GIS Analysis of Macro Landform

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Abstract

The automatic classification of macro morphological landforms using GIS and digital elevation models (DEM) was investigated. A process developed by Dikau et al, which automates Hammond's manual procedures, was applied to a cross section of the South Island of New Zealand. Although it produced a classification that has good resemblance to the landforms in the area, it had some problems. For example, it produced a progressive zonation when landform changes from plains to mountains, it does not distinguish open valleys from a plains-mountain interface, and it was affected by micro relief. Also, Hammond's slope threshold was used even though slope was measured differently. Although automating existing quantitative manual processes is an important step in the evolution of automation, definitions may need to be calibrated since the attributes are often measured differently. A new process is presented that partly solves these problems.

Keywords: Geographical Information Systems, GIS, Landform, Classification.

Introduction

Within the fields of geomorphology and hydrology, the automatic mapping of morphologic landforms is of interest for modelling erosion (Dikau et al., 1991), providing watershed information (Band, 1986), and mapping land components (Dymond et al., 1995). A morphologic landform classification is also of interest to climatologists for developing climate models, especially in topoclimatology (Geiger, 1971), and for landscape researchers wanting to classify landscape character (Linton, 1970). It is this latter perspective that motivated this research because of the need to improve on present processes for mapping landforms. Macro landforms are defined - using a scale proposed by Dikau (1989) - as landforms that are greater than 10 km^2 and less than 1000 km^2 in size.

In the past, manual methods were used for classifying landforms including those methods developed by Hammond (1954 and 1964), Wallace (1955), Linton (1970), and Crozier and Owen (1983). Hammond's method is based on explicit, quantitative procedures that use slope, relative relief, and profile type to define different landforms. It has also been the most widely applied, and Wallace's, and Crozier and Owen's methods have been derived from Hammond. In effect, Hammond's process has become the de facto standard.

Hammond (1954 and 1964) identified landform types for the United States by moving a square window, about 9.65 x 9.65 km (6 x 6 miles; about 93 km^2 or 36 square miles) across a 1:250,000 scale topographic map with contour intervals varying from 50 feet to 200 feet. The window was moved in increments of 9.65 km with no overlap. For each position of the window, Hammond calculated:

1) percentage of area where the ground was flat or gentle (less than 8 percent slope),
2) relative relief (maximum minus minimum elevation), and
3) profile type (relative proportion of flat or gently sloping terrain that occurs in upland areas).

He then grouped the resulting values for all samples into four, six, and four classes respectively. Hammond then used the unique combination of these three attributes to form the landform sub-classes. However, with the three attributes and their associated classes there were 96 possible landform sub-classes to be identified. Hammond used only 45 sub-classes that were common in the U.S. He used a three tier hierarchy of landform units based on grouping the sub-classes into 24 landform classes, and then further grouping the classes into five landform types. The five landform types were Plains, Tablelands, Plains with Hills or Mountains, Open Hills and Mountains, and Hills and Mountains. Hammond generalised his results by merging areas smaller than 2072 km^2 into adjacent units to avoid cluttering a 1:5,000,000 map.

Dikau et al. (1991) developed automated processes that virtually simulate Hammond's manual method. This process was investigated by applying it to a local setting, and testing its sensitivity to scale and different parameter thresholds. An improved process described here, has been developed that identifies open valleys, and that is also adapted for the New Zealand setting.

Automated classification

Computers have been used for extracting terrain parameters from digital elevation models (DEM) for at least the last twenty years. Collins (1975) discussed different algorithms that could be used for identifying features such as tops of hills, bottoms of depressions, watershed or depression boundaries and areas, storage potential of watersheds, slope, and aspect. Since the development of commercial GIS and national spatial databases in the mid 1980s there has been a resurgence of interest in this field (Dikau, 1989, Weibel and DeLotto, 1988, Dikau et al., 1991, and Moore et al., 1993).

Dikau et al. (1991) developed automated processes that essentially simulate Hammond's manual method and tested them in New Mexico using a 200m cell size DEM. Given that Hammond's classification has become the de facto standard for morphological landform, this was a significant development. The main difference between the Hammond's manual approach and Dikau's automated approach is the number of classes identified and the generalisation. Hammond's process can provide as many as 96 landform units, but it identifies only the more common ones (perhaps this was required for practical reasons). The automated approach identifies all 96 landform units. Hammond's process also merged areas smaller than 2072 km^2 into adjacent areas so that the information could be generalised on a 1:5,000,000 scale map. The automated approach does not do this. Hammond's approach uses a 9.65 km by 9.65 km window that moves along in 9.65km steps so the entire area within the window is generalised to one landform class. With the automated approach, neighbourhood functions as described by Tomlin (1990) are used. Dikau et al. used a window size of 9.8km by 9.8km, that moved in 200m steps. For each step, a generalization of the window was calculated and this information was assigned to the focal cell (the cell in the centre of the window). By moving in 200m increments and defining a new focal cell with each move, Dikau et al's automated process is therefore significantly more accurate.

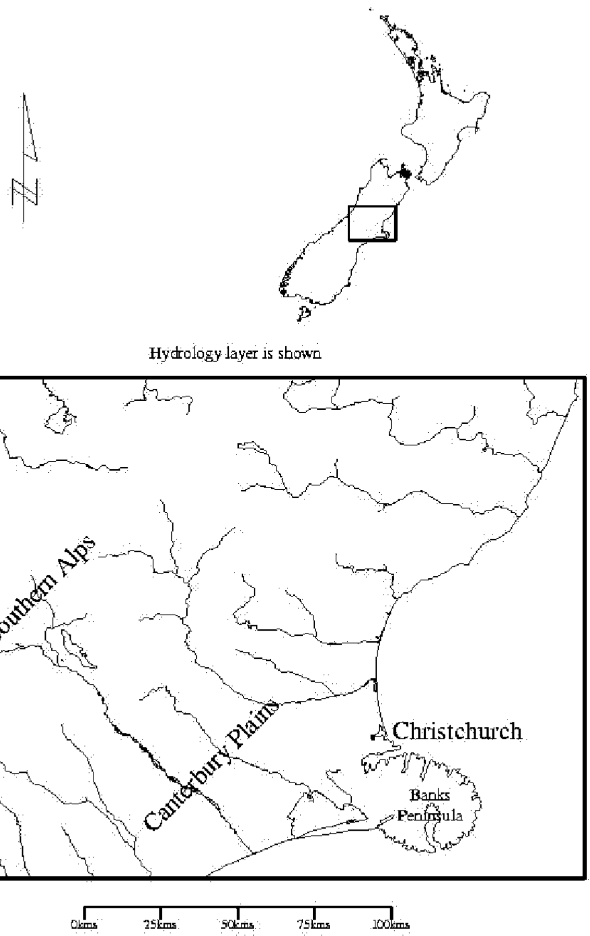
Study Area

This automated process was tested on an approximately 170 km wide strip across the South Island of New Zealand. The study area (Figure 1) contains a large variety of landforms. On the east coast are the extensive Canterbury Plains; the Southern Alps, with elevations of as much as 2500m, separate the eastern and western areas, and on the west coast there is a relatively narrow strip of flat and hilly landforms. Banks Peninsula on the east coast is an extinct volcano with hilly to mountainous topography.

