NSW Landscapes Mapping: Background and Methodology

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Disclaimer

The methodology described in this document applies to the NSW (Mitchell) Landscapes version 2, compiled in 2002 by Dr. Peter Mitchell under contract to the (then) NSW National Parks and Wildlife Service.

Since the original mapping of NSW Landscapes in 2002, several more fine scale data layers have been made available, including SPOT 5 satellite imagery, NSW wetlands, contours and improved drainage layers. The availability of these finer scale data layers highlighted spatial inconsistencies in the NSW Landscapes data layer, identifying areas where shifts in data have occurred, or where the original digitising did not capture the intricacies of the underlying environment. In response, in 2008 the Department of Conservation and Climate Change (DECC) undertook a review of the bounds of the NSW Landscapes.

The analysis undertaken originally identified a range of errors and inaccuracies with the bounds of the NSW Landscapes data layer, predominantly in the eastern half of the State, including:

- shifts in the Landscape polygons;
- problematic outliers in the Landscape layers;
- overlaps and gaps along Landscape boundaries;
- inconsistencies in the delineation of some Landscapes.

Correction of these errors was undertaken by Eco Logical Australia under contract to DECC. Correction of the NSW Landscapes layer was confined to fixing boundary errors, and no attempt has been made to redefine the landscape classes, or their descriptions. The review has resulted in a new version - version 3 - of the NSW landscapes layer being compiled and made available. As the review focussed on revision of bounds of the landscape layer rather than the definition of the landscape themselves, the methodology described in this document still serves as the basis for the NSW Landscapes version 3.

Details of the update are available in the following documents (available from the DECC Download site):

Eco Logical Australia, (2008). Editing Mitchell Landscapes, Final Report. A Report prepared for the Department of Environment and Climate Change.

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Introduction

This document provides background to the development of the NSW Landscapes mapping also known as the Mitchell landscapes. This mapping was undertaken by Dr Peter Mitchell under contract to the NSW National Parks and Wildlife Service. The mapping was undertaken to provide a meaningful framework for the NSW Ecosystems Database and by creating a consistent state wide map using the best available data also provide the means for developing conservation priorities and tracking conservation progress across NSW. The resulting mapping had a strong physical component because of the limits imposed by the best available data. However this primarily geomorphic map is a useful adjunct to more detailed vegetation mapping where the latter is available. It is because of the strong geomorphic component to the mapping that the name of the mapping was altered to NSW Landscapes. This name change occurred following the submission of the report by Dr Peter Mitchell.

This report describes the methodology adopted, the ecosystem models used, and discusses the strengths and weaknesses of the product. Recommendations for further work involving validation of the mapping are included. The report below may be cited as P.B.Mitchell (2002) NSW Ecosystems Study: Background and Methodology (Unpublished).

Previous maps with identifiable ecosystem components.

No ecosystem maps have ever been produced for the whole of NSW but several parts of the state have been mapped on a multi-factor basis and some of this material is closely related.

Over more than 50 years many different landscape mapping exercises have been conducted in Australia. The purpose of these surveys was to obtain a comprehensive overview of different regions for broad scale planning. These surveys attempted to integrate knowledge obtained by other special purpose surveys (thematic maps) such as that contained in geological or soil maps and it was expected that the resulting composite map would provide more useful information. Government agencies in all states have undertaken such work and two divisions of CSIRO were involved. Over time, a more or less common approach and methodology evolved.

Assumptions and weaknesses in multi-factorial landscape mapping.

All multi-factor maps and survey systems assume that particular land attributes are inter-dependent and that they occur in identifiable sets or patterns. It also assumed that a hierarchy of natural system patterns could be identified. These are visualized as recurring patterns of topography, geology, soil and vegetation. From these assumptions it follows that if basic patterns can be identified on air photos or other forms of remote sensing then the spatial distribution of attributes not visible on those sources can be reasonably predicted. It further follows that the resulting maps should be of value in making land use decisions, and in fact most such maps have been constructed for an expected audience of decision-makers (planners) and land users.

Arguably the most successful multi-attribute mapping technique has been the Land System approach (and its derivatives) used by CSIRO Division of Land Research from 1946 to about 1980. These maps cover large parts of inland Australia but the process through which they were prepared was both qualitative and subjective. Survey teams differed in their perception of the mapping task and there has been little assessment of the accuracy or reliability of the product. All such maps have used a hierarchical classification of Land System, Land Unit, Land Component and sometimes a Landscape Element. The key was the land unit defined as related sites that can be described similarly in terms of their major inherent properties of geology, geomorphology, soils and vegetation.

Typically land units were not mapped because they are generally small features but they were described in text and diagrams within the larger grouping of land systems – a land system being a common assemblage of land units. Land system maps were usually produced at 1:250,000 scale and were based on air photo interpretation and limited field descriptions at sample sites (for examples in NSW see; Story et al., 1963, Mabbutt et al., 1972, SCS 1978-1987, and Walker 1991.)

Another approach that was more strongly rooted in physical measurement and thus more quantitative, was used by CSIRO, Division of Applied Geomechanics in the 1980s. This was the PUCE system (Pattern Unit, Component, Evaluation) in which a more comprehensive and more rigorous hierarchy was involved. This comprised; Province, Terrain Pattern, Terrain Unit and Terrain Component. Unfortunately this mapping was only completed in NSW for the 1:250,000 Sydney map sheet (Finlayson 1982.)

For those parts of the state not covered by land system mapping (most of the Eastern and Central Divisions) only single attribute mapping is generally available, that is, topography, geology, some soil landscapes and some vegetation. Presentation scales, unit classifications, and the ages of these maps differ.

With the advent of remote sensing and GIS the mapping approach changed because greater quantities of data could be manipulated. O'Neill (1989) provided an early example of the potential of the remote sensing approach and Sattler and Williams (1999) provide a modern example that appears to be more rigorous than its predecessors but in fact still relies heavily on the earlier land systems work for identifying and defining units. In mapping Queensland's bioregional ecosystems these authors defined a regional ecosystem as a vegetation community in a bioregion that is consistently associated with a particular combination of geology, landform and soil – essentially this is a rephrasing of the definition of a land system.

Sattler and Williams (1999) adopted an open ended numerical system for regional ecosystem classification with the specific inclusion of land zones in their hierarchy. Each regional ecosystem is given a three-digit number. The first digit refers to the 13 broad scale biogeographic regions. The second digit refers to the 12 stereotyped land zones that are a simplified geology-substrate-landform classification developed for Queensland. The third digit is the unique regional ecosystem number. For example in the code 5.3.1: the numeral 5 refers to the Channel Country Biogeographic region; 3 refers to land zone 3, level alluvial plains including older floodplain remnants and piedmont fans; and 1 refers to regional ecosystem 1, *Eucalyptus camaldulensis* +/- *Melaleuca* sp., on levees and banks of major rivers.

