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Prediction Of Areas Prone To Lightning Ignition

Richard H.D. McRae

ACT Rural Fire Service, PO Box 3587, Manuka, ACT 2603.
Tel. 61-6-295 5751; Fax 61-6-293 1601

Abstract. A method for handling lightning-caused ignitions as part of a comprehensive fire hazard assessment procedure is presented. The locations at which lightning ignitions tend to occur have always been difficult to predict, and do not correlate with usual environmental factors. The model described here uses geographic information system techniques to remove large-scale trends in elevation. The meso-scale residual can be used to predict sites that are prone to lightning ignitions. The model is compared to historic records of lightning ignitions for the ACT, and is found to work very well. A range of other uses for the technique in fire management are discussed.

Keywords: Lightning ignition; GIS; Hazard; Modelling; Australia.

Introduction

Lightning has always been a major cause of fires in Australia, and was the major cause before the arrival of Man (Kemp, 1981). Today it remains the main cause in remote regions, such as the Western Bushfire Zone of Queensland, where Luke & McArthur in 1978 reported that it caused 80% of all fires. They are the main cause of damaging fires in remote parts of south-east Australia, where detection is difficult and access for suppression is awkward. These fires have been the driving force behind much public land fire protection planning, including the extensive system of fire trails built throughout the eastern highlands since 1939. About 5% of all fires in the Australian Capital Territory[1] (ACT) are caused by lightning strike, while these account for about 20% of the total area burnt.

The ACT Rural Fire Service has the responsibility of preventing the outbreak and spread of fire in the Territory and of protecting life and property from fire. Generally the Service responds to all fires reported outside the built-up area of Canberra (population 290,000).

Lightning ignitions may be addressed by fire managers at three levels. The first (reactive) involves guiding suppression forces by estimating where fires may have started with the actual passage of a storm system, using ground and aerial reconnaissance, electronic lightning detectors and modelled fuel state. The second (proactive) involves setting readiness levels by predicting what sites would support a fire should a storm system pass over in the near future, using weather forecasts and observations on paths generally followed by storm systems and modelled fuel state. The third (statistical) involves assessing, in a general sense, areas that are prone to lightning ignitions as a long-term guide to land-use. This approach has suffered from a lack of suitable algorithms, and is addressed by this study.

An important tool for fire management, that the Service has implemented, is a comprehensive fire hazard assessment procedure, allowing efficient hazard reduction or removal and a comprehensive guide to those planning land-use or recreation facilities. The hazard assessment procedure adopted in the ACT is based on an heirarchical series of models within a geographic information system (GIS) to calculate a spatial coverage of Fire Hazard Index (FHI). The major inputs to this include an Ignition Probability Index (IPI). The IPI considers both fires caused by man and natural fires (the natural ignition index, or NII). For the ACT the NII is expected to be solely due to lightning striking dry fuels.

This present study is the result of work aimed at finding an algorithm to tackle prediction of the spatial distribution of the NII based on extrapolating from correlations between a limited set of known ignitions and geographic factors. With a similar intention, Minko (1975) studied 109 lightning strikes in a pine plantation in northeast Victoria. He concluded that strike locations were related to position in the planting compartment but not to aspect, topography or elevation. These strikes only

[1] The Australian Capital Territory is situated at 149° 00'E, 35°30'S, and covers 235,000 ha.

resulted in 3 fires, which he concluded reflected the same trends. A less detailed analysis by van Wagentonk (1991) for Yosemite National Park, in the U.S.A., found only a few general trends in spatial patterns for lightning strikes.

The Service uses a grid-cell based sub-set of a geographic information system, based on the PREPLAN system (Kessell, Good and Potter, 1982), for fire hazard assessment as well as for fire management and planning. The important benefit from using GIS techniques is that the amount of data processing involved in many spatial analyses is beyond the capacity of other methods, especially manual ones. The FHI is intended to be a dynamic process, with as many of its inputs as possible treated as geographic variables. It also allows speedy testing of new ideas and updating of the algorithms.

