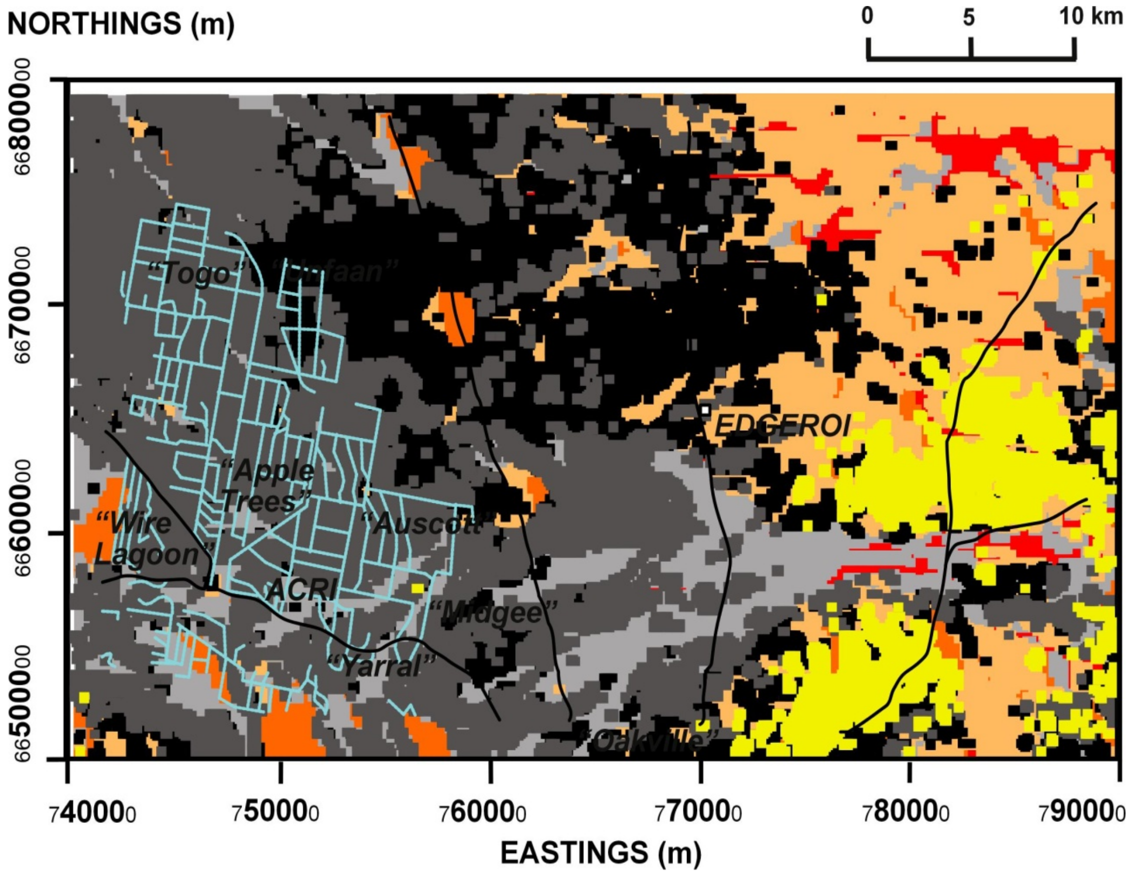
Identifying geomorphological and geological units using numerical clustering of ancillary data in the Edgeroi district of the lower Namoi valley



Alexei Nichols

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Supervisor:
Dr John Triantafilis
School of Biological, Earth and Environmental Sciences,
Faculty of Science, The University of New South Wales

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Abstract

A major impediment to effective management of soil and water resources in most agricultural and riverine environments of Australia is the lack of information on the spatial distribution of natural resources required for management planning and implementation. With respect to the soil resource the major problems are that traditional methods used for the acquisition of soil information, including soil survey, are time consuming and costly. The data collected is therefore usually sparse and because of time constraints was subjectively interpreted and therefore implications for land use management are uncertain.

Numerical clustering algorithims such as fuzzy k-means (FKM) have over the last 15 years been used successfully to continuously classify multiple soil attributes. More recently, FKM combined with geostatistical methods have been used to create representations of the soil continuum using remotely sensed information such as Digital Elevation Model (DEM) and deep sensing electromagnetic (EM) data.

The use of gamma radiometric data is increasingly being used to assist with the recognition of surface soil patterns. This is because gamma radiometric data, which consists of Potassium (K), Uranium (U), Thorium (Th) decay rates as well as the total radioactivity (i.e. Total Count-TC) of the soil and regolith, are related to the age and mineralogy of the soil.

In this project, the aim is to explore the possible use of FKM analysis of gamma radiometric data (*i.e.* K, U, Th and TC in cps) and secondary data derived from a DEM to identify geomorphological and geological units and associated soil units within the Edgeroi district. The results suggest that the FKM approach, including the use of fuzzy performance index (FPI) and normalized classification entropy (NCE), provides a framework for identifying a small number of classes (c = 7) to investigate for interpretation.

We conclude that the classes derived from radiometric data, were consistent with the known soil variability and broad geology and geomorphology of the Edgeroi district (*i.e.* erosional, depositional and dust-mantled plains). The best results were achieved within the depositional and dust-mantled plains where we were able to discern differences between the depositional Namoi floodplain and the first and second terraces from the third and fourth terraces of Namoi alluvium. The approach also discerned the location of the dust-mantled plains associated with the fourth and eroded fifth fans of local alluvium. The results with respect to the erosional landscape were equivocal.

1. Introduction

Effective agricultural management requires an understanding of the spatial distribution of soil physical and chemical properties. However, individual soil properties are distributed as a function of various soil forming factors (e.g. parent material and time) or as a consequence of man's interaction with the landscape (e.g. soil salinisation). Various pedometric and digital soil mapping (DSM) methods are increasingly being employed to map the soil. In some irrigated areas of northern New South Wales, electromagnetic (EM) instruments have been used to map the spatial distribution of individual soil physical properties such as clay content (Triantafilis et al., 2001a) and chemical properties such as soil salinity (Triantafilis et al., 2001b).

However, a given class of soil will behave as a function of inter-relationships between various physical and chemical properties (Triantafilis et al., 2001c). As a consequence, the identification and mapping of soil classes at the distirct level is important. To identify classes, the age-old questions associated with soil classification are problematic. That is, what properties need to be included, what methods should be employed to identify the classes and how many classes are actually present. Lucius Junius Moderatus Columella considered some of these issues in the first century AD when he wrote about the identification of the six species (types) of soil (e.g. fat or lean) in Book II of *"De Re Rustica"*:

> *"To enumerate them is not the mark of a skilled farmer; for it is not the business of any art to roam about over the species, which are countless, but to proceed through the classes, for these can readily be connected in the imagination and brought within the compass of words. We must have recourse, then, to certain unions, as we may call them, between qualities which are at variance with each other — what the Greeks call συζυγίαι ἐναντιοτήτων, and which we may fairly render "the couplings of opposites."*

In essence, Columella suggested the identification of soil type should ideally lead to the delineation of areas that diifer from one another. In precision agriculture parlance these are known as management classes; whereby the classes demarcate management zones of equivalent agronomic potential and will respond differently to applied fertilizer (e.g. nitrogen) or amendment (e.g. gypsum requirement).

The measurement of soil property data at the district level is prohibitively expensive (Triantafilis et al., 2003a). Increasingly, ancillary data sources such as crop yield (Stafford et al., 1988; Lark, 1998; Boydell and McBratney, 1999) and proximal and remotely sensed data (Ahn et al., 1999; Fraisse et al., 2001; Kitchen et al., 2003) are being employed as surrogates. In terms of identifying classes, subjective approaches involving a farmers knowledge (Fleming et al., 2004) and quantitative methods such as unsupervised classification of ancillary data (Johnson et al., 2003) have been proposed. The optimal numbers of classes have been differentiated by various procedures such as FASTCLUS (Jaynes et al., 2003), and indices such as the fuzziness performance index (Frigden et al., 2004; Vitharana et al., 2007) have been explored.

The main objective of this research was to determine if soil management classes could be discerned from two different sources of ancillary data, which relate to soil forming factors (i.e. climate, organisms, relief and parent material) and soil forming processes (i.e. illuviation, leaching). Specifically, we use remote sensed gamma spectrometry to assist in discriminating soil profiles based on differences in particle size fraction and cation exchange capacity. In addition, we use remotely sensed topographic attributes, generated from a DEM (including; slope, aspect, profile and plan curvature, topographic wetness index and flowac), to discriminate soil based on its location in the landscape.

2. Materials and Methods

2.1 Study area

The study area lies within the Namoi valley, in northern New South Wales, Australia. The Namoi valley is part of the Murray Darling drainage system and occupies an area of nearly 43,000 square kilometers (Triantafilis and McBratney 1993). The main area of focus for this study is an area within the lower Namoi valley defined by the Edgeroi 1:50 000 topographic map sheet (Figure 1). This area surrounds the township of Edgeroi, which lies on the Newell Highway, approximately 450 km north, northwest of Sydney (New South Wales) and 450 km southwest of Brisbane (Queensland).

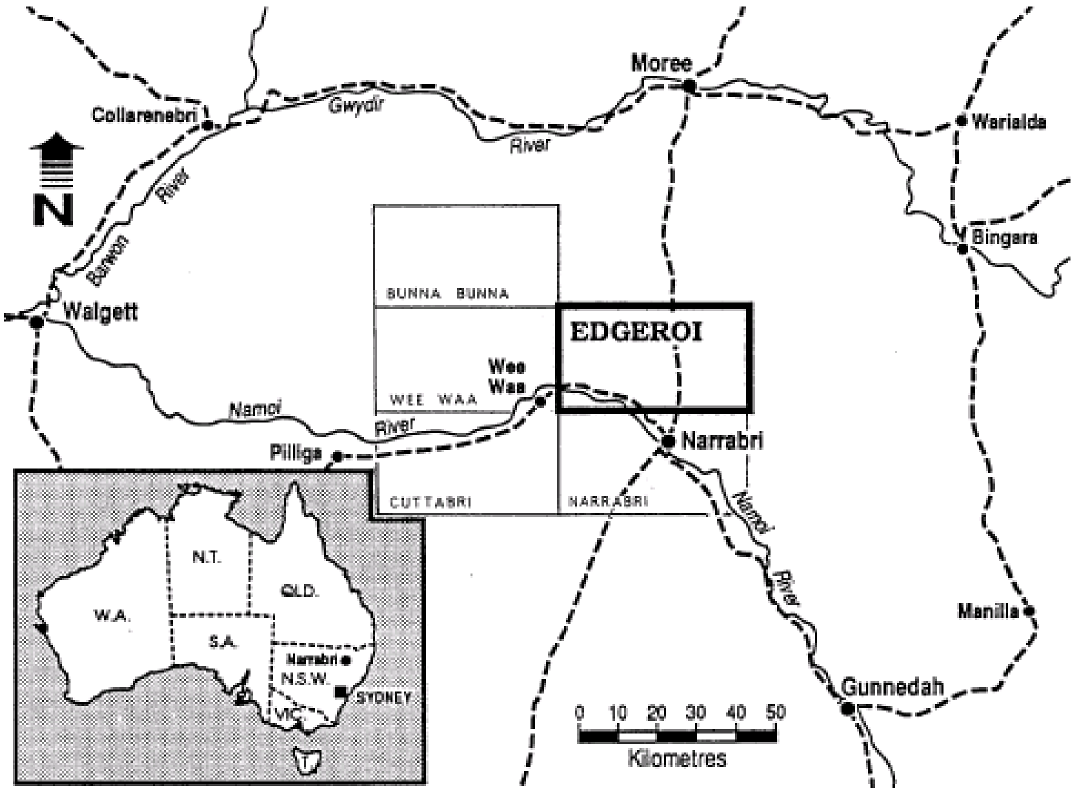


Figure 1. Location of the lower Namoi valley and Edgeroi Study area.