This specific use of a landform category (the land zone) by Sattler and Williams (1999) in the classification at a level higher than vegetation associations is an important part of the Queensland system. It has parallels in the earlier land system mapping of western NSW by the Soil Conservation Service (SCS 1978-1987). In this latter case the categorization only occurs in the legend of the map sheets where the Land Systems are grouped under different topographic environments. Although geology and soil were described for each land system by Walker (1991) those properties were not used so directly in classification.

The use of a land zone concept provided a route for defining the Western Division Land System maps into a surrogate for ecosystem maps. However the land zones identified in Queensland have been subject to criticism (Harris 2001 draft) and the same set of zones should not be uncritically applied to a NSW or to a national mapping system.

The only mapping directly linking geology, geomorphology and soils in NSW are recent examples of regolith mapping and soil landscape mapping.

Regolith studies (Ollier and Pain 1996) incorporate geology, geomorphology and soil science into a single discipline that deals with the blanket of surficial materials over the whole landscape. Regolith is both the residual (saprolite) and the transported mantle of debris derived from bedrock and moved by geomorphic processes. It differs in age from place to place and is the material in which most soils (in the conventional sense of soil profiles) are formed. Regolith studies attempt to take account of the impact of changing climates on stable landforms not only through the Quaternary (last 2 million years), but also over much longer spans of geologic time through the Mesozoic (past 225 million years) and sometimes beyond.

The Cooperative Research Centre is developing regolith-mapping techniques for Landscape Evolution and Mineral Exploration in Canberra. A number of 1:250,000 scale maps have been produced for different parts of Australia including several in NSW. This mapping has much in common with land system mapping but identifies different boundaries. Where available regolith material concepts and/or identified regolith landform mapping units were taken into account in the construction of the ecosystems maps.

Gibson and Wilford (1996) produced a regolith landform map for the Barrier Range in western NSW at 1:500,000 scale. This is the only such map yet available for western NSW and Gibson (1998) discussed its merits. It does show a relationship to the land system maps of the area but it is not possible to simply amalgamate boundaries as a step toward defining ecosystems

Soil landscape mapping undertaken by the Soil Conservation Service has been published at two scales, 1:250,000 and 1:100,000 for much of the Eastern and Central Divisions. The identification of soil landscapes is similar to the identification of land systems in that categorization takes account of geology, topography, soil profiles or soil layers and elements of vegetation. However the current extent of the mapping was not so great that it provided an immediate and uniform approach to ecosystem mapping of the entire area so this material was set aside to be used subsequently as a first pass means of validating ecosystem boundaries drawn from other sources. This checking has not been done under this contract and is recommend as further work.

The only example of specific regional geomorphic mapping in NSW was completed for the southern Riverina by Butler et al., (1973). Although this map was relatively old and not drawn on a modern base the content of it is much more detailed than any other available source material (geology or topography). The landscapes depicted are compatible with units of the land systems in the Western Division maps and because the area covered an important part of the state that is not well served by recent geologic maps this work was used as the basis for interpretation of that region.

Issues of boundary identity and scale.

It is important to recognize that even in the most defined surveys, such as those using PUCE, the mapped boundaries of any defined area are an artifact created by the surveyor. Natural system boundaries are generally imprecise zones of change and their depiction on a map as a sharp line can be misleading if their limitations are not acknowledged. At any one point on a mapped boundary it is not always possible to determine why the surveyor selected that location. At other points on the same boundary it may be more obvious, for example, as a topographic break or a geologic change. Broadly speaking, real boundaries may be one of three types; distinct ecotones such as around the margins of a lake, arbitrary lines placed within the centre of zones of change, or fuzzy boundaries reflecting a zone of change that perhaps varies with seasonal conditions. Other types of boundary might be those derived from interpretation of secondary sources, air photo interpretation for example, or those confirmed on the ground

None of the source maps used in this contract differentiated boundary types consistently and therefore no differentiation has been made in the ecosystem layers. At some later stage after verification of the maps a boundary classification might be included and this is recommended as possible further work.

Drawn boundaries and areas of land systems are also subject to the definition limits of map scales. On 1:250,000 sheets a typical line represents about 100m on the ground. The smallest area that can be plotted is about 2mm in diameter and this represents 20ha on the ground. In practice few maps would plot land system features smaller than about 1km in diameter and this represents about 80 ha on the ground. To further complicate this issue of interpretive use, it is necessary to recognize that land systems are not ecosystems although they should be a useful means of developing ecosystem surrogates. Biological processes and the exchange of energy and matter (essential parts of the definition of an ecosystem) are very likely to cross land system boundaries and 'real' ecological boundaries, or zones of minimal interchange, can be quite wide and dynamic. This is particularly true in the arid zone where ecosystem processes are driven by rare events of high rainfall and infrequent but major disturbances. To enable the conversion of land system maps or other thematic maps to ecosystem maps it is necessary to accept a model (or models) of ecosystem dynamics that identify the abiotic components of ecosystems that are believed to be important drivers and constraints on ecosystem processes. This will be considered below.

Data and map availability.

The intent of this contract was to develop 'ecosystems' that were constructed with a strong physical base that is, a geologic, geomorphic and pedologic base. The contract was intended as a paper review and did not include any field validation or original mapping. It was therefore dependent on existing data that could be used to construct geomorphic units that were then assembled into coherent 'ecosystems'. This objective immediately constrained the scale and reliability of the end product because across the whole of NSW the only consistent coverage of suitable raw data was 1:250,000-scale mapping of topography and geology plus the Western Division land systems maps. In the remainder of the state a patchy cover of land system maps, soil landscape maps and vegetation maps at several different scales and of different ages was also available. For the most part these were maps were not used other than as a secondary check on interpretations drawn from the primary sources.

Even the geological cover was found to be inconsistent in quality and reliability because the existing map coverage varies in age from first edition sheets surveyed and published in the 1960s to much more detailed and reliable sheets produced in the last few years. Age differences between adjacent map sheets created quite serious problems in identifying and extending geologic and ecosystem boundaries across map edges.

In addition to this material the National Parks Association and others had commissioned a series of reports that now cover the state at a coarser level (for example, Morgan and Terrey 1992). The whole of Queensland was covered in 1999 by Sattler and Williams and the entire country has been subdivided into bioregions in the Interim Biogeographic Regionalisation for Australia program (IBRA) through the Australian Nature Conservation Agency (Thackway and Creswell 1995, Environment Australia 2001).

Whilst all these approaches are commendable and internally consistent, they do not mesh as neatly with one another as would be desirable to obtain the most effective information sharing and data collation at a common scale and it was necessary to establish a separate framework for undertaking this mapping task.

The ecosystem concept adopted.

The objective of this contract was to produce maps of ecosystems from available resources describing other land attributes. Definition of the ecosystems was to emphasize geologic, geomorphic and pedologic factors and to achieve this it was necessary to define the concept of an ecosystem and to identify relevant land attributes of ecosystems that could be obtained as spatial data on the available maps.