Method

ARC/INFO, a Sun Sparc 10 workstation, and a 100m contour database with spot heights were used in the study. The contour database was converted to a 200m grid DTM using TIN, and a TIN to grid function. Once a DEM was created, the process was similar to that developed by Dikau, et al. (1991). The same class intervals, codes and labels were used. Figure 2 shows the different stages of the process for the Banks

Figure 1 Study Area



Peninsula region. From the DEM, slope was calculated on the basis of the elevation difference of the neighbouring cells (3 X 3 moving window) and the cell size. To be consistent with Hammond and Dikau, slope was expressed as a percentage. Each cell was then classed as flat if less than 8 percent, otherwise it was classed as sloping. The slope percent classes were calculated by assigning the value 100 to areas that were sloping and the value 0 to where it was flat, then applying a focal mean function with a neighbourhood analysis window (NAW) of 5600m. Relative relief was calculated from the DEM using a focal neighbourhood range function and the 5600m NAW. A circular pattern results because of the influence of high points, which affect the whole of the circular NAW. The relative relief values were then classed into the same intervals used by Dikau, et al. (1991).

Profile type was used to determine whether the flat areas were above or below the surrounding terrain (i.e. in upland or lowland profiles), and used principally for identifying tablelands. Upland and lowland profiles were identified by first calculating the maximum elevation using a focal neighbourhood maximum function on a DEM. The height of the central cell was subtracted from this. If this was less than half of the relative relief, then the central cell was identified as upland, otherwise the central cell was lowland. The resulting upland and lowland coverage was then overlaid with a slope coverage to identify upland and lowland flat areas. The percentage of gentle sloping areas that were in lowland profiles was then calculated using a focal neighbourhood mean function.

Once these three parameter layers were identified, their unique combination identified 96 potential subclasses. The higher hierarchic levels (landform classes and types) were determined by grouping the subclasses. Figure 3 shows the resulting landform classes for the study area. The processing time was about two hours.

One difference between the process developed in this study and that developed by Dikau et al. (1991) was the shape of the NAW. They used a square NAW, while the process developed here used a circle. A circle seems more appropriate than a square because the boundary of a circle will always be of equal distance to the focal point. For the NAW to be the same area as that used by Dikau et al. and Hammond, the radius of the NAW in this study was 5529m. This radius was rounded to a multiple of the cell size,

Figure 2 Different Stages of the Automated Process

* = Continuous grey scale, with dark as low and bright as high.