The most prominent physiographical features of the Namoi valley are the Nandewar, Liverpool, Warrumbungle and great dividing ranges, that form a westward facing semi-circle leading out to the expansive plains of the area. Further to the west, expansive alluvial plains dominate the landscape, by which more than 80% have slopes of less than 3° (Triantafilis and McBratney 1993). The Namoi River is the major river within the valley, draining the southern part of the New England Plateau and the Liverpool plains, with the main tributaries being the Manilla, Peel and Mooki rivers. Eventually, the Namoi flows into the Barwon River, in the western edge of the valley, near the township of Walgett. The study area itself receives intermittent drainage from the Mulgate, Bobbiwaa and Spring creeks, which rise in the Nandewar Range and enter from the north-east. Other important local drainage ways include the Bohena creek, which flows north from the sandstones of the Pilliga Scrub. The Galathera, Ten-Mile and Boggy creeks, which flow westward through the Edgeroi district, eventually turn toward the northwest and enter the Barwon River system.

Large areas of land within the Edgeroi study area are utilised for agricultural production. The fertile alluvial floodplains towards the western-third of the study area (Figure

2) are used for irrigated cropping, in particular the production of cotton (*Gossypium hirsutum*), sorghum (*Sorghum bicolour*) and maize (*Zea maize*). Water for these cropping activities is obtained from the Namoi river, through controlled releases from Keepit, Chaffey and Split Rock Dams, and through various groundwater bores. However in recent years, due to dry conditions, there are limited amounts of water available for irrigation purposes, as a result dryland cropping is becoming increasingly predominant. The major dryland crops include, wheat (*Triticum aestivum*), sorghum (*Sorghum bicolour*), barley (Hordeum vulgare), canola (Brassica napus), and in some instances, dryland cotton (*Gossypium hirsutum*). These crops are generally grown in the more 'marginal' areas, where the soil type may not be suitable for intensive irrigation practices, or in areas where irrigation water is unavailable.

There are large areas in the lower Namoi valley where extensive sheep and cattle grazing occurs. These areas generally include forestland and shrubland, as well as cleared land, which may be sown to introduce pasture species. To the west of the Edgeroi district, pastures are improved, while in the east native pastures merge into uncleared native stands and forests. This includes the State Forests of Moema, Couradda, Bobbiwaa and Killarney (Triantafilis *et al.* 2001d). Small areas of land are utilised for roads, stock routes, railway, residential, commercial and industrial areas.

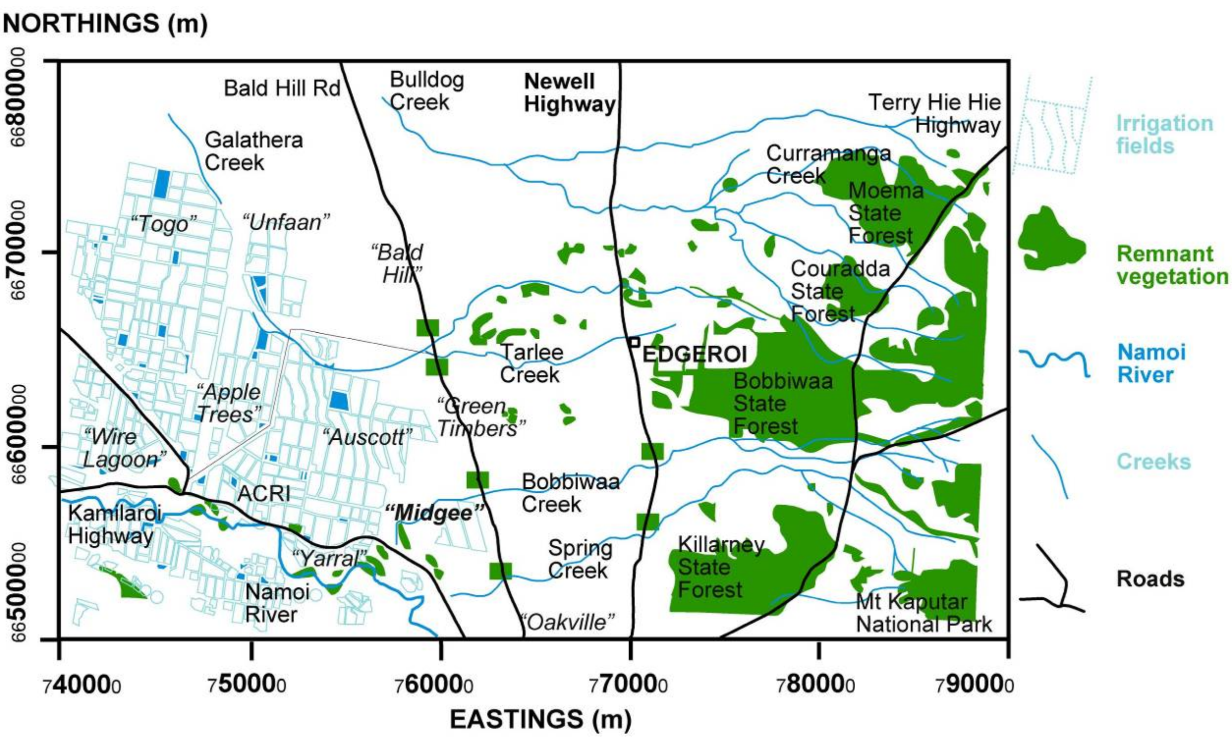


Figure 2. Cadastral information within the Edgeroi 1:50 000 topographic map sheet.

2.2 Geology and Geomorphology

Local variation in soil properties is largely associated with the types of rocks and sediments in which the soils are formed. In order to understand the spatial variability of the soil continuum it is first necessary to identify the rocks that contribute to the spatial pattern. Ward (1999) identified 3 major geological and geomorphic units in the Edgeroi study area. This includes: the erosional landscape (*i.e.* sandstone ridges, basalt hills and eroded alluvial plains); alluvial plains (*i.e.* Namoi alluvium); and dust mantled alluvial lands (*i.e.* local alluvium). These landscapes are represented in Figure 3. A brief summary of Ward's (1999) interpretation of the Edgeroi district is provided below.

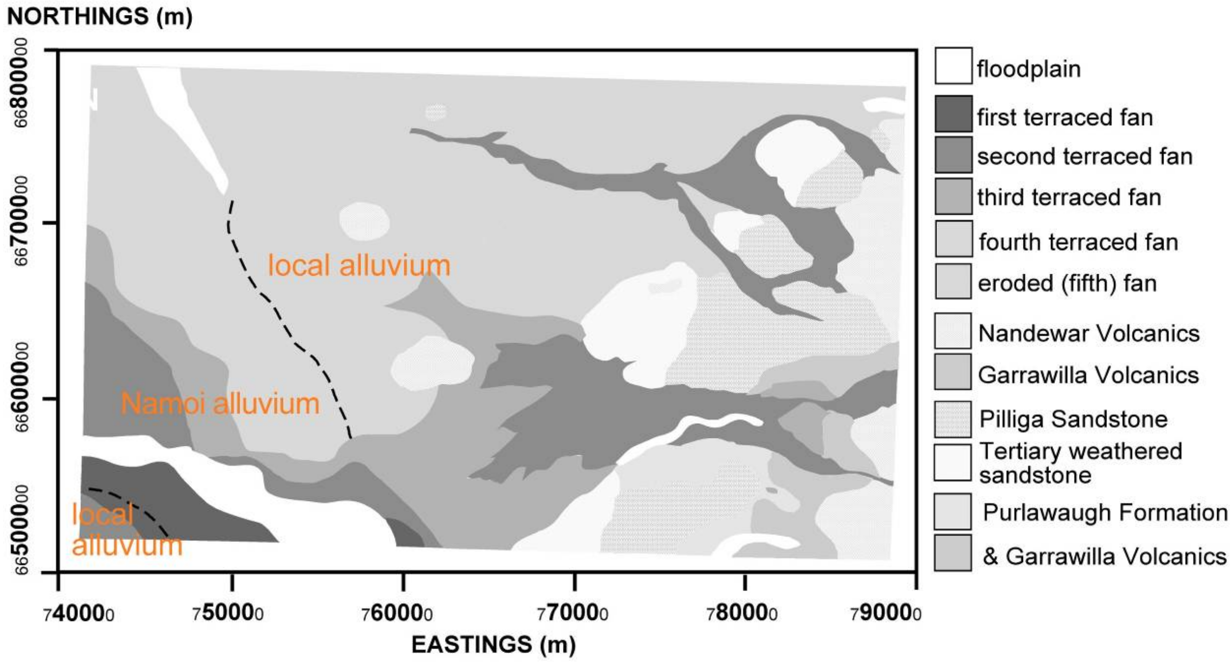


Figure 3. Geology and geomorphology within the Edgeroi study area (Ward, 1999).

The erosional landscape is dominated by the Nandewar mountain range, which is located on the eastern margin of the Edgeroi study area. This range is an eroded remnant of an enormous shield volcano built 20 to 21 million years ago in the Tertiary era (Dulhunty and McDougal 1966). The rocks of this range are termed *'Nandewar Volcanics'*, consisting of alkali basalts and trachytes. The basalts that occur at *"Bald Hill", "Oakvale"* and *"Green Timbers"* are believed to consist of Nandewar Volcanics. Outcrops of these basalts occur in other areas throughout the Namoi Valley.

The main basement rocks found in the lower Namoi valley form prominent ridges. These ridges are composed of Pilliga Sandstone, which is a coarse-textured and porous quartz sandstone, with interbedded claystones, and Purlawaugh formation. The latter generally gives rise to soft clayey sands and mudstones. Both of these geological formations tend to occur predominantly on the footslopes of the Nandewar ranges. Small outcrops of Garrawilla Volcanics occur on the south-eastern margin of the Edgeroi study area. Another prominent geological formation within the Edgeroi study area, is that of the Rolling Downs Group. This group accounts for the calcareous clays and marls, in which calcium carbonate has formed rounded nodules and cemented layers of rock-like calcrete. Soft yellow sandstones with rounded gravels occur above the rolling downs.

The deep alluvial plains of the Edgeroi study area, represented by the Namoi floodplain, the first terraced fan, and the second terraced fan, are the result of alluvial deposition of basaltic debris intermixed with sandstone. The alluvial debris is believed to have been deposited in the formation of broad valley plains and alluvial fans, across the fluvial landscape of the extensive plains, consisting of fine sized clays with inter-bedded sands and silty clays in poorly defined horizontal layers, without horizontal bedding. The depths of the alluvial plains range from up to 15m to within 3m near old river courses (Stannard and Kelly, 1977).

The first alluvial terrace (lowest) is characterised by flood channels and low natural levees, being separated from the Namoi floodplain by low scarps from higher ground, with soils that differ from the floodplain as a consequence of a greater degree of soil formation.