Ecosystems can be described as communities of organisms interacting with one another and with the abiotic parts of the environment in which they live. This definition is independent of scale.

Ecosystems are a core concept in ecology that was established in the early 20th century and dealt with the study of system forces such as energy flow, nutrient cycling, community structures, and species competition. These ideas were developed using related concepts of succession, climax communities, and equilibrium, and ecosystem boundaries were defined as zones of minimum exchange of energy and matter between adjacent ecosystems. Such ecosystems are generally considered to be closed for matter and open for energy and there is an extensive literature on the field that includes ecological modeling that is often focussed on ecosystem management.

However black box, closed ecosystems are not the only way in which natural ecological systems have been identified and investigated. Open systems are also recognised. For example a river carrying water, nutrient, sediment and life forms from mountains to the sea is a legitimate study focus. Even more open or “chaotic systems” can also be considered. Disturbance, chance, and individual animal behavior drive these. They appear to defy concepts of self-organising principles and the human belief that ecosystems should somehow contain holistic benefits to all included populations. Systems of this nature have very patchy distributions of organisms and this field has become known as the study of patch dynamics (Pickett and White1985).

Clearly the older concept of self contained, readily definable ecosystems that underlies land system mapping and much of our environmental management philosophy is not without modern challenges (see; Pickett and White 1985, Trudgill 1988, Peters 1991, and Drury 1998 for extended discussion). However the brief for this project did not allow any original mapping and as noted above, it required an emphasis on geologic, geomorphic and pedologic parameters in the definition of ecosystems. The question then became a matter of identifying available mapped data that could be used to define ecosystem boundaries.

The first stage of the selection process was to construct a table of ecosystem factors from which single properties for which spatial data was available could be selected as a basis for mapping.

The State was arbitrarily split in two with the Western Division being treated as an arid environment and the Eastern and Central Divisions as a temperate environment. Although these are political divisions they are broadly coincident with major differences in geomorphology and they have long been used as floristic divisions by many authors such as Anderson (1947) and *Cunninghamia.* The Western Division boundary was also the limit of land system mapping done by the Soil Conservation Service (Walker 1991) and that data was selected as the main base for western ecosystem mapping. Table 1 briefly describes and isolates some of the major factors and processes operating within ecosystems that individually or in concert can serve to define them. It is immediately apparent from Table 1 that only a small number of factors have readily definable spatial patterning that could be used to map discrete ecosystems. These factors and their limitations were:

- **Rainfall.** Broad patterns available across the state, and point specific information for individual observation points.
- **Temperature.** As for rainfall except that altitude and aspect effects are not mapped.
- **Topography.** Available at 1:250,000 and 1:100,000 scale and as a digital elevation model in the NPWS GIS.
- **Drainage patterns (catchments).** Available at 1:250,000 and 1:100,000 scale with two versions in the NPWS GIS. In the western half of the state there are significant differences in stream location and catchment boundaries between these versions. However entire catchments of the larger streams were too large to be used as ecosystem boundaries and this parameter was not used frequently.
- **Geology.** Available at 1:250,000 and as a digital layer in the NPWS GIS. The original source of the digital data was not certain and errors were found in a number of sheets. As mapping proceeded differences between geologic maps of different ages (1960s to 2000) had to be rationalised and acceptance of older data was one of the unavoidable constraints on the reliability of the final ecosystem maps.
- **Soil.** Not available for the entire state except at 1:2million scale (Northcote et al., 1960-1968). Included in Land System mapping in the Western Division and available for some 1:250,000 and 1:100,000 sheets elsewhere. Only the Land System maps were available digitally in the NPWS GIS.
- **Vegetation.** Only available at a range of scales on maps of different ages that typically used different forms of classification.

Table 1. Relative importance of factors influencing ecosystem structure and dynamics across New South Wales.

Western NSW	Eastern NSW
Climate and atmosphere. Limited and highly variable rainfall. This may be local rainfall, or more distant water delivered by floods over extensive areas and for a period of months – the channel country model. El Nino Southern Oscillation (ENSO) links between major flood and drought cycles are now recognised (Nicholls 1991). High rainfall intensity and high soil erosion potential. Storm rains are common and the reduced vegetation cover of the environment allows more soil erosion than in other environments. In some soils, and under some management regimes, this is modified by protective cryptogamic soil crusts. Extremes of high and low temperatures on a seasonal scale. The temporal scale of this effect ranges from diurnal cycles to seasonal cycles. The geographic scale varies with altitude and aspect. High insolation, high ultra-violet exposure, high evaporation rates, and low humidity. Persistent, desiccating, turbulent, and often dusty winds. Extensive dust mantles (parna) are a feature of southern Australia.	**Climate and atmosphere**. Rainfall is generally less limiting but snowfalls become important in high altitude areas. ENSO still controls flood and drought cycles. Rainfall is arguably less important than slope and vegetation cover in modifying soil erosion potential. Seasonal temperature extremes remain important but are also linked to altitude, as is exposure to ultra-violet light. Evaporation rates are generally lower, humidity higher. Cyclic salt inputs are higher but flushing by high precipitation and runoff is more effective.
Topography. Variable aspects and shelter. Surface water supply is limited by topographic features such as availability of deep water holes in protected gorges or scour holes on large valley floors. Variable impacts on surface water detention storage, infiltration and runoff related to slope. Strong control on soil erosion through slope. Variable impacts on nutrient redistribution in runoff also related to slope, soil conditions and bedrock type.	**Topography**. Many of the same conditions apply, but surface water and running streams are more generally available. Soil erosion is affected by slope but vegetation cover is more important.
Geology and soil. Rock outcrops provide shelter and generate very local runoff from even minor rainfall events. Rock type affects soil texture and water holding capacity of soils. Often low to very low soil nutrient availability depending on; soil/rock relationships, and erosion, transportation or depositional environments. Often high soil pH, normally caused by accumulation of carbonates that may be delivered as atmospheric dust. Sometimes high soil salinity even to toxic levels. Particularly marked in depositional environments that are local sinks for dissolved load. Sometimes unusual soil mineral composition depending on bedrock type. Soils with extreme shrink swell behavior and deep cracking are common in depositional clays. Major recent soil erosion evident as a result of human	**Geology and soil**. Many of the same conditions apply but broadly speaking there is a greater range of rock types present, many of which develop soils with greater fertility. Extremes of soil pH and salinity are less common. Depositional sands and loam are more common then harsh clays.

