Current and predicted minimum and maximum extents of land salinisation in the upland NSW portion of the Murray–Darling Basin

Department of **Environment & Climate Change** NSW

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Abstract

The extent of dryland salinisation in upland areas of NSW has been mapped from aerial photographs since approximately 1997. As part of the NSW Murray–Darling Basin (MDB) Salinity Audit update, it is necessary to understand current and historical dryland salinity to estimate its possible future extent. Outcomes from this Salinity Audit update indicate that groundwater and stream salinity responses are significantly influenced by climatic drivers such as periods of higher rainfall. Anecdotal evidence and other site-specific studies indicate that dryland salinity also responds to climatic drivers. The aim of this work is to determine the spatial extents within which known saline areas fluctuate.

This study used spatial analysis techniques and aerial photography to predict the maximum and minimum extents of saline areas within the NSW MDB. Seven catchments across NSW were surveyed over a 30- to 40-year time frame using recent and archival aerial photographs to determine the change in dryland salinity extent and severity. In general, catchments in the south of the State show a strong oscillating pattern as scalds expand and contract. Scalds in the middle and northern catchments appear to have increased continually over the period and may only now be starting to contract. All catchments were grouped according to their dominant landform as determined by topographical analyses. Catchments dominated by ‘steep’ landforms need a buffer of 150 m from the minimum to the maximum observed scald extent to delimit the changes in saline area size over time. Those dominated by an ‘even’ proportion of steep and flat landforms need a 250-m buffer, and those dominated by ‘flat’ landforms need a 575-m buffer.

The CSIRO FLAG model was used to obtain wetness values in the buffered saline areas. The predicted maximum and minimum extents of saline areas were increased and decreased on an area basis, which gives preference to areas with higher FLAG wetness values over those with lower values. The use of the FLAG wetness index constrains the expansion and contraction of the saline areas within topographic features, as opposed to simply buffering the saline extents. This information was then used to buffer the current mapped NSW saline areas according to landform dominance in upland catchments of 400 to 2000 km^2. We assumed that catchments near a study catchment and with a similar landform classification are at a similar stage in their ‘saline extent cycle’ to the study catchment, and adjusted the area of scald within the buffer accordingly. For example, if the current extent is the same as the minimum observed extent, then an increase in area equal to the observed trends from the study catchment is used to extrapolate a maximum areal extent. If the current extent is the same as the maximum observed, then a reduction in area within the buffer is used to extrapolate a minimum areal extent. If the current extent falls between the minimum and maximum, then relative proportions are used.

The current extent of scalds from the NSW portion of the MDB is approximately 644 km^2. The predicted minimum and maximum extents are 530 and 711 km^2. These estimates are based on a 30- to 40-year snapshot of climatic variability. Limitations of the method are discussed. The preliminary findings of this work have been published in Summerell *et al*. (2005a).

1 Introduction

The hydrological complexity of the Australian landscape with its ancient land forms, climatic variability and vegetation diversity has complicated our ability to understand the processes that drive dryland salinisation. The basic model of vegetation clearing leading to an increase in recharge and thus a rise in the water table, which brings salts to the surface, should be viewed only as a coarse description of the overall process. Previous assessments of the current and future extents of dryland salinisation based on this model estimated that the dryland and irrigated salinity problem would increase nationally from 5.7 to 17 million hectares over the next 50 years (Van Bueren and Price 2004). MDBC (1999) estimated that between 2 and 4 million hectares of landscape would be seriously harmed by salinisation.