The second alluvial terrace falls in elevation very gradually to the north for about 1km. The ground surface is smooth, with barely evident remnants of abandoned alluvial channels. The soil type is predominantly of Red/Brown Dermosols and Brown Vertosols. The third alluvial terrace is distinguished by a consistent and abrupt change in soil from a Red/Brown Dermosol or Brown Vertosol to a Grey Vertosol.

The fourth alluvial fan (oldest) consists of both Namoi alluvium and local alluvium. The local alluvium was believed to have once been deposited by the Namoi River, however, over time it has been influenced by the colluvial deposition of sediments and minerals from the weathering of nearby basement rocks (*i.e.*, basalt and sandstone). This alluvial fan forms extensive plains north and south of Bald Hill. Red and Brown Dermosols are common, as well as dark grey Vertosols. The deposition of aeolian material is also suspected to have contributed to the formation of the alluvial plains, particularly on the first and second terraced fan. Extensive development for irrigated cropping purposes is evident on the Namoi floodplain, first, second, third and to some extent, fourth, alluvial terrace.

The 'eroded' fifth fan, occupies high ground above the younger terraces and alluvial fans in the area surrounding Edgeroi siding. The landscape is very gently undulating in most places as a result of natural erosion of ancient alluvial beds, over the long period it has been exposed to weathering, and the streams that occupy broad open depressions. It is partly mantled with wind deposited sediments. Grey Vertosols are the dominant, with water worn gravels, including basalt, evident at the surface. The terrace sequence described for the Namoi River is matched by similar terrace sequences associated with the various other creeks and drainage ways located within the Edgeroi study area.

2.3 Airborne Radiometric Surveys

Airborne gamma-ray spectrometry has been used mainly as a tool for mineral exploration in locating U deposits (Darnley and Grasty 1971). More recently there has been a growing interest in and use of gamma-ray data in regolith and geomorphological studies (Dickson and Scott 1997; Wilford 1992). Radiometrics, or gamma-ray spectrometry is an airborne, passive remote sensing/geophysical technique (Wilford et al. 1997) and has been used for over 20 years to detect geochemical anomalies (Cook et al. 1996). It measures naturally occurring gamma-ray accumulation and assesses the K, U and Th contents of the Earth's surface (Cook et al. 1996; Wilford et al., 1997). Increasingly, research is being carried out to elucidate how radiometric data can be used in mapping of soil/regolith mapping and applied geomorphology (Wilford et al. 1997), recognition of aeolian soil (Dickson and Scott 1998; Cattle et al. 2003), erosion and deposition processes (Pickup and Marks 2000), salt stores (Wilford et al. 2001; Thomas et al. 2003), and measure plant available potassium and other topsoil attributes.

In New South Wales the NSW Department of Mineral Resources collects gamma radiometric data using an airborne platform. The acquisition platform digitally records all geophysical, navigation, and altitude data. In the lower Namoi valley flight lines were predominantly east-west, with a line spacing of approximately 400m. The survey flying height was 80m above the ground surface. Readings were obtained at an average measurement spacing of 67 m. The K, U, and Th windows, centered on the 1.46 MeV (K), 1.76 MeV (U) and 2.61 MeV (Th), photopeaks were recorded; with the total count window also measured providing a measure of total radioactivity.

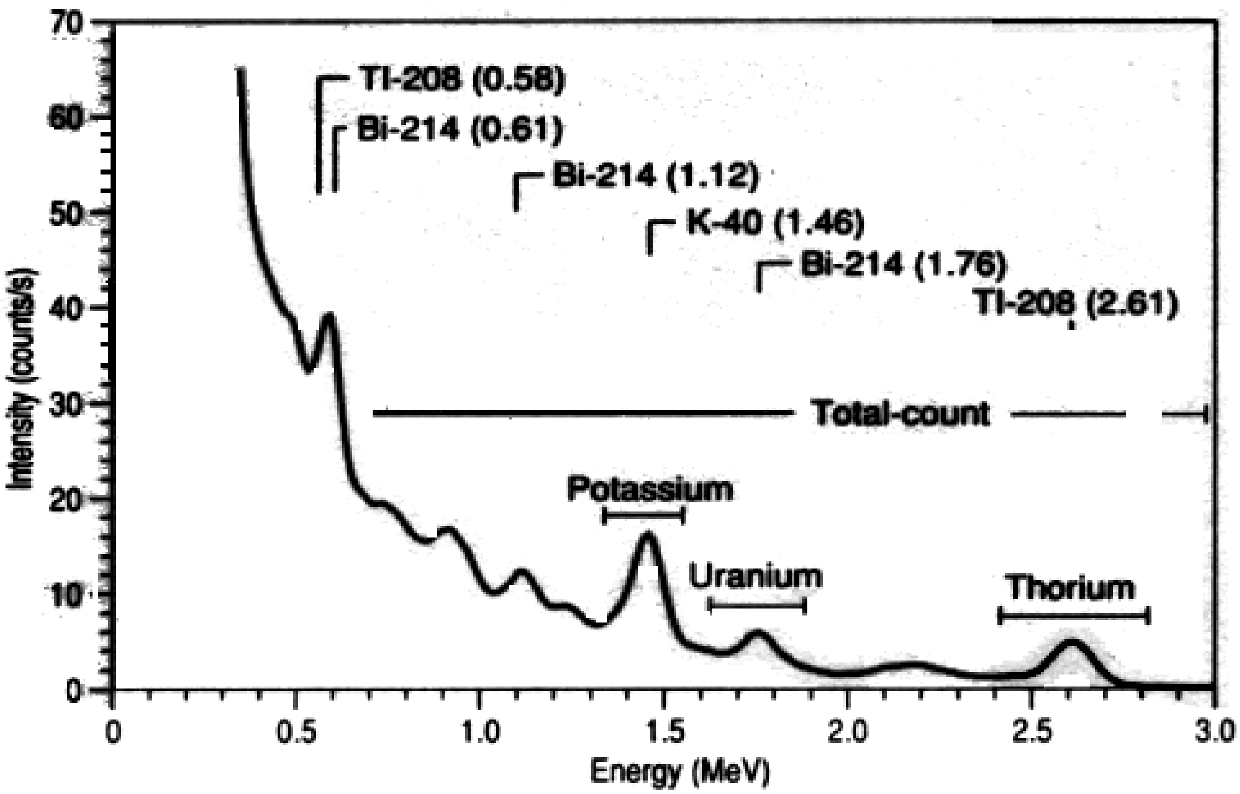


Figure 4. Airborne gamma-ray spectrum and position of Potassium (K), Thorium (Th), Uranium (U) and Total Count (TC) windows (Minty et al., 1997).

Table 1. A portion of the gamma radiometric data matrix of the Namoi valley. Note: Easting and Northing in GDA and MGA94, height and altitude (m) of gamma radiometric sensor in metres and Total Count (TC), Potassium (K), Uranium (U) and Thorium (Th) in cps.

Easting	Northing	DEM	Slope	Aspect	ProfC	PlanC	TWI	FlowAc	DR	K	Th	U
740511	6649183	199	0.0334	21	0.0000	0.0001	9.22	0	26.16	0.37	6.13	1.23
740511	6649283	199	0.0334	21	0.0000	0.0001	9.22	0	27.58	0.38	6.21	1.19
740511	6649383	199	0.0334	21	0.0000	0.0001	9.22	0	28.65	0.38	6.30	1.18
740511	6649483	199	0.0239	64	0.0002	0.0002	9.25	0	28.59	0.39	6.11	1.19
740511	6649583	199	0.0239	64	0.0002	0.0002	9.25	0	27.60	0.38	6.04	1.22
740511	6649683	199	0.0338	122	0.0001	0.0001	9.09	0	27.32	0.39	6.00	1.26
740511	6649783	199	0.0338	122	0.0001	0.0001	9.09	0	27.21	0.38	5.95	1.25
740511	6649883	199	0.0338	122	0.0001	0.0001	9.09	0	27.24	0.39	5.96	1.25
740511	6649983	199	0.0590	151	0.0000	0.0005	9.17	0	27.47	0.38	6.01	1.24
740511	6650083	199	0.0590	151	0.0000	0.0005	9.17	0	28.27	0.37	6.40	1.24
740511	6650183	199	0.0839	173	0.0001	0.0009	9.36	0	28.51	0.36	6.78	1.35
740511	6650283	199	0.0839	173	0.0001	0.0009	9.36	0	28.88	0.38	6.81	1.33
740511	6650383	199	0.0839	173	0.0001	0.0009	9.36	0	28.69	0.41	6.44	1.32
740511	6650483	200	0.0792	208	0.0003	0.0016	9.22	0	28.48	0.42	6.41	1.27
740511	6650583	200	0.0792	208	0.0003	0.0016	9.22	0	28.20	0.44	6.40	1.19
740511	6650683	200	0.1315	328	0.0018	0.0018	9.33	0	28.39	0.42	6.40	1.25
740511	6650783	200	0.1315	328	0.0018	0.0018	9.33	0	28.85	0.43	6.51	1.34
740511	6650883	200	0.1315	328	0.0018	0.0018	9.33	0	29.24	0.43	6.58	1.32

The gamma-ray detection system consists of a gamma ray detector and the detector controller/spectrometer. These measure the fluorescence produced in the detector material from its excitation by gamma-rays. The fluorescent photons (scintillations) are reflected onto a photo-multiplier tube cemented to one end of the detector, where the charge they produce is amplified by the magnitude of 10^6. The scintillation detector used by the NSW Department of Mineral Resources consisted of sodium iodide (NaI) treated with thallium in the form of single crystals up to 4L in volume. For this survey three detector packages were used to measure gamma-ray emission, each containing four individual crystal detectors, giving a total detector volume of 48L. The spectrometer was calibrated using procedures described (Minty et al., 1997). It was also corrected for influences not related to geology. The data recorded by the data acquisition system (observed spectra) was also transformed to equivalent concentrations of radioelements (K, U and Th) being emitted from geological and soil material for each sampling period (*i.e.* 1 second). Each count was assigned a digitally recorded Northings and Eastings in the Geodetic Datum of Australia (GDA94) and Map Grid of Australia (MGA94) co-ordinate system.

In order for analysis to be conducted on the data, a few minor adjustments were made using the statistical analysis computer program JMP (SAS, 1999). Such adjustments included removing the negative values recorded for K, U, Th and Total Counts obtained during the survey. The negative radiometric emission values coincided with mountainous regions, including Vinegar Point, Billy Goat Hill, Long Tom Mountain, The Pimples and Mt Kaputar National park. It is probable that this may be due to the aircraft needing to increase altitude to manoeuvre around the mountains. Negative or small gamma-ray emission values also occurred where large bodies of water are present, due to attenuation of gamma-rays through more than 2-4m of water. This is mainly evident in the western-third of the Edgeroi district where irrigation reservoirs are common.

In all over 148,603 measurements were made during the radiometric survey in the Namoi valley. Of these, more than 10% or approximately 58,000 measurements were made in the Edgeroi district. A sample of the original dataset is provided in Table 1. Because of the detailed knowledge of the geologic and geomorphic units described by Ward (1999) within the Edgeroi study area, and the detailed radiometric data collected at the district and sub-catchment level, knowledge gained at the district level can be extrapolated to the larger sub-catchment level.