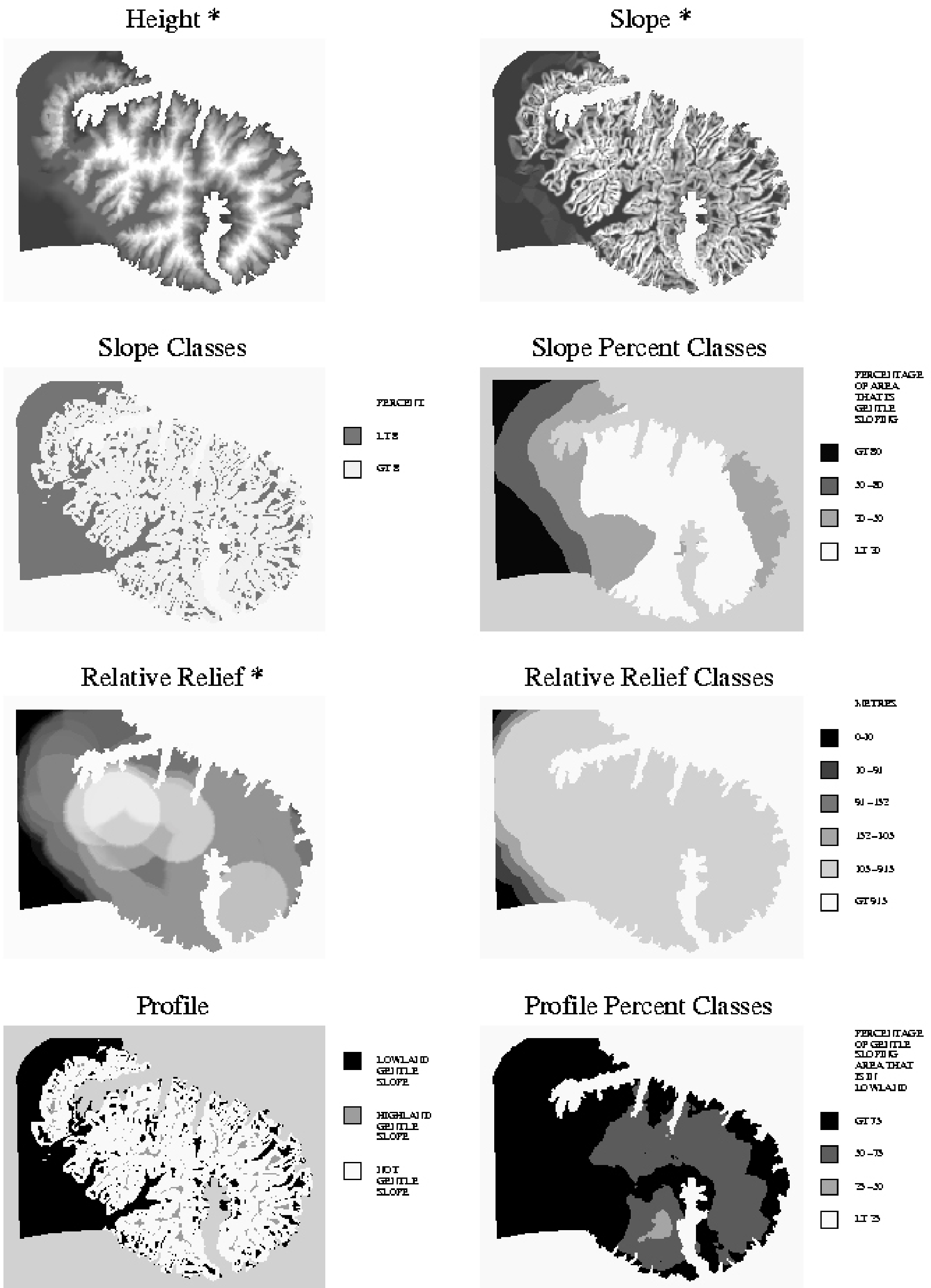
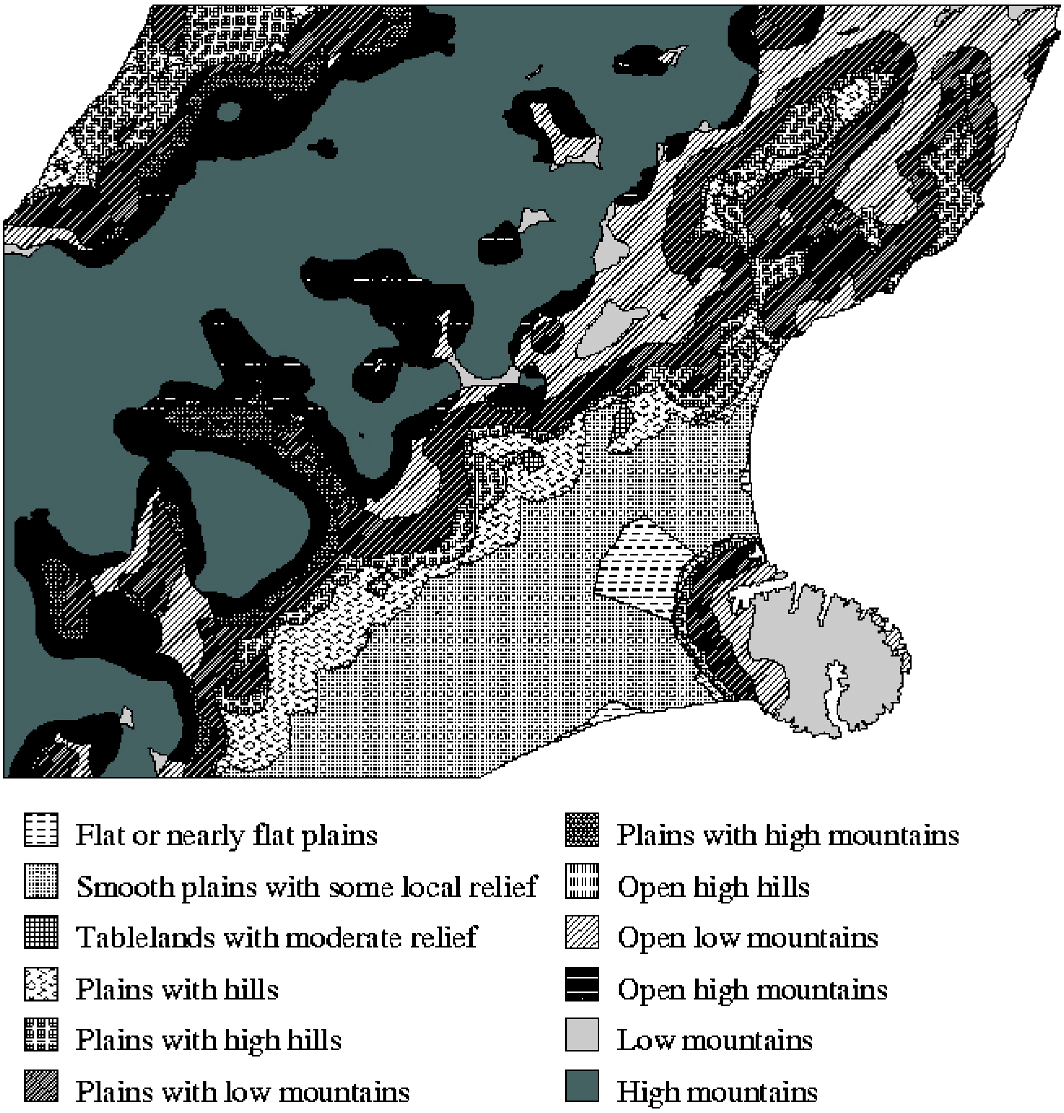


Figure 3 Landform Classes



which with a 200m x 200m cell size became 5600m. The automated process produced a classification that resemblance the landforms of this area, and was similar to Wallace's (1955) classification of the same area (which was based on Hammond's process). The automated process, however, does have some problems.

One problem is the progressive zonation as the distance from the areas of relief increases. For example, in Figure 3 the area between the Canterbury Plains and Banks Peninsula has a series of classes going from "plains" to "plains with hills" to "plains with high hills" to "plains with low mountains" to "low mountains". This reflects a progressive change in relative relief as you get closer to Banks Peninsula and is not a particularly desirable result. It is not how you would expect people to conceptualise the landforms in this area. It is desirable to have a composition class that incorporates the change from plains to mountains but this should not be done with progressive zonation.

A second problem with this automated approach is that some areas which have quite different macro landforms are being classified the same. This is particularly true with areas classified as “open”. Some areas are “open” because they are at the interface between the plains and the mountains, while other areas are “open” because they are in broad valleys, or on flat spurs. The process has not been able to distinguish between these different landforms. On the north-eastern side of Banks Peninsula, an area is classified as “open low mountains” because of the presence of large flat spurs in this region. It does not seem appropriate that this area should be classified the same as areas that are at the interface between mountains and plains. The operational definition is unable to distinguish some objects that are of micro or meso scale, such as flat spurs, from objects that are of macro scale, such as plains.

Related to this scale issue is slope. Slope is very dependent on the scale at which it is measured. This process uses the same slope criteria as Hammond (8 percent), but measures slope at a different scale and therefore, in effect, adopts a different slope criterion. It is necessary to determine whether this new slope criterion is appropriate.

Even though this automated classification has problems, it has important advantages over manual processes: it is totally explicit and that it can be applied to large areas to produce results relatively quickly. This automated approach can also be viewed as just the start of a process that can evolve as better techniques develop. Because this process is explicit, it can be analysed and improve upon.