interaction.	
Organisms. Unusual but very variable fire regimes. Fire frequency and intensity is largely dependent on available fuel and this reflects previous good seasons and high biomass. Limited shelter in many plant communities because of low canopy and/or low density of cover. Booms and busts in populations relating to episodic water availability and thus very variable levels of competition, predation, and grazing pressure etc. Limited trophic pyramids where invertebrates play significant roles (before the introduction of domestic stock). Short life cycle times and other adaptations to the "stop/go ecosystems" driven by water availability. Major recent invasions of new species and loss of native species as a result of human interaction.	**Organisms**. Fire regimes reflect climatic conditions of drought. Multiple layered canopies are more common. Boom and bust cycles are rarer as bioproduction is less limited by climatic variablity. Complex foodwebs and trophic pyramids are more normal and this reflects greater stability in ecosystem composition and structure. Bioproduction is more consistent through the year. Organisms with longer life cycles are more typical.
Combined conditions. Rare event conjunctions are a major disturbance factor. For example, extensive flooding at a time when grazing pressure was reduced by extreme drought. These events are unusual (frequency is typically greater than 1:10 or more) but are also often linked. Floods do follow drought, and fire does follow flood. The combined pressures of two or more events occurring close together can fundamentally change the composition, structure and functioning of entire communities. Disturbance at this scale is possibly the most important factor in defining ecosystems in the arid zone at any one time.	**Combined conditions.** Rare event conjunctions are still important in affecting composition and structure of the ecosystems. However there may be more resilience in the system and unexpected directional changes are perhaps less frequent.

Mapping framework adopted for the Western Division.

As noted in the context of Table 1 many of the factors affecting ecosystem dynamics are not readily available from maps and it was therefore necessary to be selective of the components represented in the map framework. Fortunately one universal component of all terrestrial ecosystems is the availability of water. Water is variably distributed in the landscape depending on other factors such as precipitation, soil conditions, slopes, vegetation cover etc., and water plays major roles in the redistribution of plant nutrients and toxic compounds such as salt. The relative absence of water (drought) can even be seen to be a factor in other forms of biotic disturbance such as fire. There are feedbacks in all of these relationships and it follows that if water distribution is used as the key identifying factor in any landscape then the role of water driving geomorphic, pedologic, and biologic processes can be used to identify ecosystem boundaries. The general relationships outlined here are illustrated in Figure 1.

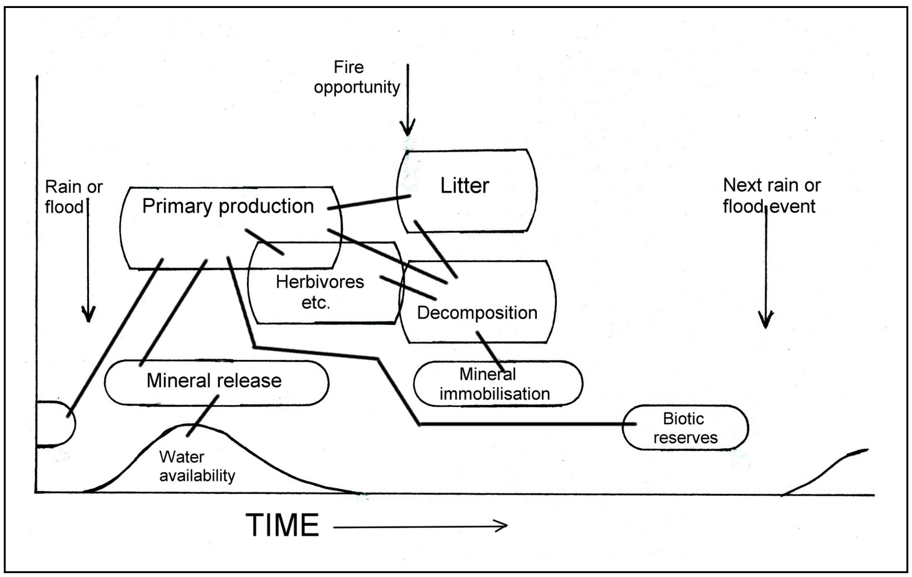
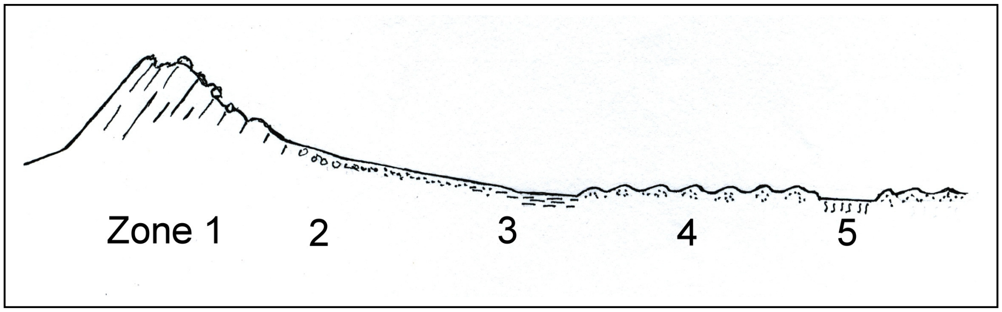


Figure 1. The general effects of water provided as a pulse on the sequential timing and processes in an arid zone ecosystem. Timing may vary from weeks to decades depending on ecosystem scale and geographic location. In a more humid environment pulsing is less important and other factors become limiting.

This model applies in the arid western zone where it has been recognised explicitly or implicitly by many workers including; Mabbutt (1984), Ludwig (1987), Thomas and Squires (1991), and Safriel (1999).

Figure 2 illustrates how water distribution can be used to assemble a simple geographic model of an arid zone ecosystem that can be interpreted at any scale from a single range of hills to a more regional view such as across a major catchment. Despite the obvious risk of over-simplifying a complex real environment this model of arid zone dynamics was accepted as the basis for ecosystem identification in the western half of NSW. Water distribution in turn is controlled by small to medium catchments and it can also be used in discrete parts of larger catchments such as by identifying flood flow patterns on riverine fans.



Zone 1. Hill country with rock outcrop, steeper slopes and thinner soils. These act as source areas for runoff, sediment and nutrients. They are erosion zones. They also provide aspect shelter, shade and refuge areas during drought because even small rainfall events enable some primary production when runoff from rock surfaces irrigates soil patches. Soil quality relates directly to bedrock type.

Zone 2. Colluvial footslopes and pediments where soil material is redistributed from the upper slope, or bedrock is exposed on etch surfaces. These are transport zones for runoff, sediment and nutrients. As the slopes decrease the soil mantles become finer and may exhibit runoff/runon patterning in the vegetation such as mulga groves. After good rains the highest bio-production occurs in transport zones and this may lead to more frequent fire.

Zone 3. Distant footslopes, clay pans and playas where fine sediment is deposited from Zones 1 and 2. Although nutrients are available bio-production decreases relative to Zone 2 because the more clayey soil yields less water. This area is a changing interface between the transport zone and the depositional zone. It is less frequently irrigated because larger rainfall events are needed to drive it.