2.4 Numerical clustering

Numerical clustering algorithms are employed in an attempt to synthesise multivariate data into groups of similar attributes. Fuzzy k-means (FKM) is one such algorithm. The concept of fuzziness was first presented by Zadeh (1965) to provide a mathematical method for dealing classifying continuous data. Natural phenomena, such as soil, which are continuous in nature, have been effectively described and mapped using FKM algorithms.

Early examples include: Powell et al. (1991) who delineated drainage units from pH profiles and later classified soil profiles and horizons (Powell et al. 1992); Odeh et al. (1992a) applied the algorithms to soil morphological and particle size data along orthogonal transects; McBratney et al. (1992) identified soil mapping units; McBratney and de Gruijter (1992) delineated common soil profiles using coded morphological horizons and Triantafilis et al. (2001c) who used the method to classify soil layers of the Edgeroi soil data set (McGarry et al. 1999) and demonstrated how similar soil layer sequences could represent the variation inherent at depth across the Edgeroi district (Triantafilis and McBratney 1993).

Increasingly, FKM algorithms are being applied to remotely sensed geophysical data to assist in the process of representing the soil continuum. This includes: De Bruin and Stein (1998) and Burrough et al. (2000) who respectively used FKM to cluster of attribute data derived from Digital Elevation Models (DEM) to represent transition zones in the soil landscape and classification of landforms; Burrough et al. (2001) topo-climatic data as an aid to forest mapping; Triantafilis et al. (2003b) who classified EM34 signal data to elucidate physiographic and hydrogeological units in the lower Namoi valley; and, Triantafilis and Lesch (2005) who used a similar approach to identify soil landscapes and assist in developing a soil sampling scheme. Radiometric data will be analysed using FKM algorithm implemented in the FuzME program (Minasny and McBratney 2002). In the following section a description of the theory which underpins the FKM algorithm is implemented in FuzME is provided below.

2.5 Fuzzy k-means

To determine whether soil management classes can be discerned mathematically from numerical clustering of ancillary data (i.e. digital soil class mapping) we carried out fuzzy k-means (FKM) analyses of gamma radiometric and secondary derivatives of digital elevation model data. The FKM method is described in detail elsewhere (Triantafilis et al., 2001d). Briefly, it calculates a measure of similarity between an individual *i* and a cluster *c*, determining how much they are alike in multi-variable space. The best outcome minimizes the objective function $J_1(\mathbf{M},\mathbf{C})$:

$$J_1(\mathbf{M},\mathbf{C}) = a \sum_{i=1}^{n} \sum_{c=1}^{k} m_{ic}^{\varphi} d_{ic}^2 (x_i, c_c) \tag{1}$$

where $\mathbf{M} = m_{ic}$ is a $n \times k$ matrix of membership values (n denoting the number of objects), $\mathbf{C} = (c_{cv})$ is a k x p matrix of class centers (p denotes the number of variables), c_{cv} is the value of the center of class c for variable v, $x_i = (x_{i1},\ldots,x_{ip})^{\mathrm{T}}$ is the vector representing individual i, $c_c = (c_{c1},\ldots,c_{cp})^{\mathrm{T}}$ is the vector representing the center of class c, and $d_{ic}^2(x_i, c_c)$ is the square distance between x_i and c_c according to a chosen definition of distance (Euclidean, Mahalanobis or Diagonal), further denoted as d_{ic}^2 and ϕ (fuzziness exponent) determines the degree of fuzziness of the final solution. The distance dependent metric is needed to optimize the objective function. Of these, the Mahalanobis distance accounts for correlations among variables (Bezdek, 1981) and is defined:

$$d_{ic}^2 = (x_i - c_c)^{\mathrm{T}} \mathbf{S}^{-1} (x_i - c_c) \tag{2}$$

where **S** is the sample variance-covariance matrix of **X**. The exponent ϕ determines degree of fuzziness of the final solution; whereby the value of $\phi = 1$ is equivalent to the hard partition.

Validity functionals such as the fuzziness performance index (FPI) and the normalized classification entropy (NCE) are commonly employed to determine a suitable number of *k* and a value for ϕ. The FPI is a measure of the continuity between classes. A value of 1 represents a very fuzzy classification, while a value approaching 0 indicates distinct classes with little membership sharing. The NCE is a measure of the degree of disorganization created by partitioning the data into various classes. Values near 0 indicate that the classes are well structured. Values approaching 1 indicate that these classes are disorganized and exhibit large entropy. The least fuzzy and least disorganized number of classes (i.e. minimum) is optimal (Odeh et al., 1992). Calculations of the FKM analysis were performed using the FuzME program (Minasny and McBratney, 2002).

3. Results and Discussion

3.1 Spatial distribution of radiometric data

In order to better understand the spatial distribution of the various radiometric data and also to better understand the classes produced by implementing the FKM algorithm, the spatial patterns for K, U, Th and Total Counts are described. The contour plots produced show the spatial variability of the K, U and Th within the Edgeroi district (Figures 5, 6 and 7, respectively). The Total Count was also mapped (Figure 8). The maps, broadly speaking, show similarities when compared to the geological and geomorphological features of the Edgeroi landscape as described by Ward (1999).

Figure 5 shows the recorded K from rocks and soil within the Edgeroi district. The pattern in evidence compares favourably with respect to the geological and geomorphological interpretations (see Figure 3) of Ward (1999). The dark green areas indicate where K counts were highest and coincide, almost exclusively, with the Nandewar Volcanics (*i.e.* > 4 cps). K counts are also rather large (*i.e.* K >2 per second) in the vicinity of upper parts of Bobbiwaa and Spring Creeks.

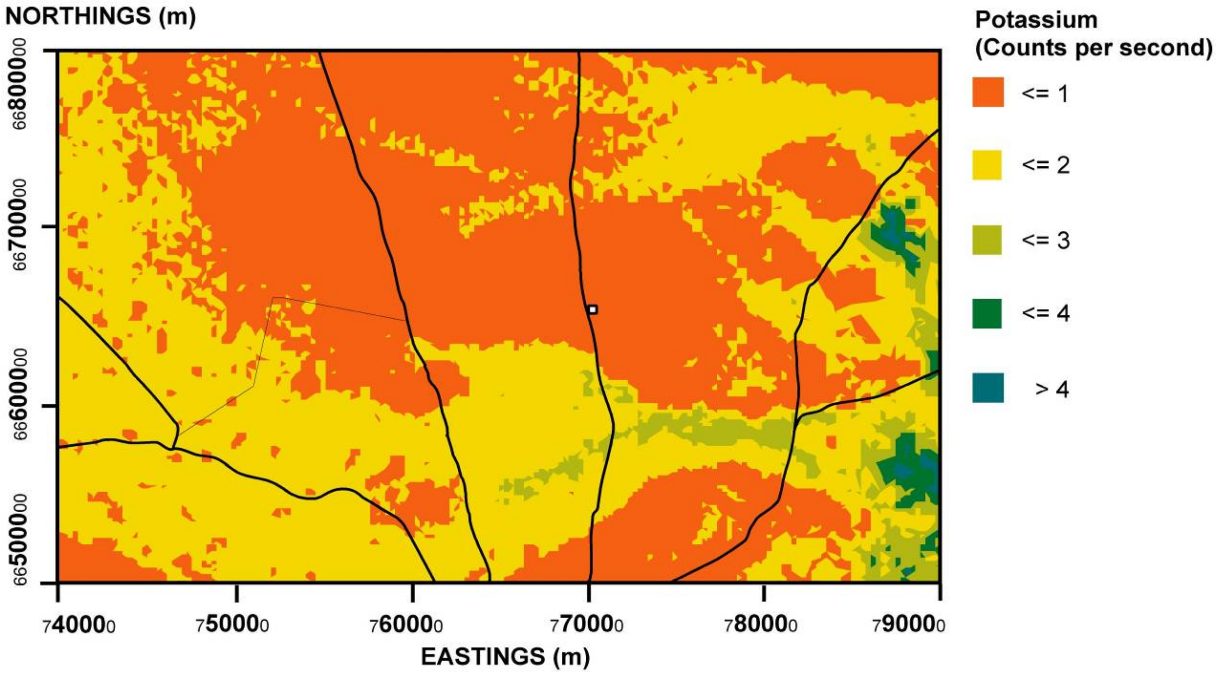


Figure 5. Spatial distribution of Potassium (K counts per second-cps) within Edgeroi area.

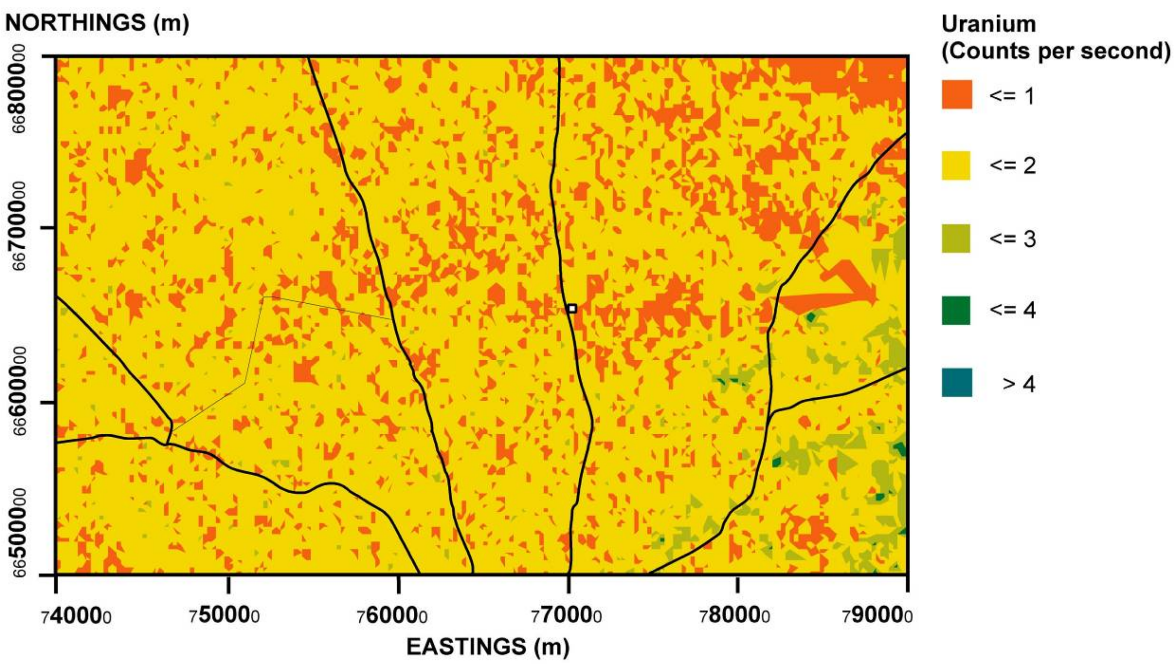


Figure 6. Spatial distribution of Uranium (U counts per second-cps) within the Edgeroi study area.

