells would be classified as valley. A low-angle threshold would wrongly classify slightly steeper parts of a plateau as valley; and a high-angle threshold would classify less steep cells (inside a valley) as plateau. The fairly low threshold gradient of 12 degrees was finally settled on, which successfully resulted in the selection of nearly all the valley cells within the DEM.

The new valley-selection algorithm was further refined to delete erroneous areas (of plateau cells), as well as to include those gently-sloping parts of a valley that might have been missed in a previous iteration. This final refinement was based on the third assumption mentioned above, where valleys would have a certain minimum size. All selected valley cells were grouped together, and areas smaller than 10,0000 square metres were assumed to be part of the plateau surface, and thus excluded from being a valley. Because the Mamaku Plateau is extensive, even the smallest valleys tend to be at least a few kilometres long. A two-kilometre long valley would consist of 40 cells, each with a 50 metre diameter.

Inclusion of the low angle parts of the valley is based on assumption 2: that the valleys will generally be of lower elevation than the plateau surface. It would have been ideal to find a transitional elevation above which *all* cells were plateau and below which *all* cells were valley. However, because the surface of the Mamaku Plateau is dipping towards the north and west, the valley floors towards the centre of the plateau do have a higher elevation than the plateau surface on the outer margins (especially to the north and west of the plateau).

Other researchers have looked into the classification issue tackled in this research. Mark (1984) and Tribe (1991) addressed the problem of valley classification by comparing each cell in a classification matrix with its immediate neighbours. If a cell was at a lower elevation than its neighbours, it was likely to be part of a valley. However, Arc/Info does not have the facility to process a grid on this basis. On the other hand, Arc/Info does allow the comparison of each cell in one grid with those at the same location in another grid. Consequently to refine the algorithm in this study, a separate grid called Cutoff was created. This grid contained cutoff values for each cell. This cutoff value relates to the maximum elevation at the location of the cell. If the elevation at a specific point is lower than the elevation in Cutoff, the cell is added to the *valley* cells. If not, the cell is assumed to be a plateau cell.

The creation of Cutoff was based on two characteristics of the topography of the plateau:

1. The relief on the plateau surface itself fluctuates within a range of 25 to 50 metres.
2. The valleys are at least 50 metres deep.

The combination of these two characteristics have indicated that in general the valley floors in the plateau are about 75 to 100 metres lower than *the highest point in the surrounding area*. The 'surrounding area' is defined as an area of 4 square kilometres around the cell in question. The area has to be at least 4 square kilometres large, because the widest valleys are 1.5 kilometres wide, and the choice of 4 square kilometres ensures that the maximum elevation used remains part of the plateau surface.

3.3.3 The 'Cutoff' Elevation Points

The selection of the cutoff elevation produced two problems that relate to the special topographic characteristics of the Mamaku Plateau.

1. Four rhyolite domes are present on the Mamaku Plateau, resulting in too many cells being selected as valley near these domes. To overcome this problem, the absolute maximum cutoff elevation was set at 400 metres. To qualify for this cutoff fine-tuning, the elevation of the lowest point in the surrounding area has to be higher than 350 metres. Thus only high areas of the plateau, rather than isolated domes, would be included.

2. The Mamaku Plateau dips more gently in some places than in others. Therefore a low cutoff would have produced an accurate selection in some areas, but would have falsely included parts of the plateau surface in others. Further, a high cutoff elevation would have excluded parts of the valley floor. It was not possible to select the cutoff elevation following the same procedures throughout the study area without the creation of errors. A high cutoff elevation was chosen and another step in the algorithm was written to include those parts of the valley floor that had not been included thus far.

The procedure designed to include the flat valley floors was based on assumption 2: that the valleys will generally be of lower elevation than the plateau surface. First, the cells that were labelled as plateau, but not connected to the main body of the plateau surface were isolated. The elevation of the selected cells was compared with (masked by) the *mean* elevation of the surrounding area:

- If the mean elevation was lower than the elevation of the selected cells, the cells were likely to be part of a valley floor, and were labelled as valley cells.
- If, however, the elevation of the selected cells was equal to, or higher than the mean elevation of the surrounding area, the cells would be labelled as plateau cells.

The integration of all these selection criteria, produced a satisfactory delineation of the valleys. Figures 3-6 represent windows taken from the results of the DEM-based classification discussed in this research.