Zone 4. Aeolian sand plains or dunes distant from hillslope or other sand sources. These are normally beyond the reach of flooding and irrigation from hillslopes and rivers. Primary production is limited by low nutrients in the sandy soil, and by available water because the regolith absorbs virtually all the rainfall and does not concentrate it by runoff/runon except in clay swales between dunes. Paradoxically fire frequency can be quite high in some environments such as hummock grasslands where the fuel is very flammable.

Zone 5. Salt lakes where soluble elements delivered by surface or groundwater flow may concentrate as calcite, gypsum and halite. Primary production is normally low and the biota are specialised. These are one of the few clearly defined ecosystems in the arid zone.

Note: Large rivers with external water sources may flow through any part of this model.

Figure 2. Schematic model of the geography of an arid zone ecosystem.

Step by step methodology: Western Division.

In the Western Division the SCS land system maps were accepted as the base data. Work was split into manageable pieces on the boundaries of the 1:250,000 sheets and within the IBRA regions and the provinces or sub-provinces identified by Morgan and Terrey (1992). As the interpretation progressed IBRA boundaries were sometimes found to be inconsistent with ecosystem boundaries and these were highlighted for subsequent revision.

Step 1. The 1:250,000 Land System map sheets were reviewed to identify groups of land systems that could be assembled into coherent ecosystems on the basis of the model in Figure 2. The identification of natural topographic boundaries such as ranges and their catchments were important in this selection process. Because water flow was accepted to be the driving agent ecosystem boundaries extended downstream into floodout zones and often crossed IBRA boundaries and the province boundaries of Morgan and Terrey (1992).

Step 2. The GIS coding of all land systems within the defined ecosystems were listed and these were assembled in the GIS for editing on the screen (Step 3).

Step 3. Screen editing was a protracted process that involved making judgements about outlying elements and the coherence of the identified patterns. Editing went through several iterations:

i) on first assembly,
ii) when extending ecosystems to a new map sheet,
iii) after checking boundaries against other maps such as geology and regolith,
iv) after review by the Technical Working Group,
v) on final assembly of meso-ecosystems.

Step 4. When ecosystem boundaries were deemed to be acceptable, groups of ecosystems were assembled into meso-ecosystems representing larger natural entities based on topography and geology. The naming of ecosystems and meso-ecosystems was standardized so that each name provided location information and a meaningful descriptive landscape term.

For example: the Broken Hill Complex meso-ecosystem consists of the following ecosystems:

Barrier Ranges (parts of 6 land systems)
Barrier Tablelands (parts of 4 land systems)
Barrier Downs (parts of 9 land systems)
Barrier Alluvial Plains (parts of 6 land systems)
Barrier Sandplains (parts of 6 land systems)
Barrier Fresh Lakes and Swamps (parts of 2 land systems)
Barrier Salt Lakes and Playas (parts of 1 land system).

Step 5. The final step was compilation of a generic description of the ecosystems by assembling the common and dominant elements in the separate land system descriptions of Walker (1991). Walker's text was used for this step as inconsistencies were found in the map legend descriptions for the same land system on different map sheets.

Mapping framework adopted for the Eastern and Central Division.

In the more humid environment of the Eastern and Central Divisions of the state, water availability is more uniform and it can be argued that other factors such as; total rainfall, temperature gradients, and soil quality will limit seasonal variation in ecosystem bioproduction. Geology and topography using the following arguments can substitute these factors.

Geology.

Geological structures have a strong impact on geomorphology and where such data is available it should be incorporated. For example some landforms are the direct result of geologic events such as volcanic cones and craters, and fault scarps. Other landforms secondarily reflect geologic structure such as; drainage patterns dictated by joint sets, weathering depth (regolith) controlled by joint spacing or fracturing, and mountain range forms related to fold patterns.

Lithology or rock type has a very strong influence on landform and on the composition of regolith materials including soil. This is related to its component mineralogy and mineral grain size that are very strong determinants of; soil particle size (soil texture), fertility, and water holding capacity. To simplify the analysis of these relationships it is only necessary to consider igneous rocks because all other rocks (sedimentary and metamorphic) can be interpreted as derivatives or variants of igneous rocks within the rock cycle.

Two broad categories of rock can be recognized as the extremes that produce very different end products on weathering. Firstly, those rocks that do not contain free quartz but have abundant dark coloured minerals (mafic minerals such as augite, pyroxene and olivine) that will change entirely to clays with moderate to high fertility on weathering. Secondly, those rocks containing free quartz that will generate both inert sands and clays with lower fertility.

Thus volcanic basalt and their coarse grained plutonic equivalent, gabbro, will yield clay rich soils with high primary fertility because they have no minerals that normally yield sand on weathering. In contrast, volcanic rhyolite and their coarse grained equivalent, granites will yield bimodal sands and clays with generally lower fertility. This is because their small amounts of dark coloured minerals limit available nutrient elements like phosphorous, potassium, and trace elements.

As surface materials are moved by erosion processes sands and clays concentrate in different environments. The inert mineral quartz dominates the sands, and these deposits have well drained sandy soils with very low fertility. The clays produce poorly drained clay soils that either have low fertility, or an excess of soluble elements such as sodium, calcium and magnesium that adversely affect plant growth. Some of the clays also have high shrink/swell potential and cracking clay soils are formed that limit tree growth.

In the case of sedimentary rocks (conglomerate, sandstone, shale, limestone etc.,) each of these may be related to the comparable igneous rock in terms of their weathering products as being dominated by either sand (usually quartz) or clay. Soil materials derived from them will have similar physical properties as in the igneous examples. They generally have lower nutrient status because most nutrient elements will have been leached to landscape sinks or the ocean in previous cycles of weathering.

In the case of metamorphic rocks a breakdown model equivalent to the volcanic and plutonic igneous rocks can be expected.

The end results of rock weathering and surface movement processes on all rocks are broadly similar except in a few special cases where the rock mineralogy is unusual (for example; limestone or serpentine).

Table 2 lists common rock types and the normal end products of weathering and surface processes in an Australian landscape framework that can be used to justify the use of broad rock type groups in ecosystem mapping. For a more complete discussion of these relationships see Paton et al., (1995).