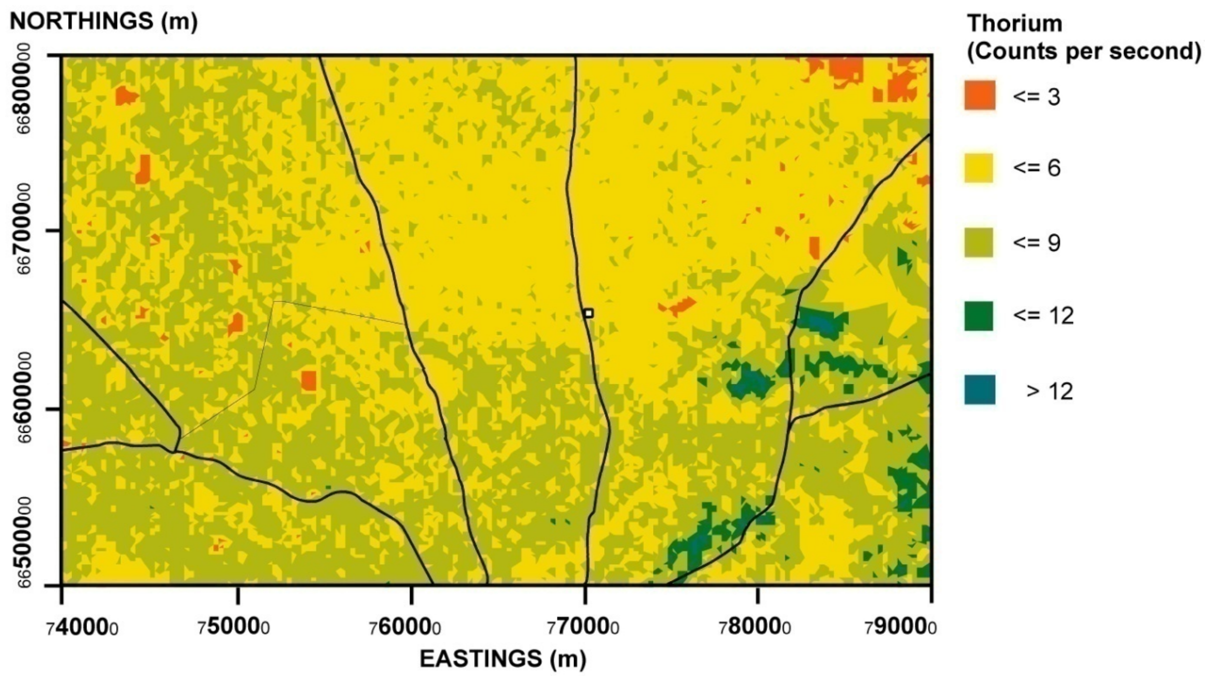


Figure 7. Spatial distribution of Thorium (Th counts per second-cps) within the Edgeroi study area.

Figure 6 shows the contour plot of the spatial distribution of U counts. The spatial pattern is subtler in comparison with K. Nevertheless, the highest U counts (*i.e.* green areas: U counts > 2 per second) prevail on the eastern margin of the Edgeroi study area, are again associated with Nandewar Volcanics and Pilliga Sandstone. Throughout the remainder of the area, U count is small (i.e. <2 cps) with no real spatially contiguous areas apparent. A significant area of low U counts (<= 1 ps) occurs in the north eastern corner of the Edgeroi landscape. As compared with K the results with respect to U are equivocal.

Figure 7 shows the contour plot of the spatial distribution of Th counts across the Edgeroi district. The higher Th counts were recorded along the eastern margin of the study area associated with the Nandewar volcanics, Pilliga sandstone and Purlawaugh Formation (*i.e.* >12 cps). The depositional parts of the Edgeroi landscape had the next highest Th counts (*i.e.*> 6 cps). The lowest Th counts (*i.e.* <= 6 cps) are associated with the dust-mantled alluvial lands. This includes the areas associated with the fourth terraced fan of local alluvium and the eroded fifth alluvial fan. Various discrete areas of low Th counts are evident to the west of Bald Hill Road. These are associated with large water storage reservoirs which inhibit radioelement decay from being measured.

Figure 8 shows the contour plot of the spatial distribution of Total Counts recorded across the Edgeroi district. As with the individual radioelement windows, the Total Count produces distinct contiguous units and patterns across the Edgeroi landscape, within which, similar total gamma-ray counts were recorded. Once again higher counts (*i.e.* TC > 50 cps) within the study area are associated with the Nandewar Volcanics and small drainage ways associated with these areas along the eastern margin of the Edgeroi district. The Total Count generally decreases from here towards the Namoi floodplain (*i.e.* 40-50 cps) to the west and the erosional part of the landscape to the north (*i.e.* TC <30 cps). The eroded fifth fan of local alluvium again coincides with the lowest Total Count readings obtained. The dark orange shaded areas shown, which display the lowest total counts (*i.e.* TC <=10 cps) from within the study area, are areas where water is present on the soil surface and again show distinctly the location of the various large earthern water reservoirs which have been constructed in the Edgeroi district.

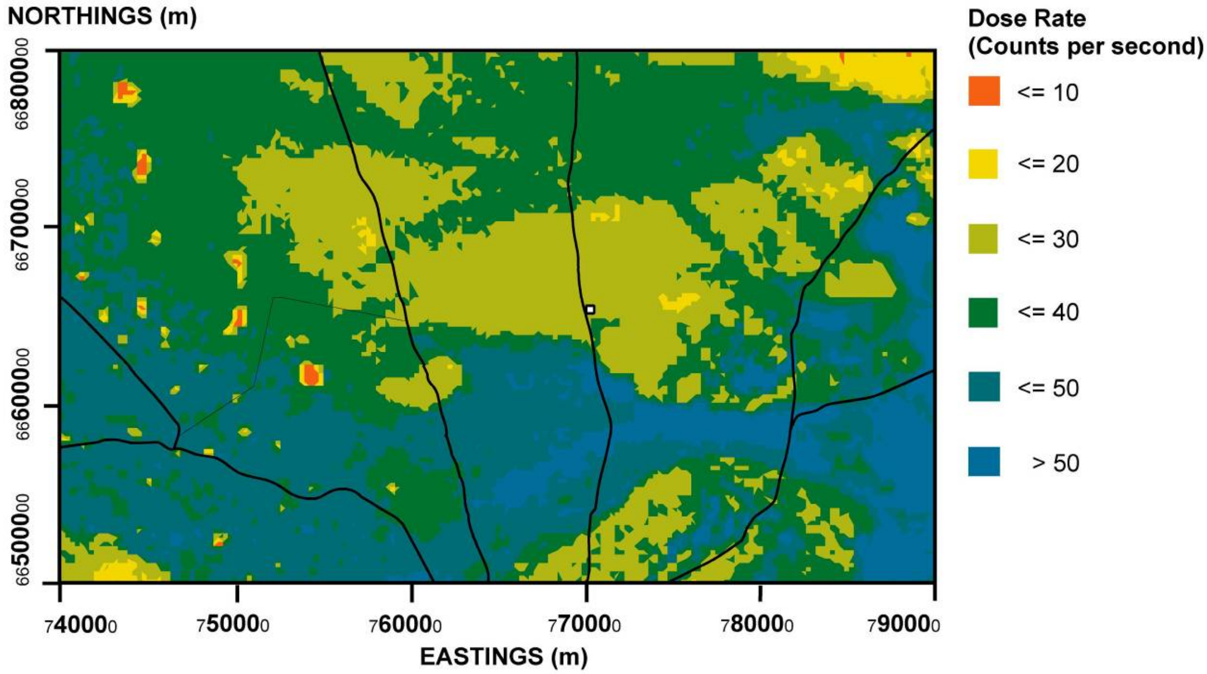


Figure 8. Spatial distribution of Total Count (counts per second-cps) within the Edgeroi study area.

3.2 FKM analysis

Owing to the size of the radiometric data matrix of 576,520 individual measurement locations and four gamma radiometric windows (*i.e.* K, U, Th and Total Counts), various secondary DEM parameters and due to the huge amount of computational time this would require to determine an optimal number of classes and fuzziness exponent, a smaller subset of the data was extracted. Based on preliminary analysis it was decided that 1/10 of the data would be selected and analysed to determine a suitable value of ϕ and k. This left a final data matrix of 57,652 x 10, that is, n = 57,652 radiometric measurement locations and p = 4 gamma radiometric windows (*i.e.* K, U, Th and Total Counts) and 6 additional topographic variables (DEM, slope, aspect, ProfC, PlanC, TWI and FlowAc).

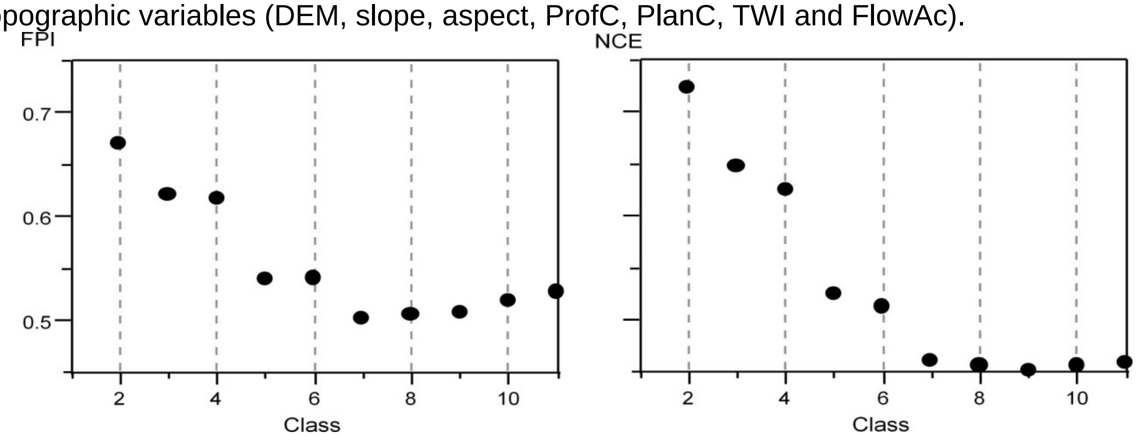


Figure 9. Plots of Fuzziness Performance Index (FPI) and normalized classification entropy (NCE) against number of classes (k) at ϕ = 2.

FKM analysis was performed on this data using the computer program called FuzMe (Minasny and McBratney 2002). FuzMe was used to objectively determine spatial relationships and structures in the data and to produce meaningful clusters, based on the radiometric data windos of K, U, Th and Total Counts from rocks and soil regolith. The implementation of the objective function J_2(M,C) was carried out using Mahalanobis metric, as it appeared to best cluster radiometric data into recognisable classes. The success achieved with this metric is possibly due to the fact that it gives equal weight to all measured variables and is insensitive to statistically dependent variables.

In order for a suitable number of classes (k) to be determined, FuzMe was used to derive outcomes of J_2(M,C) over a range of classes k (2-11) respectively using fuzziness exponents ϕ, ranging from 1.0-2.5. Figure 9 shows that a local minimum occurs at seven classes for NCE and a global minimum for FPI. We also found that the optimal ϕ value was 1.3 for the Mahalanobis distance metric.

3.3 Soil management zones

In order to better understand the nature and spatial distribution of the 7 classes (Classes A, B, C, D, E, F and G), maps of each were prepared.