A new automated landform classification process

To address the problems with, Dikau’s et al. classification process a new process was developed that partly solves these problems. A 500m cell size was used because of the advantages of increased processing speed, and because it was considered to be adequate for the spatial accuracy needed for a macro landform classification.

Figures 4 and 5 illustrate the different steps in the process. Starting with a DEM, a slope grid is derived as in Dikau’s et al. (1991) process. This slope grid is classified as flat if it is less than 4 percent, otherwise as non-flat. The small flat areas that are less than 10 km^2 in size are converted to non-flat areas to produce a grid of macro slope classes. This prevents micro relief, such as flat spurs, from affecting the classification. The next three steps identify open valleys. An open valley is a large flat area that has relief on opposite sides. To recognise this pattern, expand and shrink functions are used. These functions actually expand or shrink a specified zone by a specified number of cells. Areas that have been identified as non-flat are expanded by 3000m (with a 500m cell size this corresponds to 6 cells). This is then shrunk 3000m. The effect of these two steps is that flat enclosed and semi-enclosed areas (open valleys) that are less than or equal to 6000m (2 X 3000m) wide become non-flat. Open valleys can then be identified by using a conditional statement on the macro-slope classes grid and the shrunken grid; i.e. if a cell is flat in the macro-slope classes grid and is not in the shrunken grid then it is an open valley. For an area to be classified as open valley it also had be more than 10 km^2 in size. The 6000m valley width threshold was decided upon after experimentation. If the maximum valley width criterion is set too high then some large basins become identified as open valleys (Fjords are not identified in this classification because this is a morphologic rather than a genetic classification).

Relative relief was determined using Dikau’s et al. process but the classes were slightly different. For areas that were previously identified as non-flat, the relative relief was classified into 6 classes to produce a relief type grid: 0 - 150m = low hills, 150 - 600m = hills, 600 - 900m = high hills, 900 - 1500m = mountains, and above 1500m = high mountains. These relative relief classes are intended to reflect how New Zealanders conceptualise terrain, although there is very little substantive evidence to suggest how this is. The Banks Peninsula region is classified as high hills by Glasson (1991) in a visual assessment study. A relative relief interval of 600-900m achieves component being examined was high for this cell.

Figure 4 Different Stages of the Automated Process (Brabyn)

* = Continuous grey scale, with dark as low and bright as high.

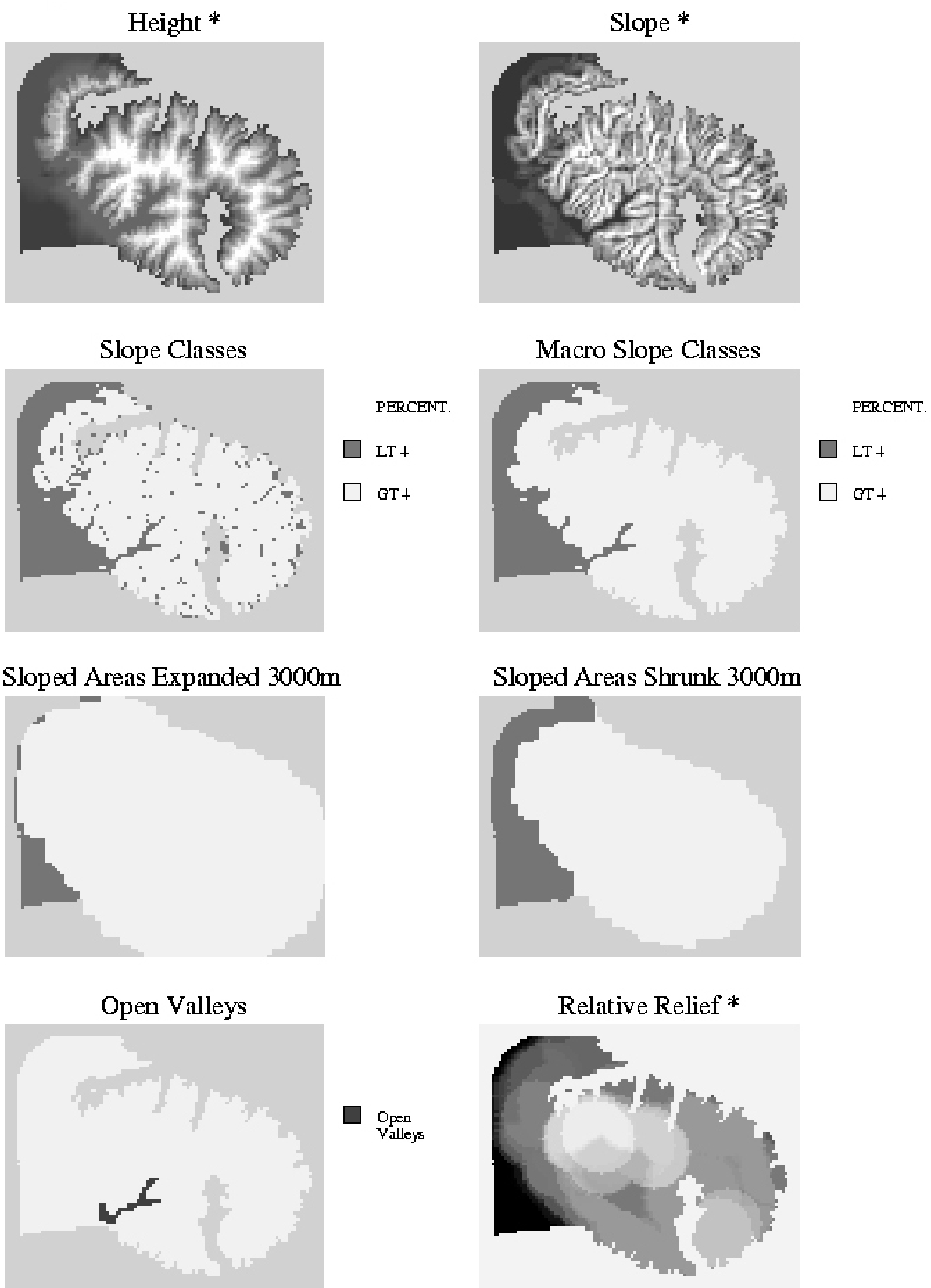


Figure 5 Different Stages of the Automated Process (Continued)

* = Continuous grey scale, with dark as low and bright as high.