Careful mapping of records of past lightning-caused fire ignitions revealed little obvious pattern. It was decided to use GIS techniques to check in detail for any less evident patterns. The observation was made that an intermediate step in a topographic unit classification model (recently developed by the author) could explain most of the pattern, so much so that the effort of developing a predictive model seemed warranted. This involved removal of micro- and macro- scale variation of elevation, leaving only the meso-scale residual. It appeared that most ignition points fell on or near the zero residual contour.

To explain further, the land surface may be thought of as the sum of a series of surfaces, each of which represents the variation at different scales: the micro-, meso- and macro-scales. The micro-scale covers the effects of features smaller than 100 m. The meso-scale covers the effects of basic terrain features, such as hills, ridge-tops, gullies, etc. The macro-scale covers the effects of all larger terrain features and regional trends. Figure 1 shows a generalised example of the process.

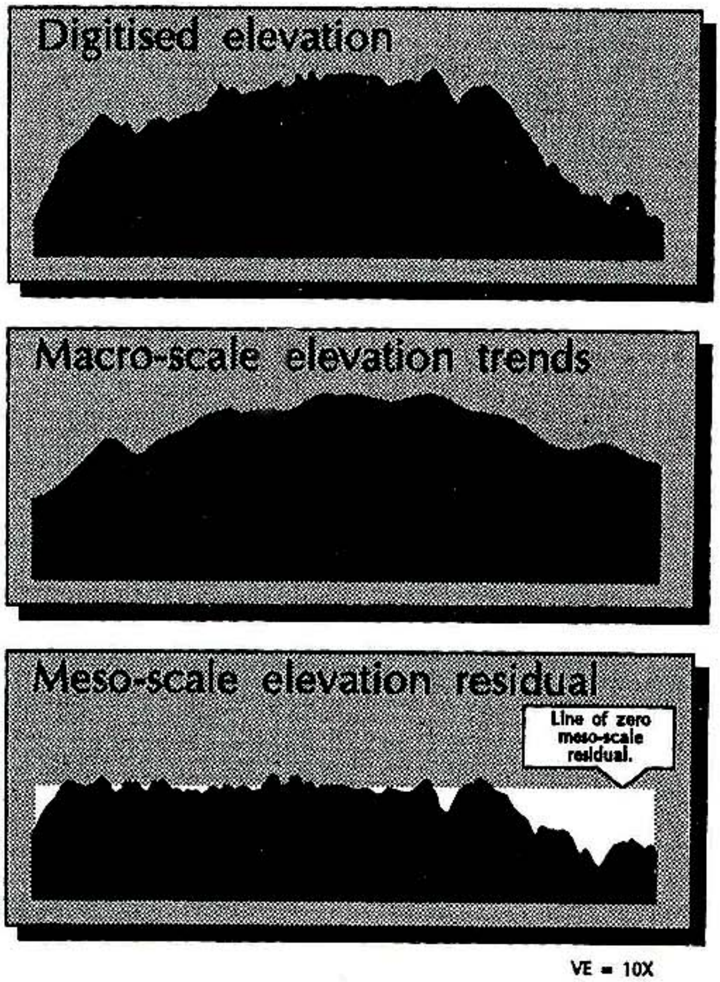


Figure 1. Generalised example of the generation of meso-scale elevation residuals. Digitised elevation already excludes micro-scale variations. The meso-scale residual is the result of subtracting the macro-scale trends from the digitised elevation. Note that the two-dimensional cross-section used cannot show all of the influences acting over the three-dimension land-surface.

Methods

All work to date on this project has been done in the middle of the range of operational scales for land managers in the ACT. In this case the operational scale is 1:100,000 and the base resolution is around 100 m.

The Model

The model requires the identification of all sites with zero meso-scale elevation residual. The micro-scale residuals do not show up in 1:100,000 scale mapping, the source of the elevation data, and so may be ignored. In other words, the cartographers have previously filtered them out.