The methodology previously used in NSW (Beale *et al*. 2000) for the 1999 Salinity Audit had two parts. First, Woolley *et al*. (1999) analysed and extrapolated groundwater trends to calculate the potential salt loads discharging to the ground surface in 2000, 2020, 2050 and 2100. Problems within this methodology resulted in estimates of salt load well in excess of those calculated for in-stream salt load in the second part of the methodology. Consequently, the second part used these groundwater salt load estimates to calculate the rate of change in potential discharge in a river basin only as a scaling factor: that is, the 2020, 2050 and 2100 estimates of salt load discharge were indexed to the estimate for 2000. These scaling factors for individual geologies were aggregated on an area-weighted basis for each tributary catchment in a basin. Estimates of future in-stream salt loads were simply the quasi-observed monthly salt load time-series (obtained via stochastic modelling of observed flow and discrete electrical conductivity measurements for 1975–1995) scaled by the aggregate factor for each tributary to represent target date conditions. Although Woolley *et al*.'s (1999) methodology included an 'area salinised' term, no estimate of these areas was ever published by NSW: the areas calculated were considered too misleading as they assumed a flat topography. This limitation could not be overcome at the time because NSW did not have a suitable digital elevation model (DEM) with which to correct for the effects of topography.

The methodology used by Victoria (SKM 1999) was an improvement from the NSW method as they disaggregated the landscape into hydro-geomorphic units based on a 9″ DEM (250-m cell size), creating small landscape units for analysis. However the comments of Walker *et al*. (1999) when reviewing the 1999 Salinity Audit for the MDBC are still pertinent to both the analysis as the extent of land salinisation was overestimated on account of:

- the difference in scale between the 250-m DEM and spatial patterns of land salinisation
- the lag between waterlogging and salinity
- the assumption that a constant rise in water table increases areas of land salinisation.

Walker et al. (1999) also identified historical changes in the salinised area over discrete time intervals, and suggested that these changes might be used to predict future trends. They cited the work of Furby *et al.* (1995) and Kirkby (1996) as examples of where changes in salt scalds were mapped visually from historical aerial photograph sequences. Walker *et al.* (1999) concluded that scale is very important in predicting land salinisation: as scale increases from paddock to catchment to region, areas become increasingly overestimated, mostly because only larger-scaled DEMs (i.e. 250-m) are available for the larger-scaled regional studies.

Later, Littleboy *et al.* (2001) estimated land salinisation in NSW once a suitable DEM (25-m) became available. They explored the use of the 25-m DEM and other techniques to spatially extrapolate groundwater data levels and so infer areas at risk. However, they considered the results from various interpolation methods to be statistically inadequate on account of an insufficient spatial density in the network of available bore data for these types of analyses. Therefore, saline expressions could not be extrapolated on the basis of topography. Instead, they focused on identifying areas where there was direct evidence of discharge. Current discharge areas were either mapped areas of salt outbreaks delineated from air photo interpretation or areas having one or more actual bores with a measured depth to the water table of less than 2 m. From this analysis, Littleboy *et al.* (2001) estimated that 150 509 ha of landscape was affected by shallow water tables (<2 m). They then studied the impacts of salinity on infrastructure. In the Murrumbidgee, Murray, Lachlan and Macquarie catchments, shallow water tables could affect 107 km of highways, 48 km of major roads, 62 km of railway lines, 12 bridges and 954 km^2 of urban development (Littleboy *et al*. 2001; Wild *et al.* 2005). The total present value of the cost of salinity to the largest inland city in NSW (Wagga Wagga) over 30 years is approximately $94 million, or $3.2 million per year. This is due mainly to impacts on roads (59%), houses (21%), and pipes for sewerage and gas (15%).

The Hunter River Salinity Audit was a progression from the 1999 Salinity Audit required by the NSW Salinity Strategy (Beale *et al*. 2001). The issue of topographic constraint on the area potentially salinised was dealt with in the Hunter River Salinity Audit by determining a maximum discharge area for each subcatchment by using the FLAG (‘Fuzzy Landscape Analysis GIS’) model’s ‘wetness’ index. The choice of the cut-off value of the index was determined subjectively by visually checking that the index covered the extent of currently mapped sites of saline discharge. The choice was further justified on the basis that the range of discharge area per subcatchment was in agreement with the range cited by Freeze and Cherry (1979: from 2.5% to 30% of the catchment area depending on topography. The inclusion of a topographic constraint in the Hunter methodology substantially reduced the prediction of in-stream salt load and salinity trends, creating more realistic etimiations.