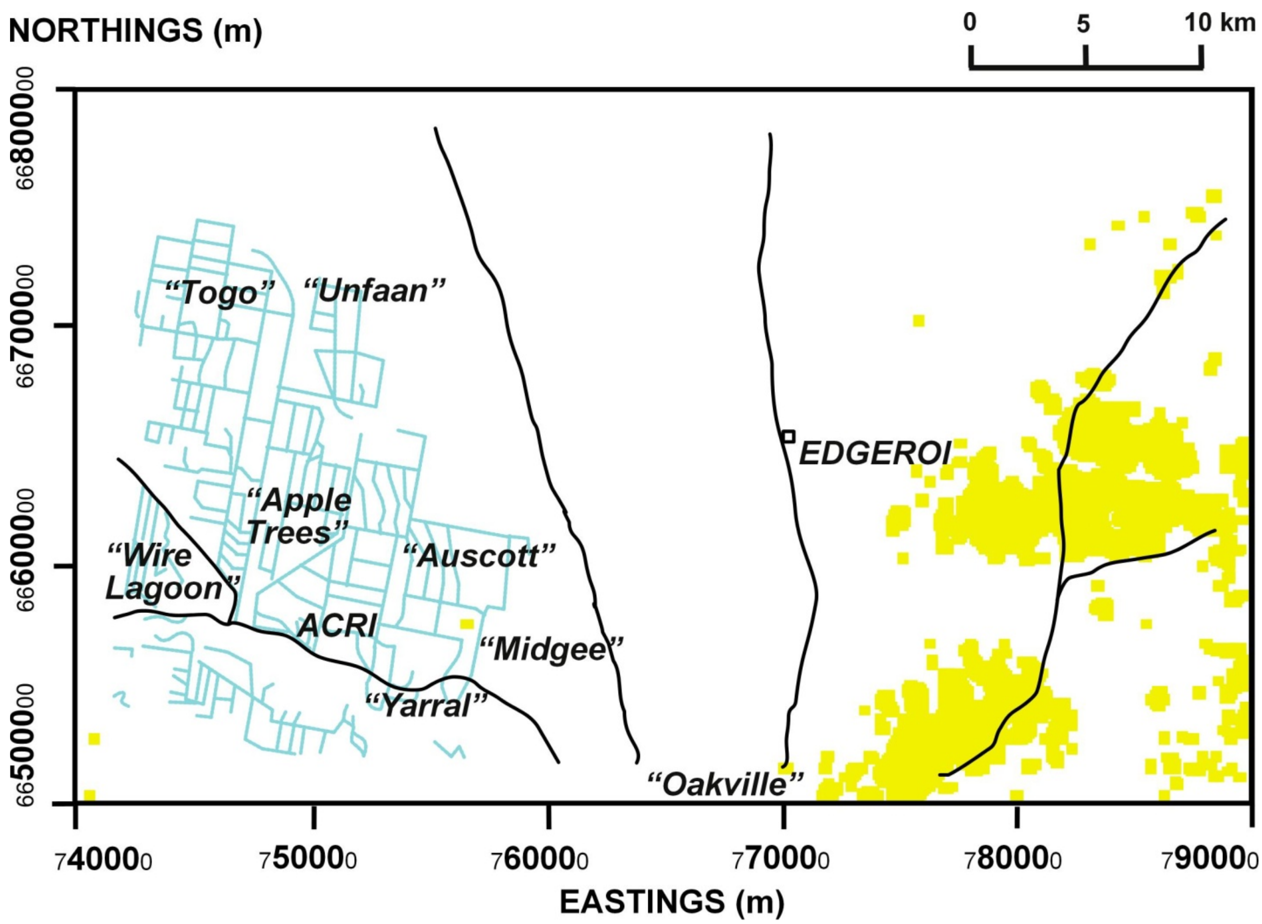
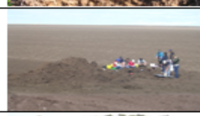
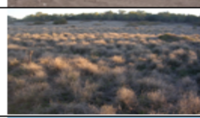


Figure 10. Spatial distribution of Class A across the Edgeroi study area.

Figure 10 shows the spatial distribution of Class A. It represents the extent of the Pilliga Sandstone outcrops (343 m) along the footslopes of the Nandewar Range. The soil is shallow and very sandy and provides low radiometric counts of K (0.991 cps) and high counts with respect to Th (8.669 cps) and U (1.690 cps). These values are typical of sandstones, which tend to accumulate Th and U. Given the soil is prone to erosion, the agricultural value of the land is not high and has remained relatively untouched and today is used as a State Forest.

Table 2. Attribute values for the centroids of the seven (*Classes A, B, C, D, E, F and G*) recognized classes defined by gamma radiometric data (*i.e.* Potassium (K), Uranium (U) and Thorium (Th) and Total Counts (DR)) and secondary data derived from a digital elevation model (i.e. DEM, Slope, Aspect, Profile (ProfC) and Plan Curvature (PlanC), Topographic Wetness Index (TWI) and flowac.

class	DEM	DEM	Slope	Aspect	ProfC	PlanC	TWI	FlowAc	DR	K	Th	U
A		343.8	1.85	246.8	0.101923E-02	0.274956E-02	9.57	120.8	44.40	0.991	8.669	1.690
B		227.2	0.39	267.1	0.312568E-03	0.489260E-03	10.55	41.59	43.03	1.329	6.320	1.340
C		212.8	0.28	286.5	0.266712E-03	0.216010E-03	12.79	86.87	39.60	1.158	6.237	1.286
D		229.1	0.42	273.1	0.359514E-03	0.259301E-03	12.08	66.67	30.36	0.690	5.471	1.300
E		285.7	0.94	272.3	0.705699E-03	0.102201E-02	10.20	49.50	30.75	0.837	5.170	1.143
F		250.9	0.85	67.99	0.897110E-03	0.116162E-02	10.45	101.4	38.26	1.085	6.191	1.321
G		299.4	0.88	265.8	0.122283E-02	0.496906E-03	13.49	401.6	41.20	1.378	5.702	1.264

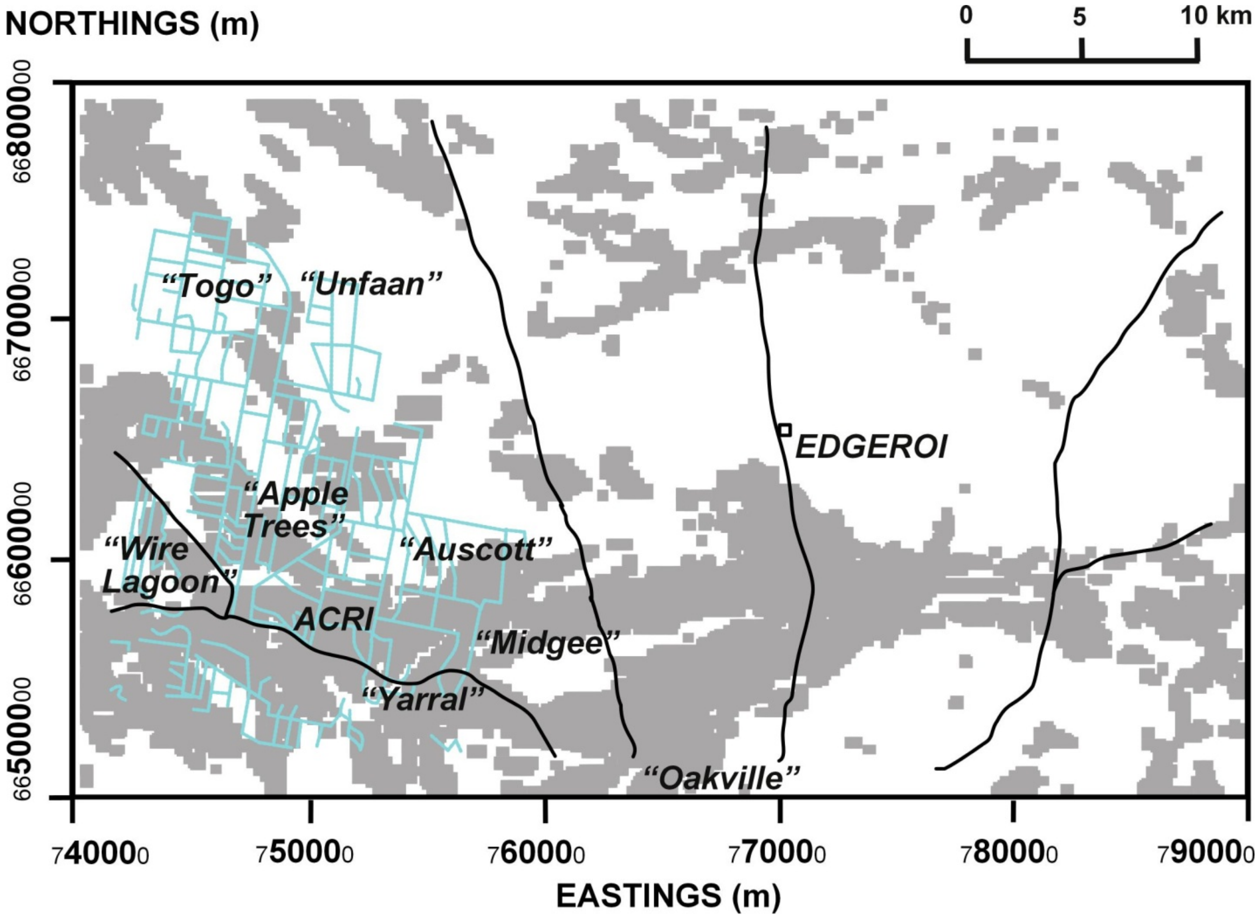


Figure 11. Spatial distribution of Class B across the Edgeroi study area.

Figure 11 shows the spatial distribution of Class B. This class represents the highest ground (227 m) associated with the depositional landscape. The class is synonymous with the current active drainageways and indicates the location of various prior stream channels. The latter is most apparent in the vicinity of ACRI and between *"Apple Trees"* and *"Wire Lagoon"*. Here the Namoi River used to run in a northwesterly direction. Given the sediments are slightly higher and the associated soil is less reactive that the Vertisols associated with Classes B and C, the early settlers developed Spring Plains Road on this type of soil. This is consistent with the belief that this material is a mix of basalt debris and Pilliga Sandstone.

Given the relatively younger age of the soil, this class has the second highest radiometric measurements in terms K (1.329 cps). It is also apparent that these sediments have equivalent radiometric signatures to those found in the northeastern part of the study area associated with Curramanga Creek and in the southern part of the study area associated with Spring and Bobbiwaa Creeks.

More specifically and with respect to the geomorphological and geological interpretations, it is evident that class B is strongly correlated with the youngest alluvial terraces of Namoi alluvium. Here, Ward (1999) identified distinct boundaries between the Namoi river floodplain, the first, second and third terraced fans. The clustering of the radiometric data suggests the geomorphological and geological units identified by Ward (1999) are more intermixed. This is consistent with the interbedded nature of sands and silty clays which appear as distinct strata in the soil profiles found in this strongly depositional environment which floods regularly.