The method used, the *detrending* model, requires generation of the macro-scale surface through interpolation between a set of spot heights, then subtracting this from the digitised elevation surface to leave the meso-scale surface (*or residual*). The interpolation involves the noting of the spot heights at any main saddles or "passes". These are large features with uphill slopes in two opposite directions and downhill slopes in the two directions in between. There is no assumption about slope steepness. Saddles due to geological discontinuities, earth movements and human activities are ignored. A contouring procedure is then used to interpolate between the spot heights, generating a surface that includes all of the saddles and which resolves ambiguities by following the general trends in the land surface (a generalised map for the ACT is given in Figure 2). For working purposes in southeast Australia a minimum horizontal radius of curvature of 200 m, a modal radius of curvature of 4000 m and a maximum grade of 1 in 4 may be applied to this surface (with occasional exceptions allowed). It is worth noting that depressions are permitted in this surface - their actual drainage outlets are meso-scale features.

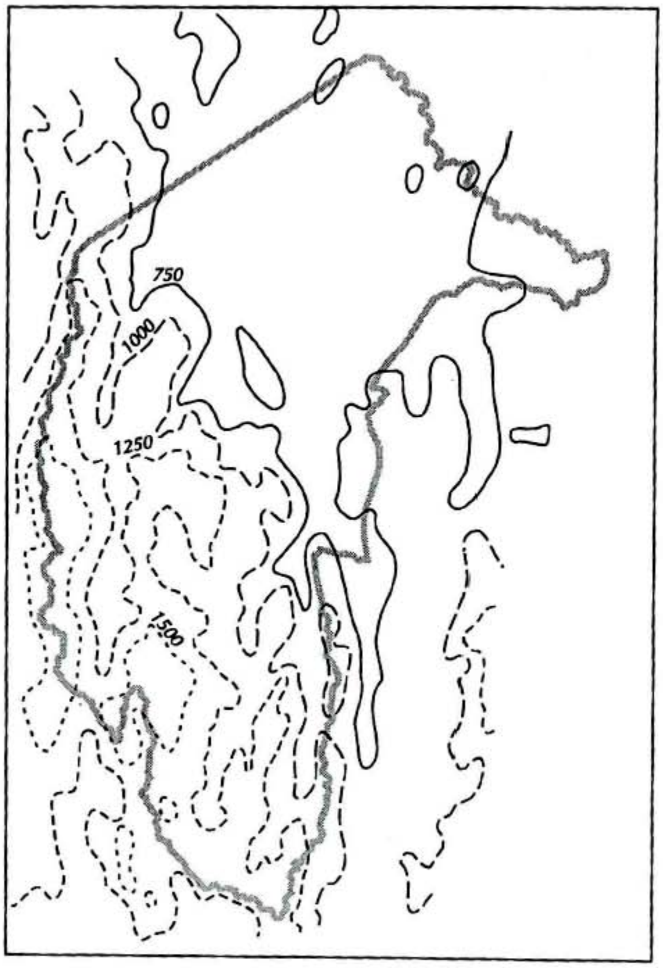


Figure 2. Generalised macro-scale elevation trend map for the ACT, using 250 m contour intervals only (reduced from original scale, but without loss of resolution). In Figures 2 to 6 north is to the top of page, and scale can be deduced from the Territory's north-south extent of 88 km.

Lightning Ignition Records

The Service has maintained detailed records of wild fires in the Territory since 1971. The people responsible for these records in the past have not needed detailed locations, with the following implications for this study:

* Many of the lightning ignition records were unusable due to inadequate location data.
* Of those used, a typical positional error in any direction of 200 m about the best guess must be assumed.

A record was used only if it met the following criteria:

* Reliable identification of lightning as the cause.
* Provision of an accurate grid reference or placement of the source of ignition to within 200 m of a definite location.