Table 2. Common rock types and typical end products of weathering in the Australian environment

Rock type	Approximate mineral composition	Typical end products of weathering	Common soil profile on a residual site	Common soil profile on a transportational site	Common soil profile on a depositional site
Granite	25% quartz 50% feldspars 25% dark minerals	Coarse quartz sand, clays and inert oxides.	Uniform sandy loam with porous fabrics.	Texture contrast soils.	Discrete deposits of sand or clay.
Rhyolite	As for granite but fine grained	Fine quartz sand and clays	Uniform, loam, with porous or pedal fabrics.	Texture and fabric contrast soils.	Discrete deposits of fine sand or clay.
Gabbro	40% feldspars 60% dark minerals	Clays with high nutrients, inert oxides	Uniform pedal clays	Fabric contrast clay soils.	Deposits of cracking clays
Basalt	As for gabbro but fine grained	Clays with high nutrients, inert oxides	Uniform pedal clays	Fabric contrast clay soils.	Deposits of cracking clays
Quartz sandstone	80-100% quartz	Quartz sand plus inert oxides.	Red or yellow, deep or shallow sands, often single grained.	Shallow red or yellow sands often with abundant rock fragments.	Deep sand deposits some with secondary profile development.
Lithic sandstone	50% quartz 50% other rock or mineral fragments	Quartz sand, some clay and inert oxides.	Uniform, sandy loam or loam, with porous or pedal fabrics.	Texture and fabric contrast soils.	Discrete deposits of fine sand or clay.
Shale	80-100% clay	Clay with low nutrient levels and inert oxides	Uniform pedal clays	Fabric contrast soils.	Deposits of massive or cracking clays
Limestone or marble	80-100% calcite circa 20% clay	Clay with low nutrient levels, inert oxides and alkaline pH.	Uniform red or red brown pedal alkaline clays.	Fabric contrast soils.	Small deposits of massive or cracking clays with alkaline pH.
Slate and Phyllite	20% fine quartz 20% mica 60% clay and chlorite	Fine quartz sand, clay and inert oxides, moderate nutrient levels.	Uniform loam, fine sandy loam or pedal sandy clays	Texture and fabric contrast soils.	Small discrete deposits of fine sand and larger deposits of massive or cracking clays
Schist and Gneiss	25% Coarse quartz 40% mica and feldspar 35% dark minerals	Similar to granite with moderate nutrient levels	Uniform sandy loam with porous or pedal fabrics.	Texture contrast soils.	Discrete deposits of sand or clay.

Topography.

Altitude, aspect, distance from the coast and topographic rain shadow effects are all well known controls on average precipitation and daily or seasonal temperature ranges. Edwards (199) divided the state into discrete climatic environments based on meteorological records and his map was accepted as an initial sub-regional pattern within which ecosystems would be mapped from other data. Specific combined limits of altitude and rainfall (Table 2) were drawn from the work of Edwards (1979), Beadle (1981), Kessell (1982) and others to establish important boundaries such as between montane, sub-alpine and alpine communities. Different limits were applied in the northern and southern parts of the state and an arbitrary adjust was made in intermediate areas. This use of regional average climate categories was a relatively crude surrogate for plant communities and soil moisture budgets but given the other levels of uncertainty in the mapping process refining was judged not to be worthwhile at the map scale selected.

Table 3. Altitude limits used in critical parts of the ecosystem mapping in the Eastern and Central Divisions of NSW.

Northern NSW	Southern NSW	Environment limit
2000m	1800m	Lower limit of alpine communities = 10 to 11^0 January isotherm, the tree line, and >100 days of snow on the ground.
1700m	1500m	Lower limit of sub-alpine communities
1200m	1000m	Lower limit of montane communities
>900m alt >1000mm rain	NA	On basalt = tropical rainforest
>900m alt >1800mm rain	NA	Cool temp rainforest (Beech) on any rock type.
	<1000m alt <1000mm rain	Coasts and Tablelands mixed forest
<500m alt 400-800mm rain	<500m alt 400-800mm rain	Western slopes box, ironbark and pine woodlands or open forests.

Climate.

Climate was incorporated to assist decision making as an overprint on the basic geology/soil and topography layers being used to identify ecosystems

A number of approaches were considered.

1. Rainfall isohyets – as a single parameter these were rejected, as the data was not readily available at 1:250,000 scale and it was not immediately obvious which isohyet should be chosen as critical ones.
2. Temperature and altitude – these properties are linked by the lapse rate (about 0.6^0 per 100m) and altitude can substitute for temperature. Some critical figures are known. For example, the alpine tree line is coincident with the 11^0 isotherm for January (Wardle in Good 1989) and other altitude limits for communities and species are established in the general botanical literature. These figures were incorporated in the final selection criteria shown in Table 2.
3. Using BIOCLIM type models. Such models focus on the expected distribution patterns of single species but the contract did not include provision for this level of

modeling. A commercial equivalent called CLIMEX was examined but proved to be unsuitable for the broad scale prediction needed.

4. One older model was located that did effectively integrate rainfall (totals and pattern of delivery), temperature, general site location in relation to sources of rain (rain shadows) and coarse topography. This was the work of Edwards (1979) which also took into account water balance and plant growth models and defined 14 climatic zones (Figure 3) and a larger number of sub-zones across the state (Figure 4).

Figure 3. NSW climate zones defined by Edwards (1979).

Zone 3 occurs as four discrete areas (Figure 4) and the main body (Hunter Valley and places west) is split into 5 sub-zones with different rainfall totals and different plant growth characteristics as the following two examples illustrate:

Zone 3A. Median annual rainfall 447-549 mm, slightly higher falls in summer months, greatest variability in autumn, only a couple of months of good plant growth, local rainfall is rarely sufficient for prolonged stream flow.

Zone 3E. Median annual rainfall 691-796 mm, marked peak in summer months, greatest variability in winter, soil moisture is high almost all year but plant growth is temperature limited in winter, runoff is uncommon but does occur.

In practice zone boundaries were plotted onto the 1:250,000 base maps and used as a layer in the mental model. The first cut of ecosystems was made on geology/soils, the second pass added topography and third pass added the climate factor especially where there were large areas without internal detail identified in the first two passes.