To achieve better estimates of the current problem, we need to develop a better understanding of land salinisation dynamics. Two recent studies in NSW have attempted to increase our understanding of land salinisation processes. Dominis (1999) studied the causes of the fluctuation of the size of salt scalds in the Baldry catchment, Central West NSW, using aerial photographs taken from 1958 to 1999. The area of scalds generally increased from 1958 to 1996, then appeared to stabilise. She investigated seven interrelated factors—climate, geology, geomorphology, soils, vegetation, land use, and remediation measures—to see which of them influenced the changes in scald size. She concluded that geology, geomorphology and soils dampened the impacts of changes in climate, land use and remediation measures, making changes not always consistent with the patterns of climate change. However, the average trend was attributable to climate.

Plowman (1999) studied the changes in scald behaviour in the Spring Creek catchment on the South Western Slopes of NSW. He observed a different scald response, in which the saline areas appeared to oscillate in size from 1953 to 1994. These oscillations occurred more than once over a relatively short period. Saline areas were greatest in 1953, 1963, 1973 and 1989 and smallest in 1970 and 1983. Plowman considered the fluctuations to be a short-term phenomenon related to immediate environmental processes occurring in the landscape, of which climate appeared to be the main driver. Interrelations with other factors such as soil type and land use changes were discussed.

Wagner (1986) undertook the first large-scale assessment of dryland salinisation changes over time (1941–43 to 1986) using historical aerial photographs at approximately 10-year intervals. The study included 92 saline sites within the Southern Tablelands of south-eastern Australia. Wagner reported that the extent of individual sites has fluctuated over the years, but felt that the study sites are showing no improvement or are still degrading. Overall, there appeared to be a significant increase in scalding in the late 1950s to early 1960s. Through the 1960s to 1970s most sites continued to degrade. In the early 1980s, half the sites continued to degrade, a quarter remained stable and the other quarter began to regenerate.

This study aims to expand on the two case studies above and the work of Wagner (1986) by studying in detail a further seven land salinisation areas across NSW to assess variability in land salinisation expansion and contraction patterns. The seven study catchments are Begalia, Williams Creek, Wattle Retreat, Cowra, Applewood, Mumbil and Box Hill (Figure 1). Using terrain analysis techniques, we determined the maximum and minimum extents of the scalds to allow extrapolation to all mapped scalds within the uplands areas of the NSW portion of the Murray–Darling Basin (MDB). The initial results of this study have been published in Summerell *et al.* (2005a).

Figure 1: Location of the seven study catchments within NSW

1.1 Begalia

This catchment lies within the Lachlan Fold Belt as a subcatchment of the Yass River catchment. It covers an area of about 230 ha and ranges in elevation from 620 to 730 m a.s.l. The geology is dominated by volcanics. The mean annual rainfall in nearby Yass and Blackburn is 639 and 737 mm respectively. Sheep and cattle grazing is the dominant land use. Wagner (1986) also studied this catchment.

1.2 Williams Creek

Williams Creek is a small subcatchment of the Yass River catchment covering about 200 ha between Gundaroo and Murrumbateman. The catchment geology is of Ordovician age and consists siliceous slates which traverse the area from north to south (Smith 1979). Elevations range from 400 to 640 m a.s.l. The mean annual rainfall is about 640 mm. Sheep and cattle grazing is the dominant land use. Wagner (1986) also studied this catchment.

1.3 Wattle Retreat

Wattle Retreat is adjacent to the regional divide between the Lachlan and Murrumbidgee rivers and covers 540 ha. The mean annual rainfall is 596 mm. The catchment consists of undulating hilly country with a flat valley bottom. Elevations range from 340 to 400 m. Sheep and dryland cereal crops are the dominant land uses (Lawson 1994). The geology is dominated by igneous feldspar–quartz porphyry.