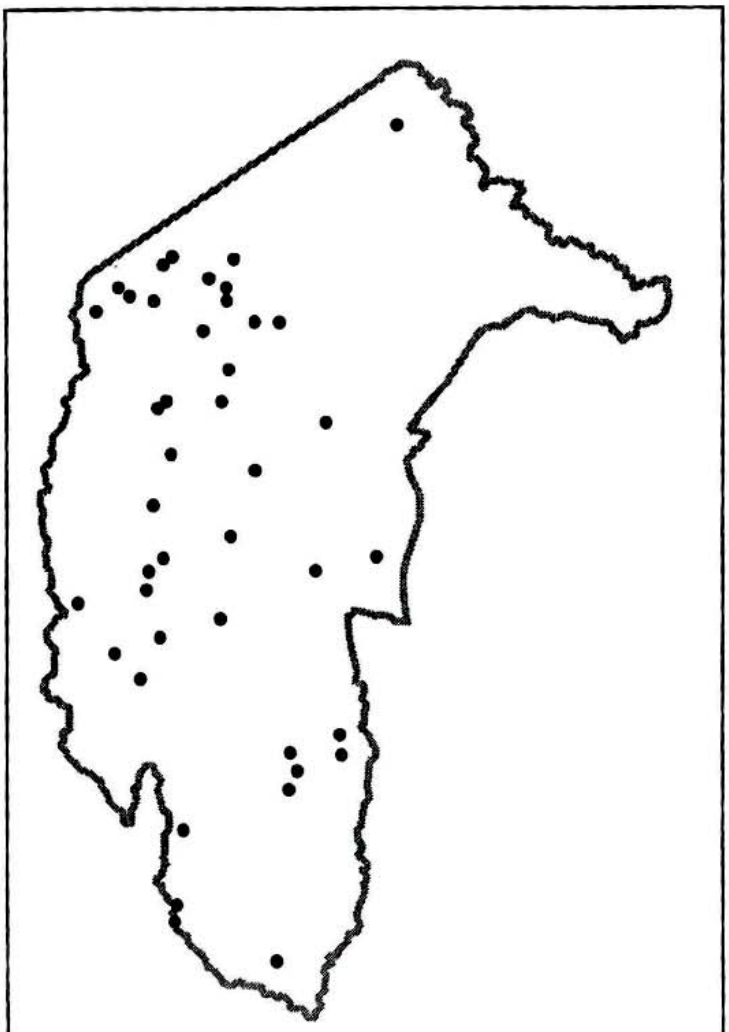
Comparison Between Records And Predictions

There was a need to compare the frequency distribution of distances from the zero meso-scale elevation residual contour to a set of random points with that of distances from the zero meso-scale elevation residual contour to the ignition points.

These were compared using a chi-squared statistic to test the null hypothesis that the data from the fire reports were no better than randomly placed with respect to the zero meso-scale elevation residual contour.

Two tests were conducted:

(1) Best guess from the fire reports compared to the random data. The best guess was taken as the most likely position of the fire ignition.



(2) Maximum distance for the fire report data compared to the random data. The maximum distance was taken as the furthest point on a circle, of radius of 200 m and centred on the point of best guess, from the closest portion of the zero meso-scale elevation residual contour.

Algorithm Revision

The model contains certain guesses for its parameters — modal and minimum radii of curvature and maximum slope. It was felt that if the model, based on purely geometric considerations, proved successful then it could in future be "retuned" to ensure the best possible fit to the fire records. The retuning would involve altering the values of the parameters until the maximum number of fire records were brought close to the model's output.

Given a best possible model based on fire reports up to 1989, a further test on goodness of fit for later fires was carried out as an independent verification.

Results

The usable locations where records show fires caused by lightning in the ACT between 1971 and 1989 are shown in Figure 3. A map showing the location of the zero meso-scale elevation residual contour, as output by the detrending model, is shown in Figure 4.

Comparison Of Records And Predictions

The results from the chi-squared tests are presented below. (All distance classes used below are in 100 m units.)