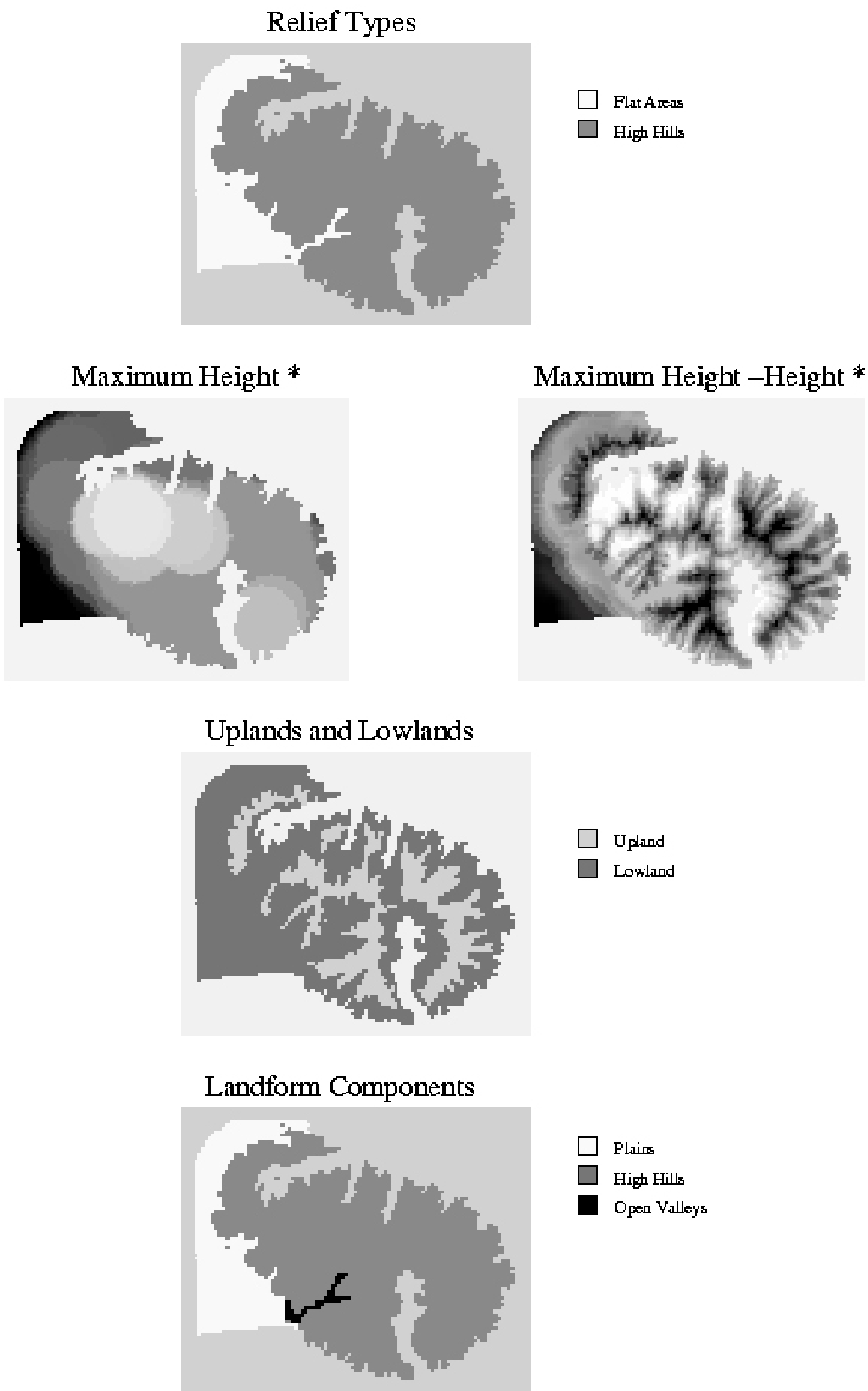


Figure 6 Landform Components

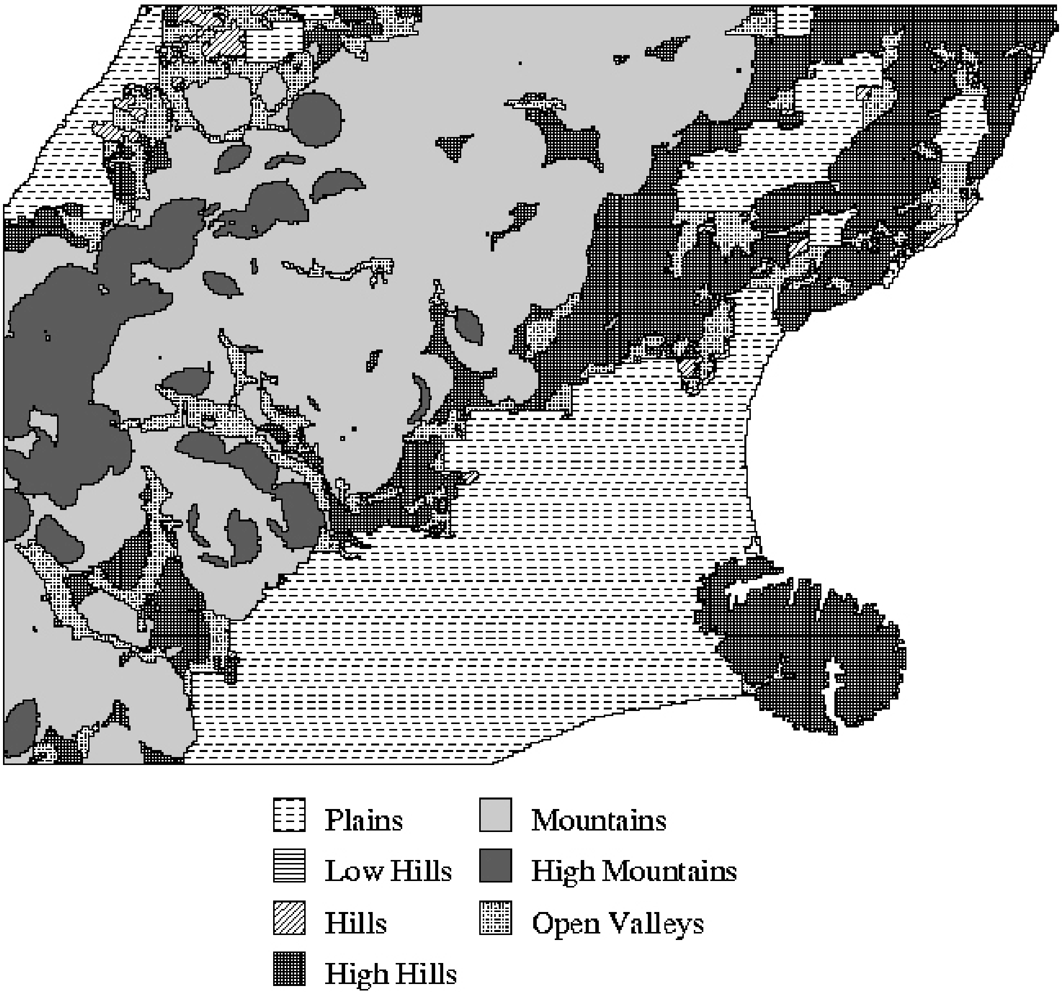
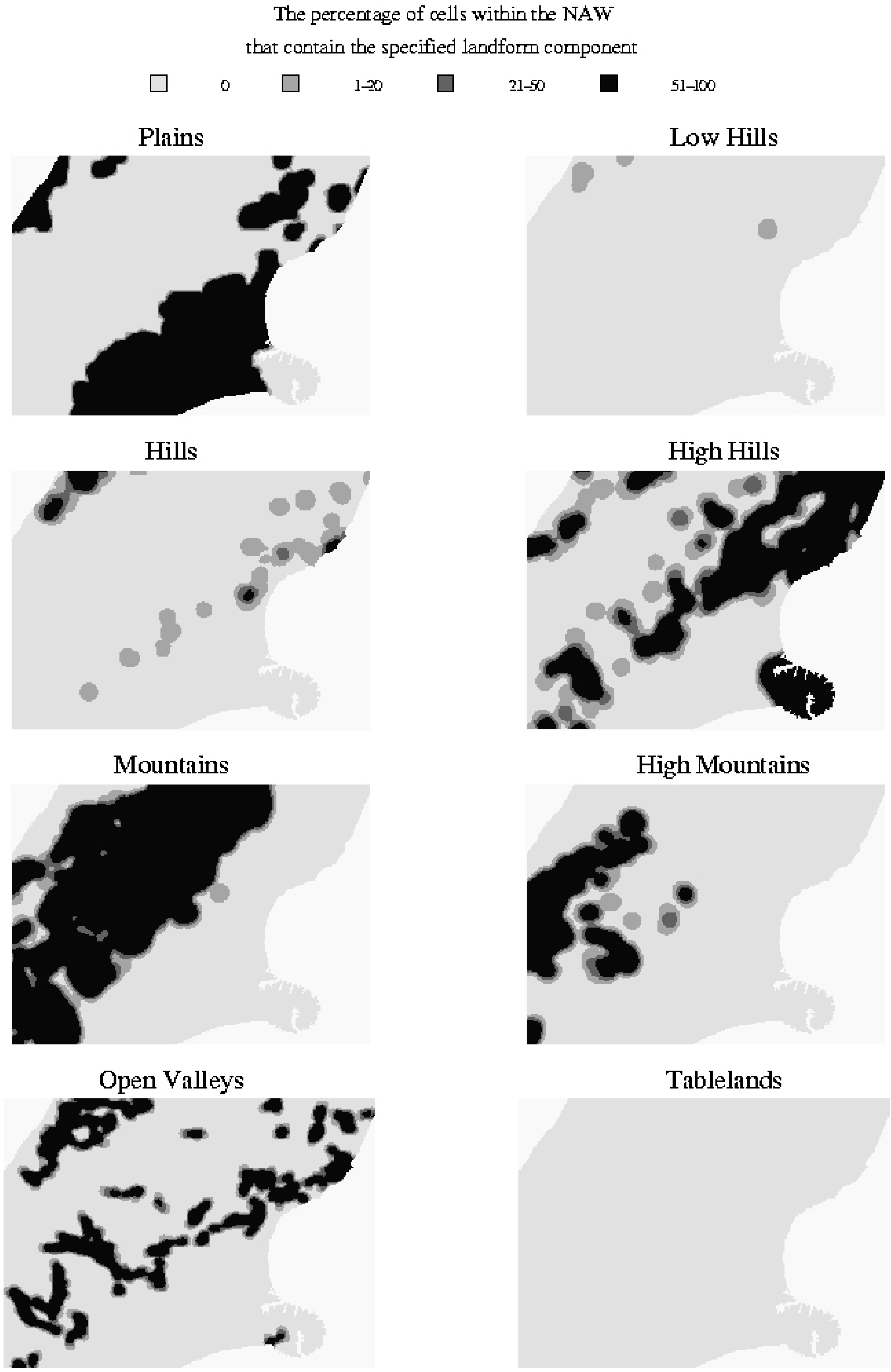


Figure 7 shows the output after the focal mean values had been placed into class intervals. The effect of these steps was that the spatial influence of each component within a 3000m radius could be expressed. The value 100 was used instead of, say, 1 to avoid the use of floating point coverages. Floating points require more memory because they not only require more bytes of storage, but also give an increased number of unique values, so compression techniques do not function well. The particular class intervals used were chosen so that a high range of influence classes could be expressed without having too many classes.

These eight spatial influence grids were then overlaid to produce a new grid that contained unique combinations. Since there were eight grids being combined and each grid had the possibility of four different classes, then the combined grid had the possibility of 65,536 unique classes. However, there were only 613 unique combinations in the study area. From this combined grid, landform compositions could be identified. When coverages are combined in ARC/INFO, information on all the input grids was retained in the combined output grid. Each unique combination then had information on the spatial influence of all the different landform components. The attribute table of this combined grid was queried, and landform compositions were identified. In ARC/INFO this can be done in ARCPLOT. For example, a class called "plains/mountains" can be identified by selecting areas where the spatial influence of mountains (or

Figure 7 The Spatial Influence of the Different Landform Components



plains) is above a specified threshold. The threshold used was 20 percent, i.e., a particular landform component needed to be present in more than 20 percent of the area in the NAW. It was necessary to decide which components dominated over other components. For example, if an area is influenced by mountains and plains but there is also an influence of low hills, is the influence of low hills significant enough to warrant a separate class consisting of mountains, low hills, and plains? Generalisation using logical statements is needed or there will be too many landform classes.