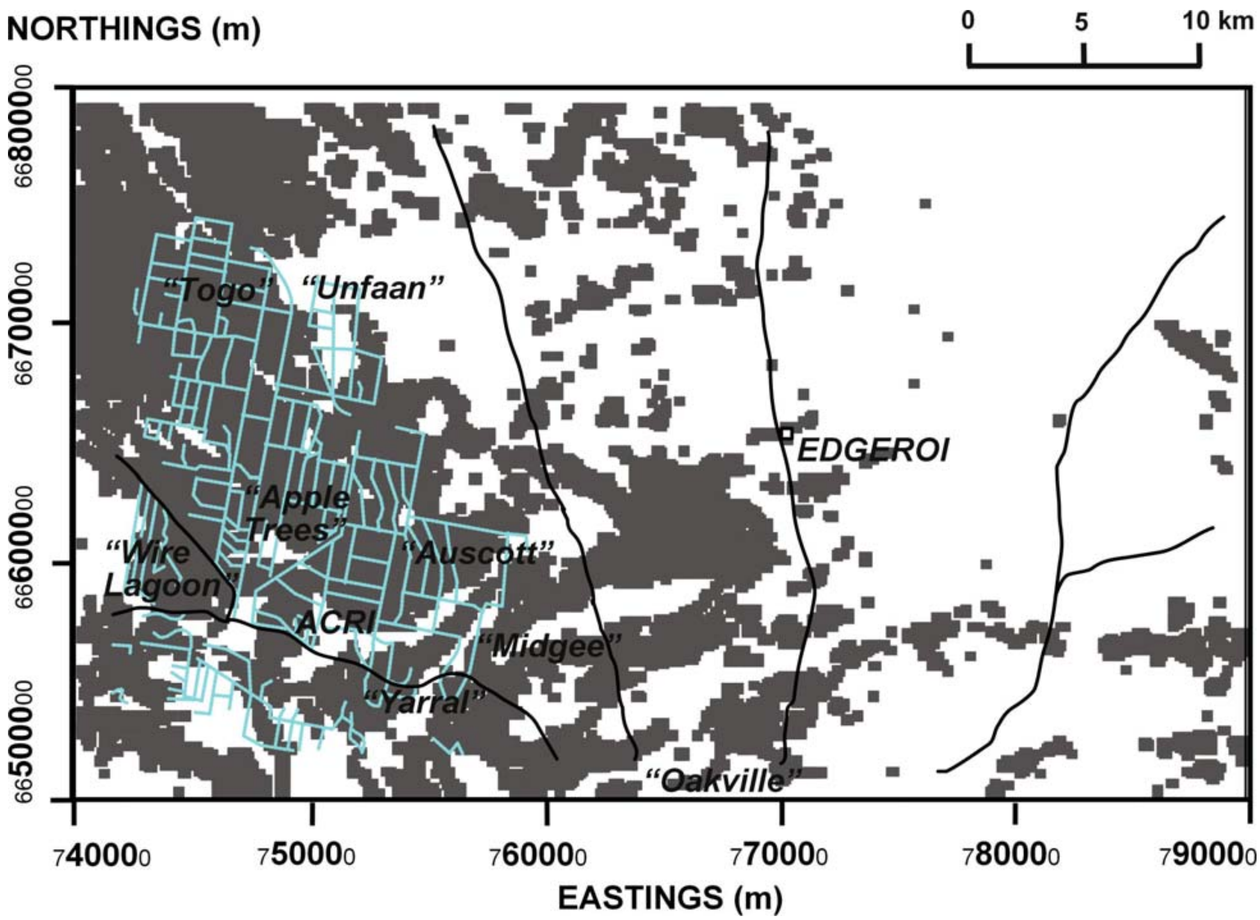


Figure 12. Spatial distribution of Class C across the Edgeroi study area.

Figure 12 shows the spatial distribution of Class C. It represents the next most recent alluvial sediments associated with the depositional landscape. It represents predominantly the third and fourth terraced fans of Namoi alluvium. The soil provides high radioelement counts in terms of K, which is consistent with the siltu clay nature of the topsoil. The high K (1.158 cps) can be attributed to the weathering of the felsic Nandewar Volcanics parent material in the upper parts of the catchment. This is because Felsic rocks contain large amounts of quartz, potassium and sodium feldspar. The latter two minerals are susceptible to chemical weathering due to the processes of carbonation and hydrolysis. The weathering of these feldspars can give rise to large amounts of K and Na. The dry climate means little of this is leached and results in the formation of montmorillionite clay minerals. Soil high in this mineral give rise to fertile Vertisols. This type of soil has very high agricultural value, particularly with respect to irrigation given the ability of the soil to shrink when dry and swell when wet. Much of the irrigated cotton growing area of the Edgeroi district has been developed upon this type of soil (e.g. *"Auscott"*, "*Yarral"* and *"Togo"*).

Ward (1999) identified the midpoint between Bald Hill and Wee Waa Roads as the demarcation between sediments associated with the fourth terraced fan of Namoi and local alluvium. Class B is strongly associated with the Namoi alluvium. It is clear that the fuzzy k-means clustering of radioelement data is able to delimit the soil in terms of age of sediments. That is, the soil close to the Namoi River the soil is younger than the soil on the first, second and third terraced fans of Namoi alluvium. The radiometric data reflects this as the relatively less weathered sediments closer to the River have much higher radiometric counts than those of the more weathered sediments on the older Namoi alluvial terraces.

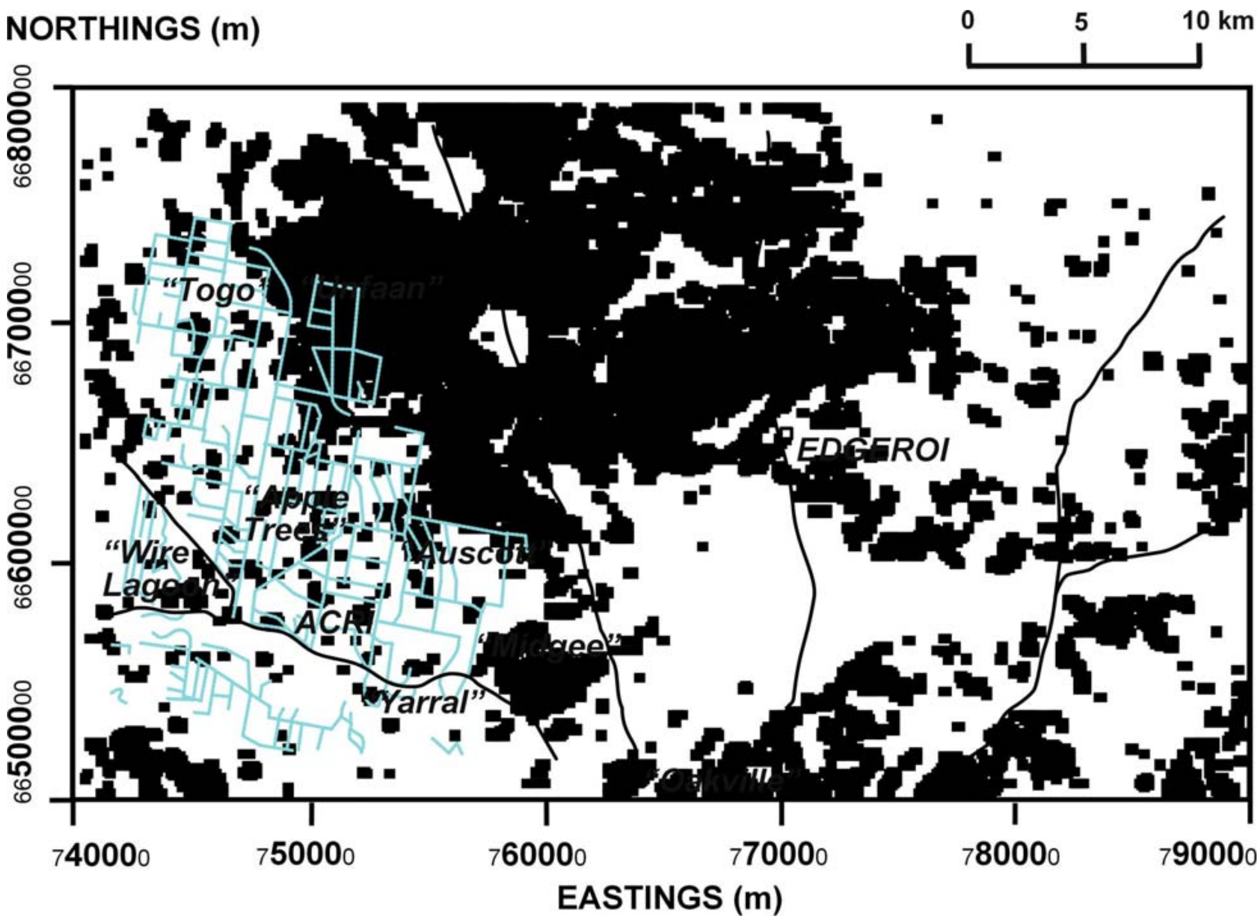


Figure 13. Spatial distribution of Class D across the Edgeroi study area.

Figure 13 shows the spatial distribution of Class D across the Edgeroi study area. It represents one of the largest contiguous areas identified and is associated with the older Namoi alluvial sediments associated with Namoi alluvium. Specifically, it demarcates the approximate extent of the fourth terraced fan and eroded fifth fan. The soil here is characterized by lower radioelement counts in terms of K (0.690 cps) as compared with the closely related Class C. This is consistent with the older nature of the soil. The reason for the lower K counts is attributable to the greater degree of weathering this soil has been exposed. Whilst the parent rock (Nandewar Volcanics) is similar, the soil has been exposed for a longer period of time to the action of chemical weathering. As a consequence the soil particle size fraction is clayier in nature and lower in K.

The Vertosols here however are higher in exchangeable sodium. This is due to the more mobile nature of sodium in the landscape and its redeposition via rainfall and winblown dust. Owing to the higher content of Na, the Vertosols in this part of the landscape are susceptible to dispersion. Soil dispersion causes clay particles to plug soil pores, resulting in reduced soil permeability. This is particularly problematic if the soil is repeatedly exposed to wetting and drying cycles (e.g. irrigation). The three main problems caused by sodium-induced dispersion are reduced infiltration and hydraulic conductivity, and surface crusting. This is particularly evident given the predominant land use in these areas is improved and native pastures for cattle grazing. This land use gives rise to a strongly poached topsoil particularly near stock dams and post heavy rainfall events. Along with the fact these Vertosols are located some distance from the Namoi River, the dispersible nature of the topsoil is the most likely reason the area was never developed for irrigated agriculture.

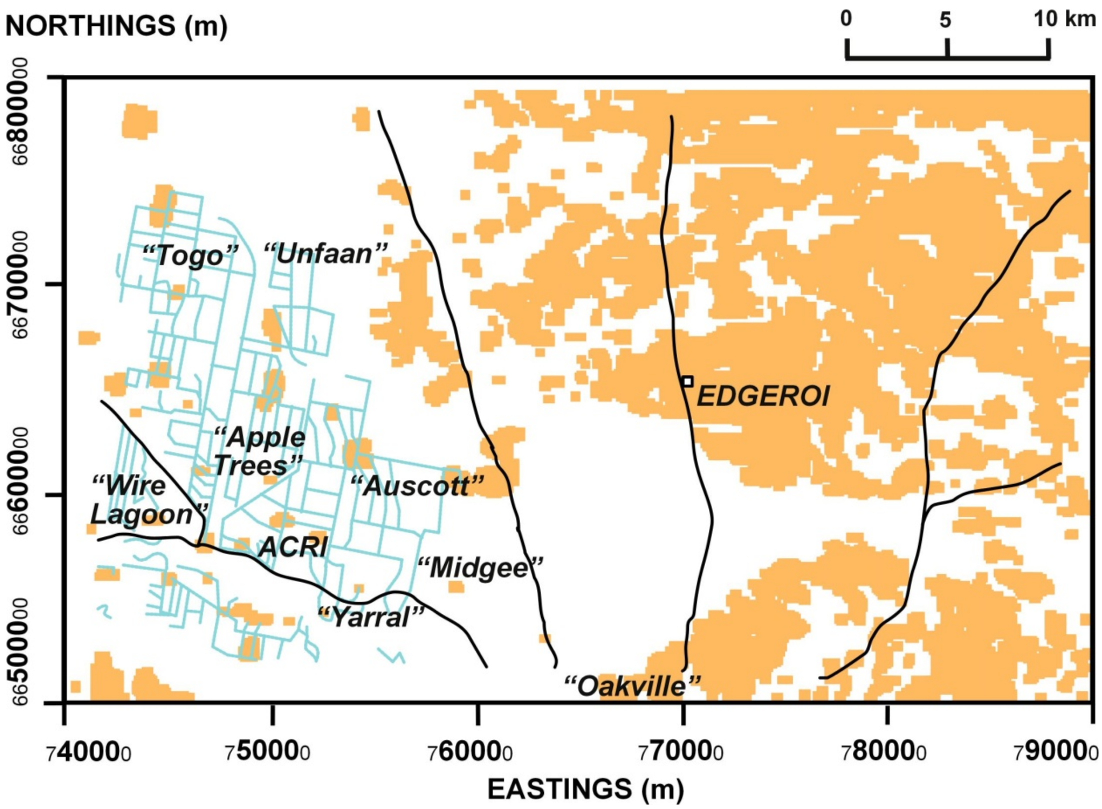


Figure 14. Spatial distribution of Class E across the Edgeroi study area.