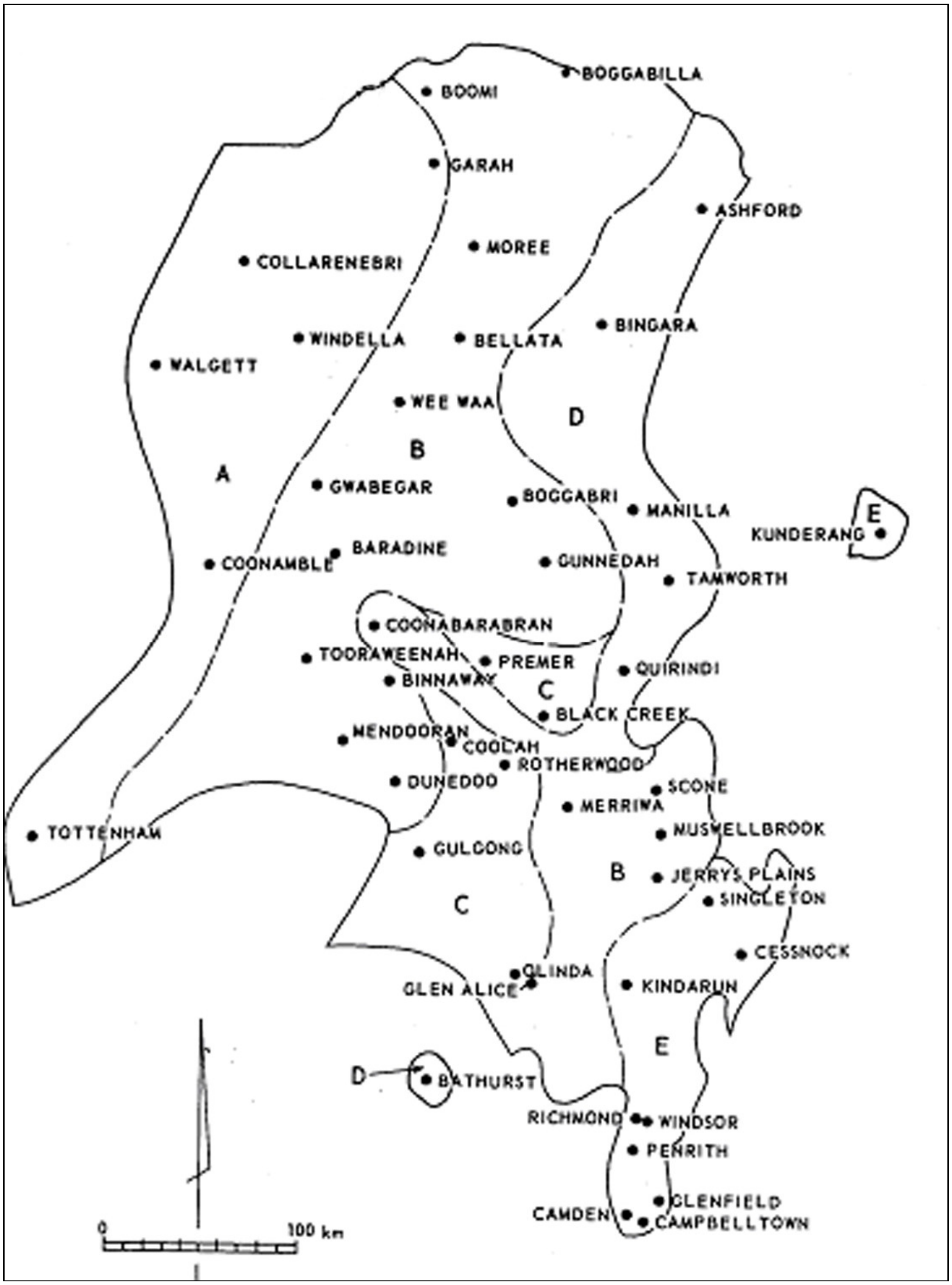


Figure 4. Detail of climate Zone 3, from Edwards (1979).

Step by step methodology: Eastern and Central Divisions including the Riverina.

For most of the Eastern and Central Divisions the geological maps were accepted as the base data. In the Riverina the work of Butler et al., (1973) and Eardley (1999) was adopted directly, see below. Work was split into manageable pieces on the boundaries of the 1:250,000 sheets and within the IBRA regions and the provinces or sub-provinces identified by Denny (1997), Eardley (1999), Morgan and Terrey (1999), RCAC (2000), and NPWS (2001(b)). As the interpretations progressed IBRA boundaries were sometimes found to be inconsistent with ecosystem boundaries ands these were highlighted for subsequent revision.

Step 1. Ecosystem mapping in the Riverina was a relatively simple task because Eardley (1999) who had used the work of Butler et al. had laid the foundations, (1973). These interpretations were accepted with little modification other than to mesh boundaries effectively with the SCS land systems and some additional mapping by NPWS (2000). The geomorphic forms were grouped in process sets consistent with the land system mapping and linked to the terminology of Butler et al., (1973) as shown in Table 4.

Table 4. Basis of Riverina ecosystems.

River channels and floodplains:

- Annual flood system – confined traces, channeled plain,
- Decade flood – plain with drains, plain with channels.
- 100 –1000 year events? – depression plain, plain with depressions
- Highest level fossil forms now with red-brown earth soils and vegetation without flood tolerant species – plain with scalds, scalded plain, plains of indistinct character

Relic channels and associated features – source bordering dunes

Lakes and swamps

- Permanent and intermittent lakes, swamps, all with attached lunettes
- Relic lakes Plain where there are lunettes, lunettes
- Groundwater playas – gypsum deposits

Dunefields – dunefield, dunefield with irregular dunes

Sandplain – indistinct dunefield

Basalt hills

Tertiary gravels and sands

Granite hills and colluvial slopes

Other Palaeozoic bedrock hills and ranges with colluvial slopes.

Step 2. Using the data tables of the NPWS GIS geology layer the polygons of all 1:250,00 map sheets were coded for lithology on the basis of general rock weathering characteristics and expected soil nutrient levels as shown in Table 5. Eleven basic codes were used and modified for geological age where that was reflected in the topography and for any other important geomorphic feature. These codes were only used as an intermediate working step and were listed in Excel and converted to shape files for each 1:250,000 map sheet where the data quality was deemed to be acceptable. Several map sheets were rejected because of poor data quality, errors in the data tables, or because a more recent map was available in hard copy.

Table 5. Lithology codes used in step 2 for the Eastern and Central Division.

Consolidated rocks

1. Coarse grained felsic igneous rocks with low proportion of ferromagnesian minerals: granite, pegmatite, quartz diorite, monzonite.

2. Coarse grained intermediate igneous or metamorphic rocks with a moderate proportion of ferromagnesian minerals and some quartz: granodiorite, tonalite, diorite, syenite, gneiss.

3. Coarse grained mafic igneous or metamorphic rocks with a high proportion of ferromagnesian minerals, quartz absent: gabbro, pyroxenite, peridotite, amphibolite.

4. Medium to fine grained felsic igneous, metamorphic and immature sedimentary rocks with some ferromagnesian minerals or equivalent lithic components: rhyolite, dacite, crystal tuff, schist and immature conglomerates and sandstones: volcanic sandstone, lithic sandstone, greywacke, arkose. migmatite and hornfels.
4A. Permian and Mesozoic **4B.** Cainozoic

5. Medium to fine grained igneous rocks with moderate to high proportion of ferromagnesian minerals, intermediate to basic: andesite, trachyte, latite, dolerite, basalt, spilite, volcanic breccia.
5A. Permian and Mesozoic **5B.** Cainozoic

6. Coarse grained mature sedimentary rocks and quartz dominated metamorphic rocks: quartz sandstone, quartzite, mature conglomerates, chert, silcrete, laterite, quartz schist.
6A. Permian and Mesozoic **6B.** Cainozoic

7. Fine grained sedimentary (mudrocks) and metamorphic rocks: claystone, shale, siltstone, immature conglomerates with muddy matrix, fine grained schists, phyllite, slate.
7A. Permian and Mesozoic **7B**. Cainozoic

8. Coarse or fine grained rocks with a high proportion of carbonate, sufficient to affect soil pH: limestone, marble, dolomite, marl, calc silicate metamorphics, carbonatites.