This process identifies 22 different landforms. These are shown in Table 1 under level 1. Not all of these landforms existed in the study area. The resulting landform classification is shown in Figure 8.

The landform classification can be easily generalised by grouping different classes. This was done to produce six different levels of generalisation. The way the different classes were grouped is shown in Table 1 and Figure 9 shows graphically the effect of different levels of generalisation. The shading is the same as used in Figure 8.

This new process produces a landform classification that does not have the same problems as that developed by Dikau et al. (1991). The interface between relief and plains is not identified as a progressive zonation, valley floors are distinguished, and micro relief does not alter significantly the outcome. This process is sensitive to cell size. When 200m cells are used, the agreement with 500m cells is 89 percent. This is caused by the effect of cell size on slope and also because cell size also effects the original DEM, which has subsequent effects on relative relief measurements.

The use of a 3000m search radius for determining the spatial influence of different components can be questioned. There has been no cognitive research that

<table>
<tr><th>Level 1
(22 classes)</th><th>Level 2
(12 classes)</th><th>Level 3
(9 classes)</th><th>Level 4
(6 Classes)</th><th>Level 5
(4 Classes)</th><th>Level 6
(2 Classes)</th></tr>
<tr><td>Plains</td><td>Plains</td><td>Plains</td><td>Plains</td><td>Plains</td><td>Plains</td></tr>
<tr><td>Plains Low Hills</td><td rowspan="3">Plains Hills</td><td rowspan="3">Plains Hills</td><td rowspan="3">Plains Hills</td><td rowspan="8">Hills</td><td rowspan="20">Not Flat</td></tr>
<tr><td>Plains Hills</td></tr>
<tr><td>Plains High Hills</td></tr>
<tr><td>Low Hills</td><td>Low Hills</td><td rowspan="3">Hills</td><td rowspan="5">Hills</td></tr>
<tr><td>High Hills</td><td>Hills</td></tr>
<tr><td>Open Valley Low Hills</td><td>High Hills</td></tr>
<tr><td>Open Valley Hills</td><td rowspan="2">Open Valley Hills</td><td rowspan="2">Open Valley Hills</td></tr>
<tr><td>Open Valley High Hills</td></tr>
<tr><td>Mountains</td><td>Mountains</td><td rowspan="2">Mountains</td><td rowspan="5">Mountains</td><td rowspan="7">Mountains</td></tr>
<tr><td>High Mountains</td><td>High Mountains</td></tr>
<tr><td>Open Valley Mountains</td><td rowspan="3">Open Valley Mountains</td><td rowspan="3">Open Valley Mountains</td></tr>
<tr><td>Open Valley High Mountains</td></tr>
<tr><td>Plains Mountains</td></tr>
<tr><td>Plains High Mountains</td><td rowspan="2">Plains Mountains</td><td rowspan="2">Plain Mountains</td><td rowspan="2">Plain Moun-tains</td></tr>
<tr><td>Tablelands Plains</td></tr>
<tr><td>Tablelands Low Hills</td><td rowspan="4">Tablelands Plains</td><td rowspan="4">Tablelands Hills</td><td rowspan="5">Tablelands</td><td rowspan="5">Tablelands</td></tr>
<tr><td>Tablelands Hills</td></tr>
<tr><td>Tablelands High Hills</td></tr>
<tr><td>Tablelands Mountains</td></tr>
<tr><td>Tablelands High Mountains</td><td>Tablelands Mountains</td><td>Tablelands Mountains</td></tr>
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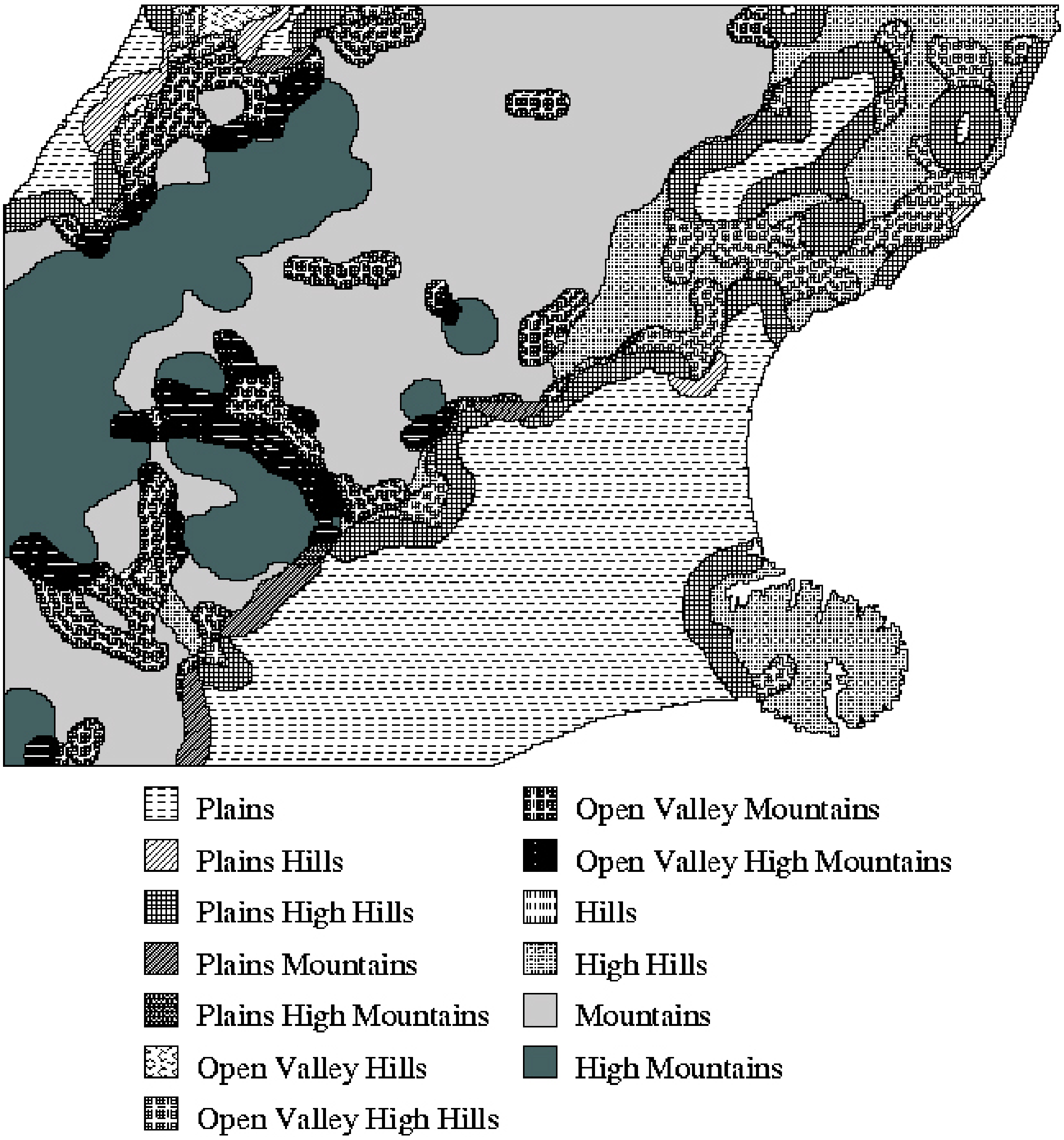
Table 1 Generalisation of Landform Classes