1.4 Cowra and Applewood

Cowra and Applewood are subcatchments (~200–280 ha) of the Waugoola catchment (37 000 ha), in the mid to upper Lachlan catchment. The primary geology is highly fractured volcanics with a minor component of metasediments. The mean annual rainfall is ~650 mm. Land use comprises wheat, sheep, cattle and some viticulture.

1.5 Mumbil

Mumbil is a small subcatchment of the Macquarie River Basin, 23 km south-east of Wellington. The catchment is dominated by undulating terrain of moderate relief. Elevations range from 400 to 500 m a.s.l. The geology is dominated by volcanics. The mean annual rainfall is ~600 mm. Cattle, sheep and dryland cereal crops are the dominant land uses.

1.6 Box Hill

The Box Hill catchment is located in the upper portion of the Gwydir catchment. It is a subcatchment of the Mount Russell catchment, which drains west in the Myall Creek system of the Gwydir River valley. The catchment covers about 640 ha and is approximately 4 km long and 1.5 to 2 km wide (Lawson 1989). The elevation varies from 660 m at the outlet to 680 m on the eastern side. The geology comprises Tertiary basalt, which in turn is underlain by Permian granite and exposed at the lower end of the catchment. The mean annual rainfall at nearby Inverell is 809 mm, of which about 25% falls during December and January (Lytton *et al*. 1994). Land use is mainly cattle grazing.

2 Methods

This study used two main methods:

- initial aerial photography surveys
- spatial representation using terrain wetness indices and extrapolation throughout the NSW portion of the MDB.

2.1 Aerial photography surveys

The changing patterns and intensities of salinity outbreaks were determined from aerial photographs. Some of the aerial photographs date back to 1944; others are dated from the mid 1950s. Sequential images were thereafter flown every 7 to 10 years. The aerial photographs came from the Department of Environment and Climate Change (formerly Department of Natural Resources) or the State Archives of NSW. The photos range in scale from 1:25 000 to 1:50 000: the Begalia, Williams Creek, Cowra and Applewood photos are mostly 1:25 000 to 1:40 000; the Box Hill, Mumbil and Wattle Retreat photos are mostly 1:50 000.

For each site, each aerial photograph was scanned and rectified to create a base map. A scanning density of approximately 400 dots per mm provided a clear reproduction of the original photograph. Each scanned photograph was rectified against all other scanned images of the same site to ensure that any identified changes in salinity conditions at the site are true changes and not simply a reflection of differences in scale or distortion.

Salinity outbreak patterns identified in the photographs were digitised over the top. Polygons were tagged to identify the intensity of the salinity outbreaks. Land management practices implemented to treat the salinity outbreaks were also digitised and tagged.

2.2 Remote sensing of saline outbreaks

Saline outbreaks identified by other remote sensing technologies were considered but not used for the following reasons. Spiers and Woodgate (2004) reviewed techniques for large-scale mapping of saline scalds such as satellite (e.g. Landsat and SPOT), airborne remote sensing and DEMs for surface mapping of salinity in the 0–10-cm depth range. Some of these methods give indirect information on salinity in the root zone through interpretation of vegetation stress, while others (e.g. radiometrics) are useful for soil mapping. The skill base needed for these techniques is highly specialised, and there are few users who are expert at more than two or three.

Airborne and satellite-based multi-spectral sensors have been advocated as technologies for reducing the cost of field-based measurement of soil salinity. However, they are limited spectrally and spatially (Landsat 7, for example, maps 30-m pixels), and it is unlikely that such data will ever successfully map vegetation down to the genus or species level. Instead, methodologies using multi-spectral data tend to rely on surrogate indicators of soil salinity such as areas of consistently poor growth. This approach works well in some environments, but is likely to be limited in slightly to moderately saline areas where salt-tolerant species can still thrive and maintain good ground cover (Anon 2004).