Unconsolidated sediments:

9. Sand and gravel.
9A. Cainozoic **9B.** Quaternary **9C.** Coastal sands

10. Mud and clay, alluvium generally.
10A. Cainozoic **10B.** Quaternary

11. Unusual geology, geomorphology or soils with a strong influence on biota: serpentine, saline environments, sodic soils, lunettes.

The logic behind these divisions is that different rock types can be expected to yield different soils (texture and nutrient status).

Step 3. A 1:250,000-scale paper copy of the coded geology was printed with a matching transparency on tracing paper of a colour coded DEM for the same sheet. Shading limits on the DEM were set to meet the altitude limits in Table 2.

Step 4. Each printed map sheet was overdrawn with the broad climatic environments defined by Edwards (1979) and then ecosystems were drawn by merging lithology, important geomorphology, major landforms and climate. Two types of boundary were used:

1. Those where geology was believed to be the dominant ecosystem control (such as basalt, limestone or serpentine). In this case the existing digital geological boundaries were accepted without change.
2. Those where a combination of factors was used to draw the line. These become firm lines on the transparency that were subsequently digitised.

Step 5. Where necessary, new data were digitised. All boundary data was merged and corrected to create shape files and the draft maps. Polygons were coded with a temporary three-digit code representing location and ecosystem type.

Step 6. Map sheets where the existing digital data were not accepted used the same basic approach except that the tracing was laid over a hard copy of the geology map and all ecosystem boundaries were drawn directly onto the tracing. Numerous difficulties were encountered linking map sheets and extending ecosystems across sheets mainly because of variations in data quality.

Step 7. The Technical Working Group reviewed a set of draft maps extending from Cargellico to the coast at Sydney and Newcastle but they did not have the opportunity to review all maps.

Step 8. Final corrections and amendments were made on the screen or on supplementary prints when necessary. Ecosystem names and codes were revised and selected ecosystems were assembled into meso-ecosystems using the same principles as applied in the Western Division.

Step 9. Outline descriptions of the ecosystems were prepared from the limited information available from the source documents and general knowledge.

Limitations of the map product.

Inevitably in a work that is dependent on different sets of data for its construction which attempts to provide a single viewpoint there will be a number of unsatisfactory elements to the interpretation. These are briefly discussed below.

General.

It is important to emphasize that none of the work has been fully tested or validated against other data sources. However a number of map sheets have been compared with other data during the mapping process and it is believed that a reasonable degree of product consistency has attained.

Check sources that were particularly useful include; the Broken Hill regolith map (Gibson and Wilford 1996), recent vegetation mapping at 1:100,000 done by the Department of Land and Water Conservation and land systems mapping in the Hunter Valley (Story et al., 1963), and some of the soil landscape maps for the Eastern and Central Divisions. It is important to emphasize that this checking has been random and opportunistic and a more thorough appraisal is recommended for future work.

Scale limitations of the maps must be acknowledged. Ecosystems were assembled at 1:250,000 scale and although some of the source data was originally assembled on more detailed maps or from more detailed air photographs the final product should not be expected to provide information at larger scales.

Western Division.

The Western Division work is substantially better than the remainder of the map simply because a more a uniform and more informative data-base was available to draw on. A few small errors were noted in the original mapping that could not be corrected.

In the Riverina and at the eastern edge of the land system maps ecosystem boundaries between different source materials were merged along subcatchment lines to avoid straight-line margins created by the map sheet boundaries. In some cases this merging may have blended different environments.

As noted above small errors of scale and location displacements were generated in the GIS between overlapping layers. For this reason no absolute precision of boundary location can be applied.

Eastern and Central Divisions.

It is important to acknowledge that data input to ecosystem recognition in this area did not include direct information about soils or vegetation. Therefore the basis of ecosystem construction across the two halves of the State was different and this must be reflected in the mapping units. A major task for further work will be to address this issue.

The weakest element of the interpretation in this part of the state was the very variable quality of the geological base maps and the digital geology data in the NPWS GIS. The original source of this data could not be determined with certainty and some map sheets were so different from current hard copy that the digital data was abandoned. A large number of coding errors were identified in the geology database, most were corrected but it is likely that others remain undetected.

Hard copy maps were used in two circumstances; when the digital data was rejected because of apparent errors and when a more recent edition of the geological map was available. In both cases many small problems of boundary matching were encountered. As far as possible the latest available information was used to resolve these conflicts and in some cases independent information was sought. But in a few instances no clear resolution was possible and arbitrary decisions based on geomorphic or topographic criteria were applied.

The geologic maps themselves, even the most recent ones, also contain errors of interpretation and location. Without independent knowledge of particular locations and extensive field checking these errors cannot be corrected.

On some map sheets displacement errors seen in mismatches between the DEM topography and the geology were found that could represent boundary placement errors of up to +/-1 km on the ground. The mode of construction of the ecosystem maps where hard copy on different media and digital information were mixed and matched makes error of these dimensions inevitable.

Recommended future work.

The mapping process has highlighted a number of discrepancies between the location of IBRA boundaries and ecosystem and meso-ecosystem boundaries. In many cases these are little more that minor adjustments that simply reflect the different map sources used but in some cases the differences are so large that debate about boundary change is desirable. In the first instance this discussion should take place within NPWS and conclusions from that referred on through the IBRA process.

At the same scale it is also desirable that NPWS compare this map with comparable work produced in Queensland, South Australia and Victoria. One to one correlations will not be expected but there should be sufficient agreement across borders to confirm the validity and workability of the product.

The limitations discussed above lead directly to a series of future tasks that should be undertaken to improve the quality of the ecosystem maps. The following activities are recommended:

All of the map sheets need to be validated. There are four sequential steps to this process:

- A paper review where the ecosystems are tested against other data that was not used in their assembly to determine the apparent validity of the ecosystems identified. Where available the best material to use for this step would be a SCS Soil Landscape map such as those of Banks (1995,1998) and Murphy and Lawrie (1998) because these were constructed with a similar philosophy.

- A second stage review using such as thematic maps of vegetation and perhaps regolith maps should follow and ecosystem boundaries should be compared with available air photographs or other forms of remote sensing imagery. Work in progress by the Dept. of Land and Water Conservation under the Native Vegetation Conservation Act could be used for this stage.

- The third stage check can be visualized as a test. One suggestion could be to use “independent” data from a source such as the RAOU bird atlas where it might be expected that bird distributions would be broadly correlated with major ecosystems such as sandplain environments or western ranges across the State gradient. A procedure for devising such a test would need to be developed and the biggest problem may be integrating the different map scales involved.

- Finally, when media review is completed a field validation step is essential. Obviously not all ecosystem boundaries can be field checked but a two stage process that involved content and boundary review by regional service staff followed by a field traverse designed to sample representative numbers and locations of ecosystems should be sufficient to establish the reliability of the maps.

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