Figure 8 Landform Level 1 (Brabyn)

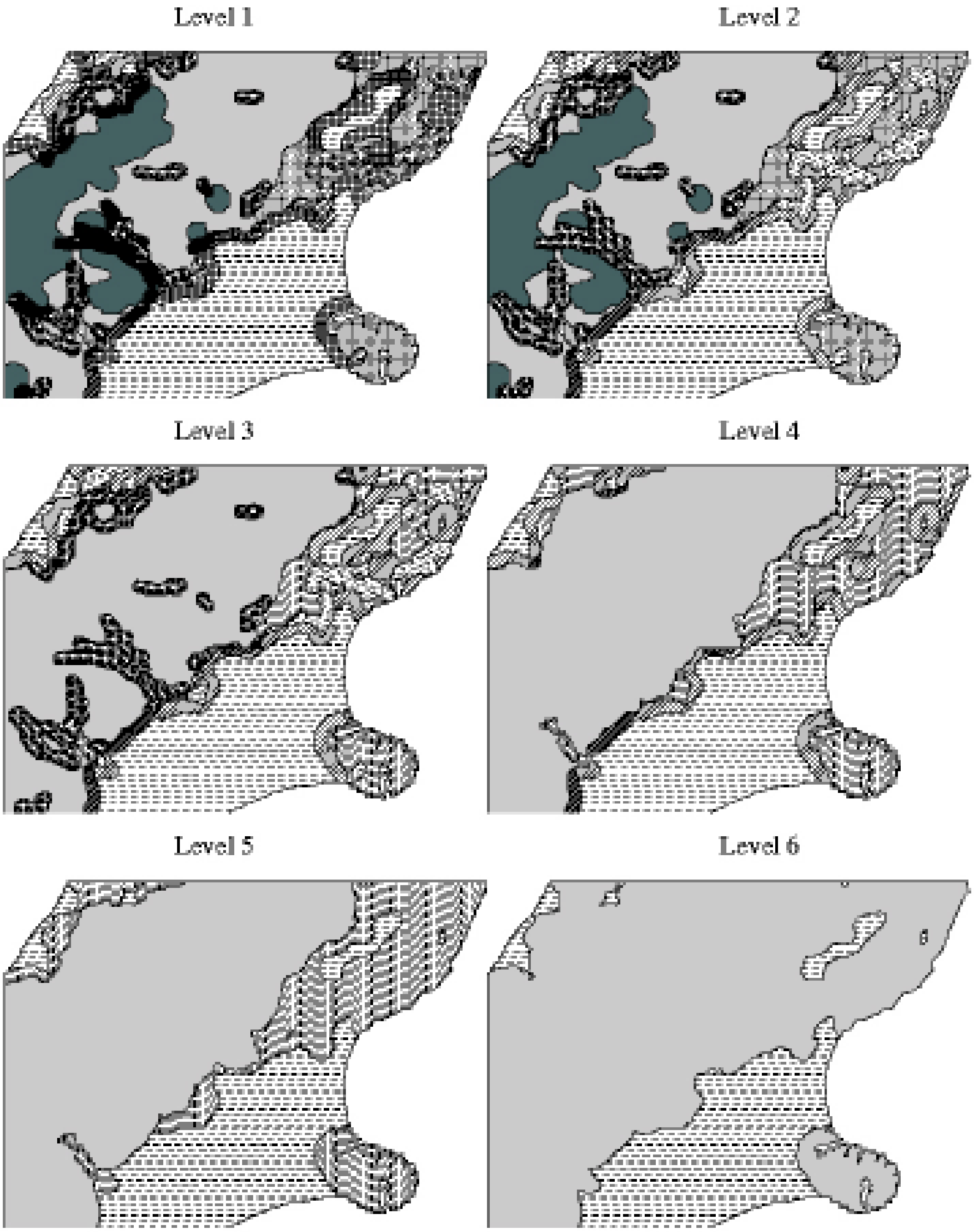


can be used for determining what spatial influence different components of the landform have on people's conceptualisation of the landform. One could argue that this figure should not be static. Some components, such as high mountains, have more spatial influence than other components, such as low hills. The use of context dependent NAWs could be incorporated into the process.

A New Zealand Macro Landform Classification

One advantage of an automated GIS process for classifying landforms is that once it has been developed and tested it can be easily applied to other areas. The process developed in this study has been applied to the whole of New Zealand producing a classification that shows the macro landforms. The main problem with applying the process to the whole of New Zealand was accessing suitable data as 100m contour data in New Zealand is unfortunately

Figure 9 The Effects of Generalisation on Landform



prohibitively expensive. Slope information from the Land Resource Inventory was used and relative relief was calculated from ESRI's Digital Chart of the World terrain data. The New Zealand macro landform classification can be viewed on the Internet (Brabyn, 1997).

Conclusions

Automating landform classification is an interesting challenge. It produces classifications that have a good resemblance to those of manual methods, and because definitions are explicit they can be easily identified, questioned, and improved. This has been demonstrated with Dikau's et al. (1991) process, and several improvements have been made. Although automation of existing quantitative manual processes is an important step in the evolution of automation, it needs to be remembered that definitions may need to be calibrated because the attributes are often measured differently. This is true of slope measurements. The effects of scale and generalisation also need special attention. There are opportunities for improving the process with the use of more context dependent definitions, and the identification of more objects (e.g. conical volcanoes), but this may make the process overly complicated.

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