In general, image data from multiple consecutive growing seasons is required to discriminate between short-term causes of low productivity, such as overgrazing, and longer-term causes of low productivity, such as salinity (Furby 1998). In areas where there is a single winter cropping or growth season, images from ideally three consecutive years are required. In areas such as northern NSW, where there are both winter and summer cropping seasons, images from each season are required over at least two years. Often it is not possible to obtain such image sequences owing to cloud cover. Drought conditions or unusually wet seasons can also make images unsuitable for mapping land condition. With image analysis, further processing using elevation data is required to indicate landform units such as hilltops, slopes and valleys. This enables the assignment of a more appropriate condition label to poor-condition land in parts of the landscape that are not prone to salinity, such as bare hilltops or slopes, greatly reducing the amount of low-productive non-saline land labelled as salt-affected. Evans and Kiiveri (1998) supported this view, indicating that without very careful analysis and modelling of satellite data, mapping salt scalds from satellite images can omit large saline areas (35%–50%) and include non-saline areas (26%–35%). Caccetta (2000) showed that it is possible to map salt scalds in a catchment with an 80% probability of being correct by adjusting a time-series of calibrated satellite imagery (i.e. over a few years) with other critical data sets, such as a high-resolution DEM, and then post-processing the result to exclude obvious errors (e.g. dry dams, roads). Given the complexity of post-processing satellite data and combining other data sets, we considered aerial photography mapping of saline scalds in NSW to be the most appropriate and reliable method of data capture, even though it also is influenced by some of the limitations discussed.

2.3 Spatial representation using terrain wetness indexes and extrapolation throughout the NSW Murray–Darling Basin

In the aerial photo interpretation, only areas classified as saline were used to measure the extent of the saline areas. Features such as waterlogging were not used, as interpretation of this characteristic is strongly influenced by seasonal change. The minimum and maximum expressions of scalds at each site were compared, and 10 random points were selected around the scalds to measure the difference in length between the extents. These lengths were averaged to determine the buffer distance required to capture the most variation between the minimum and maximum extents.

An expansion buffer around a scald does not take into account the topographical spatial variability of the area in which it lies. By incorporating a wetness index into the buffered area, we can take into account topographical influences.

The use of a landscape wetness index to represent the variability around the scalds also allowed for extrapolation to other areas. We chose the FLAG wetness index for the following reasons:

- The wetness index of FLAG (specifically the UPNESS index) gives a reasonable representation of subsurface soil water and groundwater within hillslope landscapes (Summerell *et al.* 2004).
- Summerell (2004), Summerell *et al*. (2005b), Summerell *et al*. (2006) demonstrated how the distribution of the Cumulative Distribution Function (CDF) of UPNESS provides a good descriptor of landform dominance within a catchment. This attribute of the UPNESS index distribution also provides a mechanism for extrapolation.
- A case study was undertaken in the Mona Vale catchment (within the Kyeamba catchment) to determine that the depth-to-groundwater relationship with UPNESS could be reproduced in a similar way as in Summerell *et al*. (2004). Appendix A shows that the relationship varied markedly between wet and dry periods. The relationship could be used to define an area of shallow water table within the catchment, and the change in relationship between wet and dry periods could therefore be used to estimate the

change in areas of shallow water table. The wet and dry periods could also be placed in context in relation to the bore hydrograph time-series.

The use of the FLAG model in this study was based on the following assumptions:

- Many factors influence the topography of the landscape, including geology, soils, climate, vegetation and land use. Often these features act together to shape the surface of the land. Water cycle processes also shape the land and are correlated with elevation. For this model, we assumed that a DEM with a 25-m grid (NSWLIC 1999) adequately shows important topographic features and is detailed enough to reduce errors in the over-predictions of saline scalds compared with using a 250-m DEM. This aligns with the comments made by Walker *et al.* (1999) in their review of the 1999 Salinity Audit.
- The water table conforms to the topographic surface except that it exhibits less total variation in relief than the ground surface. Therefore, we assumed that the model adequately captures these features; the water table is closer to the ground surface at low points in the landscape, and further from the surface at high points. At a local scale the LOWNESS indicator captures these patterns.
- For any given point, the area that contributes to its wetness is given by the set of points connected by a continuous, monotonic uphill path. This means that any number of topographic catchment boundaries may be crossed, provided the subsequent points in the next catchment are higher. We therefore assumed that for saturated subsurface flow, those points on an uphill path would influence the location below, thus contributing to potential discharge. In this model, the UPNESS index captures this elevation feature.
- This wetness model represents landscape features without influences such as vegetation and geology.