Figure 14 shows the spatial distribution of Class E across the Edgeroi study area. It represents a broad range of geological and geomorphological units including Tertiary Weathered Sandstone, Pilliga Sandstone, the eroded fifth fan and to some extent the Garawilla and Nandewar Volcanics. Contiguous areas are also found in the depositional part of the landscape in the western part of the study area. Given the large number of units this class characterises and its spatial discontinuity, this cluster acts as an integrade class. As a result it is difficult to draw too many conclusions on its validity as a clustering unit.

Figure 15 shows the spatial distribution of Class F. It is evident that this class is not well represented within the Edgeroi 1:50,000 topographic map sheet. However, the class does occur near the eastern margin of the study area associated with the Nandewar Volcanics. Here the landscape is steep and is characterized by the highest Total Counts as well as the highest K, U, and Th. The reason for this is that the parent material exists as exposed and steep sided rock outcrops. The reason the class centroids of this class do not reflect this is that it also represents the two outcrops of Nandewar Volcanics found along the Bald Hill Road. This includes *"Bald Hill"* itself and at *"Green Timbers"*. This is also the case at *"Oakvale".* The interspersed nature of this class makes it difficult to fully interpret its significance other than it strongly indicates the source of much of the parent material associated with the depositional landscape and dust-mantled plains of Namoi alluvium.

Figure 16 shows the spatial distribution of Class G. It is characterized by the highest K (1.378 cps) and second highest elevation (299 m). Given the class is found in close association with the various drainage ways of the pedimented slopes and foothills of the Nandewar Range it is evident these sediments represent the most recent weathered products currently being deposited within the landscape. It also reinforces the notion that much of the material, associated with the depositional environment has its origins in the Nandewar Volcanics.

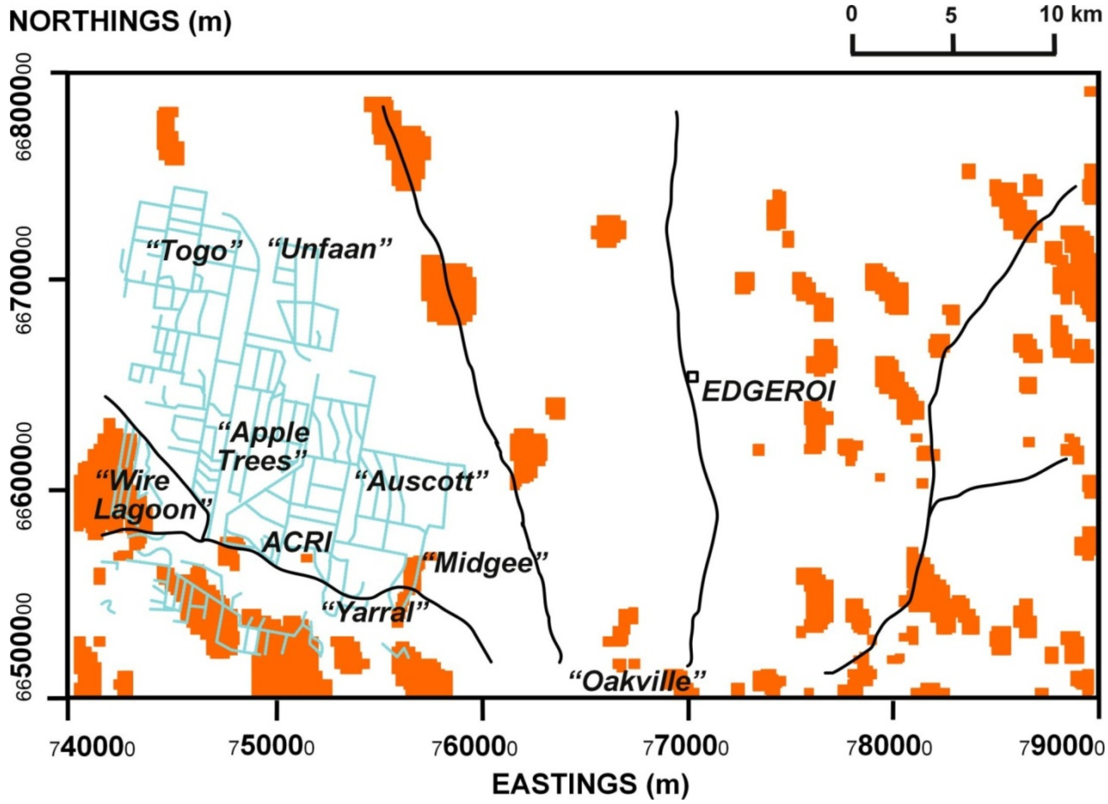


Figure 15. Spatial distribution of Class F across the Edgeroi study area.

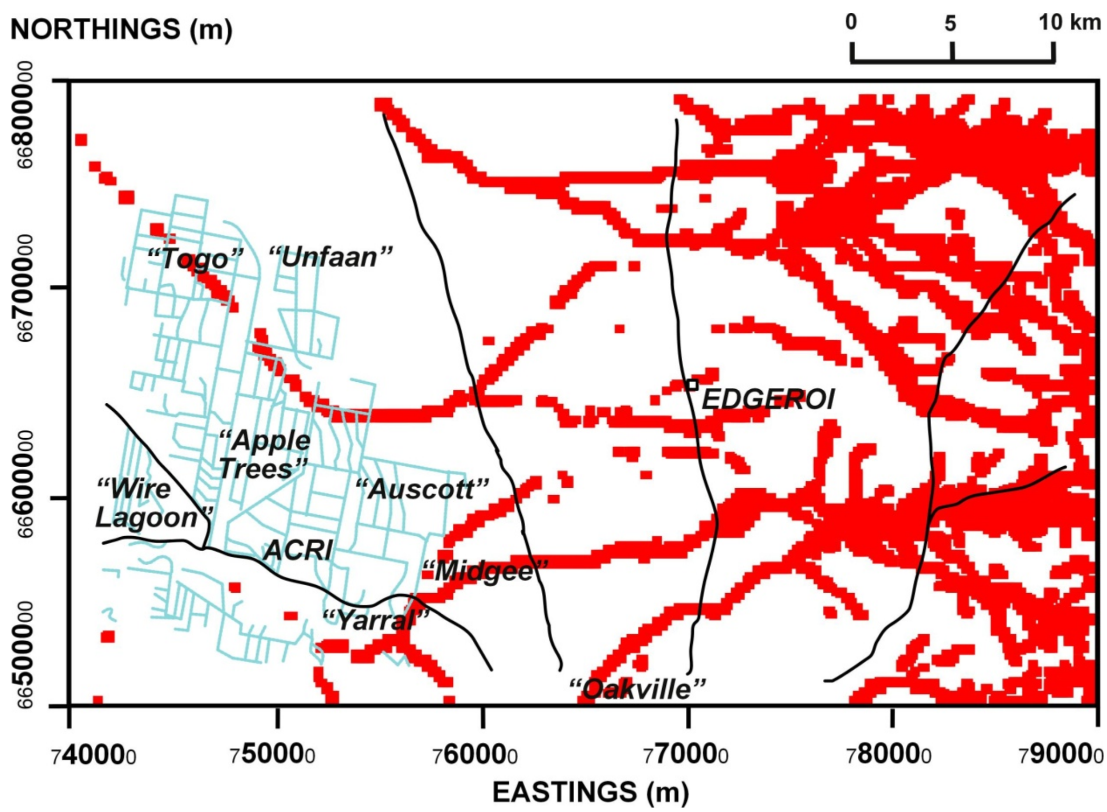


Figure 16. Spatial distribution of Class G across the Edgeroi study area.

4. Conclusions

This research showed how numerical clustering analysis using the fuzzy k-means (FKM) algorithm can be implemented to classify two sources of ancillary data: radiometric (*i.e.* K, U, Th and Total Counts); and, secondary data derived from a digital elevation model (DEM) information including slope, aspect, profile and plan curvature, topographic wetness index and flowac. The use of indices such as FPI and NCE and the derivative J_2(M,C) with respect to the degree of ϕ provided objective methods for choosing a suitable number of classes (c) and a suitable fuzziness exponent (ϕ). The approach therefore removes some of the subjectivity of conventional classifications on deciding how many classes exist and how individuals are allocated to them.

In a more practical sense, the FKM clustering of ancillary data across the Namoi valley, enabled differentiation of the three landscapes (*i.e.* depositional, erosional and dust mantled plains) identified by Ward (1999) in the Edgeroi district. With respect to the depositional landscape the approach was useful in resolving the subtle differences of geomorphological and geological units previously identified within the Namoi alluvium. This was particularly evident with the differentiation of the Namoi floodplain and first, second terraced fans (Class B) from the third and fourth terraced fans (Class C) of Namoi alluvium. In addition, the dustmantled plains associated with the fourth terraced fan of local alluvium and the eroded firth fan were also differentiated (Class D). The practical benefit of this is that research conducted in each of the areas demarcated by Classes B, C and D can be extrapolated to these areas with individual management (both agronomic and soil) tailored to meet the slightly variable nature of the soil associated with each class.

In this research the erosional landscape was not studied closely apart from the results shown at *"Bald Hill," "Green Timbers"* and at *"Oakvale"*. Here the soil was exclusively developed upon Nanadewar Volcanics and as such seemed to be classified into a discrete class (Class F). However, some caution is required as various other areas were discerned as having similar radioelement and DEM characteristics but were not recognized as such during detailed geomorphological and geological field surveying. This aspect will need to be studied in more detail, which perhaps could be achieved with more detailed surveys of these parts of the landscape using a ground based gamma radiometer or the study of a greater number of classes (*e.g.* k = 10, 11 or 12 classes).

Future work could involve the use of a similar suite of ancillary data variables with the inclusion perhaps of Electromagnetic (EM induction) data in the FKM analysis. In addition, further statistical analysis could involve the use of existing legacy soil laboratory data to test whether or not the classes identified are statistically different in terms of measured soil properties (e.g. pH, clay, silt, sand content, salinity, cation exchange capacity, and etc). Appropriate tests include: an analysis of variance or Tukey-Kramer analysis.

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