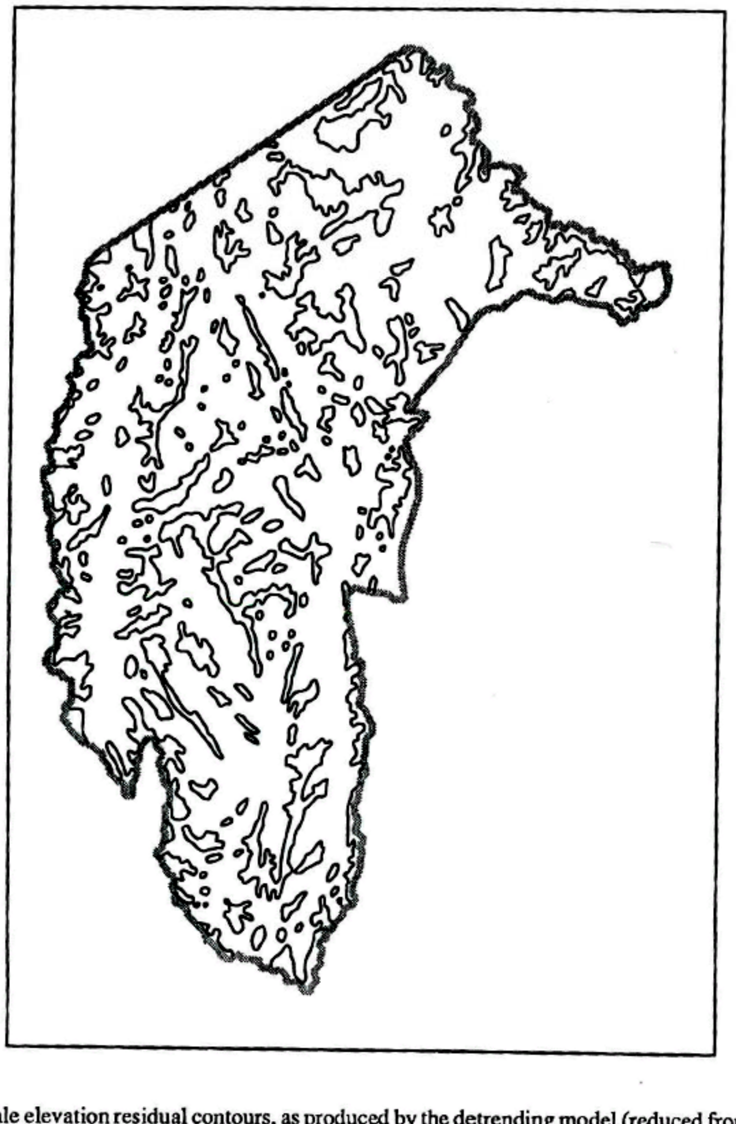


Figure 4. Zero meso-scale elevation residual contours, as produced by the detrending model (reduced from original scale, with some subsequent loss of detail).

(1) *Best guess from the fire reports compared to the random points.*

Distance class	0-1	2	3	4+
Fire report	24	9	4	5
Random	4	8	7	23

The chi-squared value for these data is 65.5, which is considerably larger than the expected value for 3 degrees of freedom and 0.5% probability, 12.8.

The conclusion is that the detrending model does much better than random at prediction.

(2) *Maximum distance for the fire report data compared to the random points.*

Distance class	0-2	3	4-5	6-7	8+
Fire report	10	9	15	5	3
Random	10	8	4	7	13

The chi-squared value for these data is 38.6, which is considerably larger than the expected value for 4 degrees of freedom and 0.5% probability, 14.9.

The conclusion is that the detrending model does much better than random at prediction.