The FLAG model uses elevation data to spatially derive several topographic measures, including the LOWNESS and UPNESS indicators. There are two main steps:

- Calculation of UPNESS and LOWNESS from the DEM.
- Derivation of the soil wetness hazard indicator as the lower of UPNESS and LOWNESS.

The FLAG indices are defined and interpreted as follows (Summerell *et al.* 2004).

LOWNESS is a measure of local lowness relative to a smoothed topographic surface for each hillslope. As the value increases, the accumulation of water is deemed to increase. Upper ridges and crests will have low LOWNESS values, and valley bottoms and features such as breaks of slope and gullies will have high values. LOWNESS is interpreted as a measure of local impacts on soil wetness or waterlogging**.** It is calculated by smoothing the DEM (in this case by a 200-m smoothing window), moving this window to create the average local elevation, and then calculating the fuzzy-set difference between the smoothed and unsmoothed elevations. Locations in the landscape which are low relative to the surrounding points have positive values of this difference proportional to the difference in local elevation. LOWNESS was then relativised so that locations which were low in the local landscape had high values in the set (maximum LOWNESS, 1.0), and locations which were at or above the local landscape had zero membership in the set (Roberts *et al.* 1997).

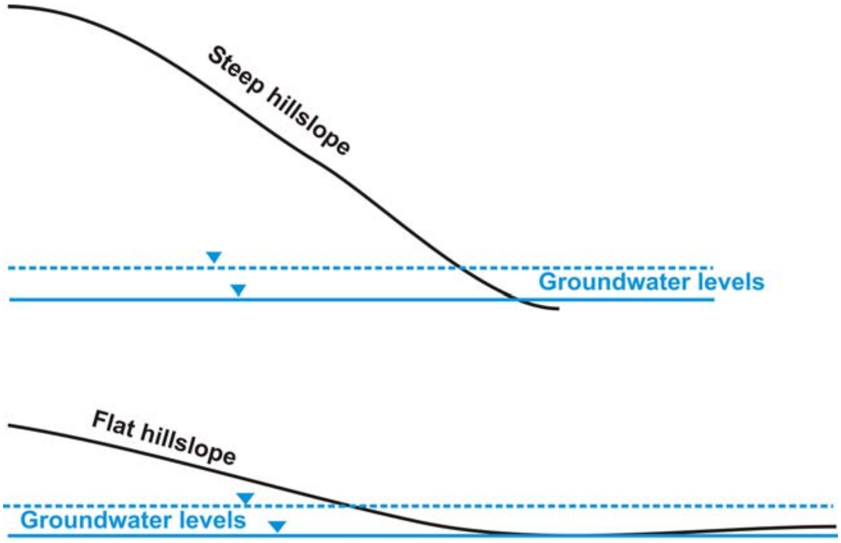
UPNESS is the relative height of each DEM grid cell in the overall landscape. It is derived from digital elevation data and is defined as the accumulation of upslope area at any given point; i.e. by the set of points that are connected by a continuous monotonic uphill path. It is assumed that for subsurface flow, all points that are connected in this way exert some hydrologic effect on the downslope location. Although the UPNESS index is considered to be a type of contributing area, measuring relative height in the landscape, it is not restricted by flow direction, and any number of topographic catchment boundaries can be crossed, provided the adjacent uphill cells in the next catchment are monotonically higher (Dowling 2000; Laffan 2002). UPNESS is also relativised so that locations which have large areas of accumulation are given high values in the set (maximum UPNESS, 1.0), and locations which have minimal accumulation have zero membership in the set (Roberts *et al.* 1997). UPNESS is interpreted as a measure of the magnitude of regional water table levels or potentiometric heads on a cell ('regional' here being the extent of the study area).