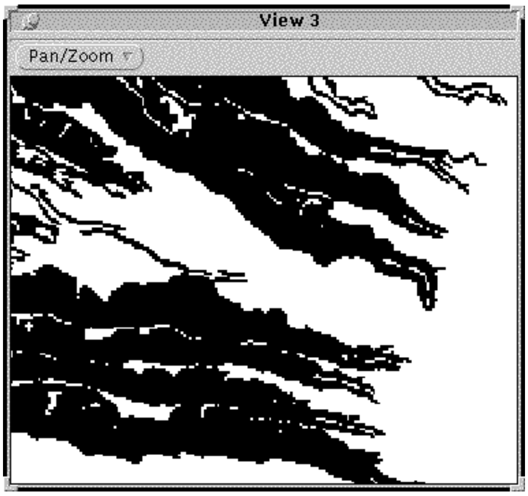

Figure 3: DEM window showing valleys after a 12 degrees threshold

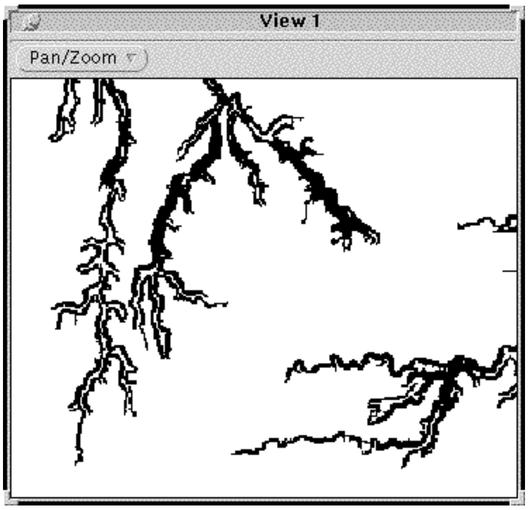

Figure 4: DEM window showing valleys after deletion of small areas

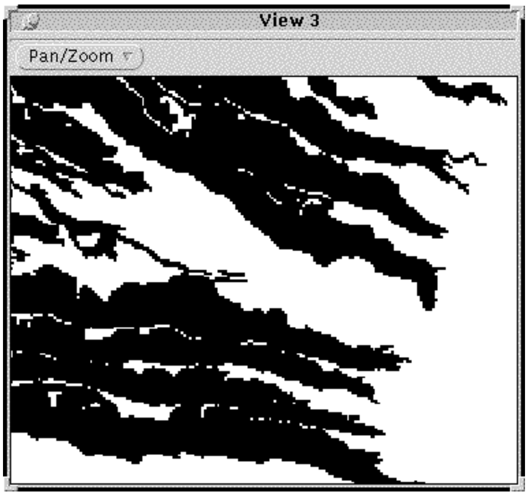

Figure 5: DEM window showing a Cutoff mask

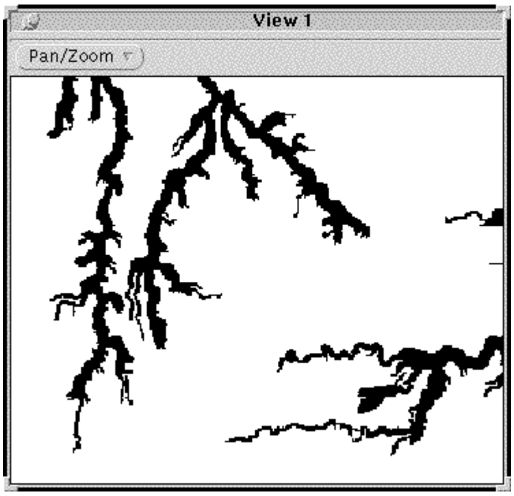

Figure 6: DEM window showing final selection of valleys

4 Conclusion

GIS is a useful tool in the study of landscape morphology when combined with traditional airphoto interpretation, and supported by geomorphological fieldwork.

Arc/Info provides a limited, but useful, range of functions for landscape studies. Many of the hydrological functions available in GIS packages, including Arc/Info, could be adjusted and employed in geomorphological studies.

Despite the limitations of GIS-based terrain analysis, as discussed in this paper, an automatic classification of the valley forms in the Mamaku Plateau was made using a DEM, within an Arc/Info GIS environment. A new algorithm was devised to identify valley systems, from the DEM data.

This study has also undertaken a conventional classification of the Mamaku Plateau's valleys, using stereoscopy to assist in the geomorphological interpretation. The results of all these classifications were compared and it was concluded that the use of a Digital Elevation Model, in conjunction with GIS, would be beneficial in landscape analysis, especially when the findings were backed up by traditional geomorphological inquiries.

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