Improving The Comparison

The detrending model was initially implemented with certain *a priori* assumptions as to radii of curvature and maximum slopes for the extrapolation surface. It was evident when evaluating the model that some refinements of these would increase the fit of the records to the model. Basically steeper slopes were seen to be allowable, as were smaller radii-of-curvature. The minimum radius-of-curvature allowed was 200 m within an unambiguous network of spot heights but grading to 800 m elsewhere, and the maximum slope used was 1 in 3. Care must be taken with these not to encroach on the micro-scale domain, where new factors may come into play. An as yet unresolved problem is how to extrapolate over steep V-shaped valleys, where it is not likely that there will be any spot heights recorded.

1990/91 Data

There were 9 lightning ignitions in the ACT during 1990/91, the third busiest year in the records. These are too few for a valid test against a random point set, but the data are presented below:

Distance class	0	1	2	3	Over 3
Fire report	3	2	2	2	0
Scaled random	0	1	1	3	4

Distances are from the revised detrending model output. There is enough difference between the observed and expected data for confidence in the model performing better than random to persist.

Discussion

Improving The Model

During the initial work on the model it was often suggested that there should be some correlation between lightning ignitions and some of the more obvious environmental factors. Geology was suggested most often, but no correlation was evident on overlaying the data on geology maps. In the absence of geology such as ironstone or soils such as laterites from the ACT there is no *a priori* basis for anticipating such a correlation.

Quick bi-variate checks for spatial correlations were conducted for a series of factors and the results of these are summarised below:

* Elevation: no pattern expected due to its role in the model.
* Slope: no pattern detected. Values ranging from 0 to 35 degrees were found.
* Aspect: no strong pattern detected. The full range of aspects was covered, however 16 out of 42 sites fell between 70 and 130 degrees (38% of sites in 14% of range). This needs to be investigated further.
* Topographic unit: The ignition sites were all classed as: plateau; exposed slopes; or ridge-top. While this partly confirms the impression of many people about where lightning tends to strike, it must be emphasised that the popular impression that lightning ignitions start on ridge-tops was shown to be wrong except on saddle points.

The conclusion, unfortunately, is that there is no clear way to identify a sub-set of the output from the detrending model, using obvious environmental factors, as being more likely for lightning ignitions than the remainder. This is in line with the findings of Minko (1975).

One idea, that was suggested by the spatial correlation with steep topographic units, to improve the fit of the model was to consider the slope of the meso-scale residual surface (achieved by running it through a digital terrain model). It appears that the steeper this surface is around the places where it has a value of zero, the more lightning ignitions will tend to occur there. Conversely, the flatter the macro-scale surface is the less they will tend to occur there. On very flat ground the model tends to predict this lower tendency, and predicts an equally low result for all local points.

Further refinement is possible by dividing the area into coherent blocks (*fire accounting blocks*) for which the number of ignitions can be summed. If an area has z ignitions recorded over x years and p grid-cells, and each grid-cell is predicted to have a value N of 0 or 1 by the detrending model, then the value for each grid-cell can be modified by:

$$N_j = N_j * z / x / \sum_{i=1}^{p} N_i$$

This gives a quantitative estimate of the number of fires per annum per grid-cell.

Application Of The Model

Based on the random point set, it is possible to estimate the area of the ACT that is prone to lightning ignition:

NII class	% ACT	Area (ha)
High	15.5	36,512
Low	79.9	199,048

By reducing the area where consideration of lightning is of concern from 100% to 15% there is the prospect of a considerable improvement in efficency of all aspects of fire management affected by lightning ignitions.

The NII model has been applied as part of the ACT Fire Hazard Assessment program. For the first time we have been able to handle lightning ignitions in a quantitative way that is compatible with that for man-made fires. A sample map of NII as used in the assessment is shown in Figure 5. (In this Figure the model's output appears more blurred than in Figure 4, due to proportional allocation of predictions to any grid-cells that contain part of the output.)

A statistical knowledge of where ignitions tend to occur is expected to be a benefit to interpreting the results of a reactive system for locating lightning ignitions. As an example, in the ACT remote area lightning ignitions are typically spotted from a distance by a fire tower as only a small puff of smoke, often in poor seeing conditions. Given a precise bearing but a vague distance, it is possible to use the NII predictions to suggest the most probable places in that range at which the fire could be, thus reducing expensive aerial reconnaissance time.