The **wetness** indicator is the minimum of the LOWNESS or UPNESS value. The assumption is that a low value of both LOWNESS and UPNESS (rapid water movement off ridges and upper slopes and small contributing area) represents a low wetness hazard, and a high value for both LOWNESS and UPNESS (valley bottoms or depressions with the potential to accumulate water and a large contributing area) represents a high wetness hazard.

2.4 Buffering width of salt scalds

The buffer widths that were determined for the seven study catchments generally fitted into three different scales: 150, 250 and 575 m. The landscape shape of the catchments indicated that catchments dominated by lower slopes had greater variation in observed maximum and minimum extents of salinity. We conceptualised that this greater variation was due to the greater influence of a given rise in a water table on a flatter land surface than on a steep land surface (Figure 2).

Figure 2: Schematic diagram showing how a similar change in groundwater level in a flat landscape affects more of the land surface than in a steep landscape



Berhane (in prep.) attempted to quantify this observation of the seepage face lengths (Ls) (which conceptualised as the area of hillslope between the low and high groundwater levels indicated in Figure 2). The seepage face lengths are a comparable measure to the buffer widths discussed above. The seepage face lengths of scald areas in the Begalia, Williams Creek, Mumbil and Box Hill catchments by two independent methods. The first was an analytical approach and it indicated that the maximum extents of seepage face length generally ranged from 80 to 250 m. This method was more sensitive to changes in horizontal hydraulic conductivity than to changes in recharge. The second method used MODFLOW (Modular Finite-Difference Flow Model of the US Geological Survey) in conjunction with MODPATH, a particle-tracking algorithm used to delineate recharge and discharge areas along a hillslope transect. It tended to indicate much longer seepage faces ranging in maximum extent from 100 to 600 m. These seepage face lengths were more sensitive to changes in recharge inputs (contributions or rainfall leakage into the groundwater system) then hydraulic conductivity changes as indicated in the analytical method. Table 1 shows the results of the study of Berhane (in prep.).

The catchment seepage face estimates by the two methods were not generally consistent with each other. There are three possible causes of the differences in estimated Ls:

- The standard MODFLOW package is ill-equipped to simulate flow of water in the unsaturated zone where the seepage faces generally occur
- The shallow local groundwater systems show non-linear behaviour.
- Hypothetical recharge inputs were used during MODFLOW simulations. The maximum recharge rate of 0.00018 m/day, representing an extremely wet period, is probably very conservative for tight geological formations, which are usually associated with areas affected by dryland salinity.

The estimations from the MODFLOW simulations however more closely related to the estimations of buffer width used in this report as observed from aerial photographs. Berhane (in prep.) coincluded in his study that overall the drivers of recharge and soil hydraulic conductivity strongly influence scald expansions and contractions. This conclusion matches the other literature reported indicating the structural processed influencing scald extents.