A computationally simpler, but less precise, alternative model, the averaging model, requires generation of the macro-scale surface through averaging the elevation of the local neighbourhood of each point in the area, then subtracting this from the digitised elevation surface. The averaging approach is easiest to implement in grid-cell based computer databases, or in image analysis systems, where a spatial averaging filter of appropriate radius may be easily applied to an image channel containing elevation data. For each point a local average of the elevations of the point's neighbours is used. The neighbours used are those in a square of 7 by 7 grid-cells, centred on the point of interest. With 500m grid-cells, this meant 3.5 km to a side. Care was taken when near the edge of the database. A map of the zero meso-scale elevation residual contour produced by this model for the ACT is shown in Figure 6.

The particular approach used here, that of spatial filtering of the elevation coverage, appears to have merit as a solution for a number of other problems in GIS applications, especially for fire management. Spatial filtering has already shown its use in improving directional slope vectoring for rate of spread prediction (McRae, 1990). This work further allows a direct process

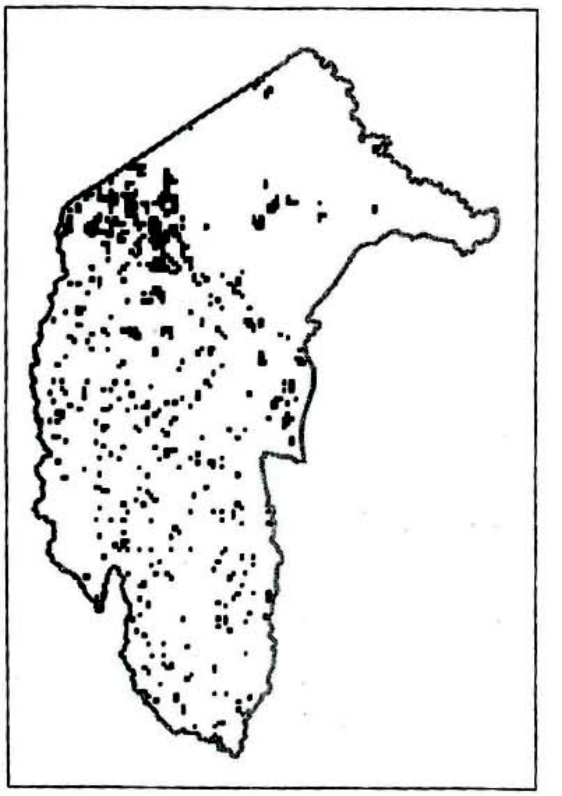


Figure 5. Simplified map of Natural Ignition Index, as used in the ACT Fire Hazard Assessment. The shaded grid-cells are those with a relatively high expected number of lightning ignitions per annum.

Figure 6. Zero meso-scale elevation residual contours, as produced by the averaging model (reduced from original scale, with some subsequent loss of detail).

for classifying sites into topography types, by using landform geometry and meso-scale elevation residual classes as indices for a look-up table containing topographic unit codes. There is a possibility that the approach will help with scaling of weather factors, when interpolating between sites of differing elevations, by allowing seperate scaling for the macro- and meso-scale surfaces. It may also be useful for modelling smoke dispersal and ecological phenomena associated with cold-air drainage.

The model should be linked in to other work being done on lightning ignitions. Latham and Schlieter (1989) have identified a procedure for predicting ignition probabilities for a fuel bed struck by lightning. They foreshadow a proactive GIS application using their model in advance of approaching storms to predict ignition probabilities, and suggest further links to models for rain and projected fire growth. Latham (pers. comm.) is proposing a GIS application that combines fuel state modelling with lightning ignition probabilties to assess resulting risk levels. Increasing the spatial resolution using the model described here should lead to more accurate risk assessment.

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