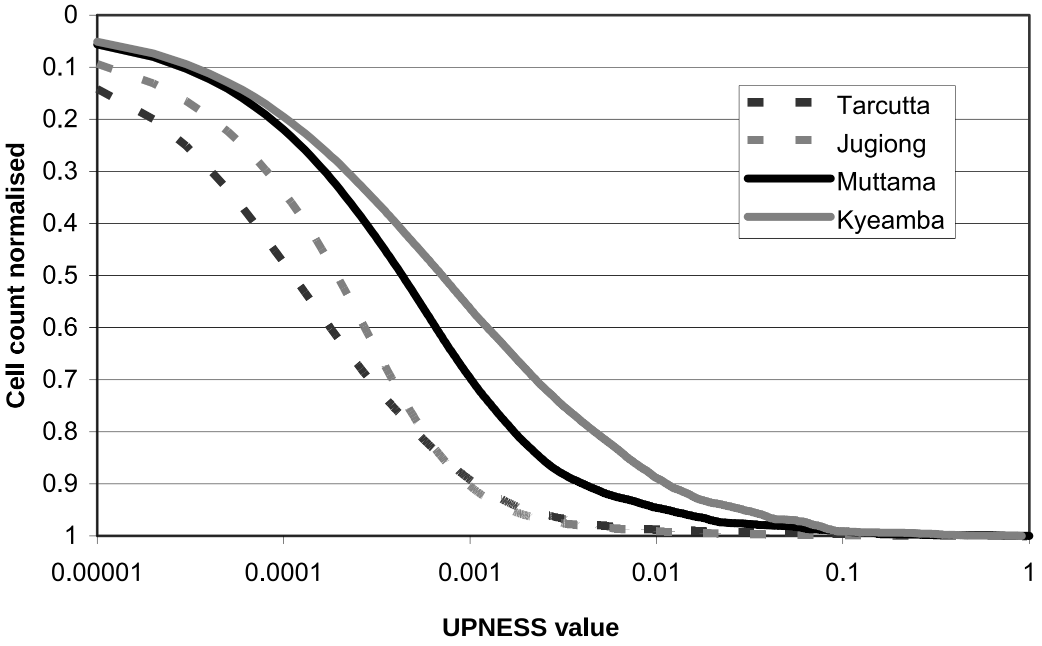
Table 1: Seepage lengths (Ls) estimated by different methods (Berhane in prep)

Catchment	Geology	Analytic approach	MODFLOW
Box Hill	Fractured rock	0–85 m	0–250 m
Williams Ck	Regolith/fractured	0–90 m	0–600 m
Begalia	Regolith/fractured	0–250 m	0–100 m
Mumbil	Sedimentary	0–80 m	0–120 m

2.5 Determining landform dominance within catchments

Developing an understanding of the dominant landforms within a catchment provides insight into the expected soils types and hydrological processes that occur within it (e.g. potential for areas of saline expansion and contraction). The 3rd-order catchments (mostly between 600 and 2000 km^2) in the current Salinity Audit were all assessed for their dominance of steep, even (dominated by neither flat nor steep landforms) and flat landforms. This classification determines which buffer length to use in the catchments. This landform dominance is a descriptor at the 3rd-order catchment scale, and site-specific variations would occur at a more detailed resolution. However, for the purpose of this study, which is at the basin or regional scale, this classification was deemed sufficient. Future studies at the subcatchment level would certainly improve this aspect of the method if site-specific issues were to be addressed. The method of assessing landform dominance followed Summerell (2004) and Summerell *et al*. (2006). The work of Summerell demonstrated how the distribution of the CDF of UPNESS grid cells provided a good descriptor of landform dominance within a catchment: The further a catchment's CDF plots to the left, the steeper is the catchment's landforms; as the curve plots progressively to the right, the catchment becomes more dominated by flatter landforms (Figure 3).

Figure 3: UPNESS index CDFs for the Tarcutta, Kyeamba, Jugiong and Muttama 3rd-order catchments in the Murrumbidgee region



From Summerell (2004). The further the catchment plots to the right, the more it is dominated by flatter landforms.

2.6 Modelling the expansion and contraction of known salt scalds within the NSW Murray–Darling Basin

The two main data sets were used to model expansion and contraction of salt scaled in the upland areas of the NSW portion of the MDB. These were the ‘Outbreaks of Dryland Salinity’ (DNR 2004) (Figure 4) and the ‘DNR-FLAG modelling of soil wetness hazard in upland NSW’ (Summerell *et al.* 2003).

The ‘Outbreaks of Dryland Salinity’ mapping represents a single snapshot of saline extents in around 2000. The more detailed salt outbreak mapping at the seven study catchments shows the variation over a 30- to 40-year time frame. The following steps were undertaken to allow a prediction of maximum and minimum extents:

1. For each region (e.g. Murray, Murrumbidgee), the mapped saline areas within 3rd-order catchments (600–2000 km^2) were classified as steep, even or flat landform-dominated catchments as per section 2.5.

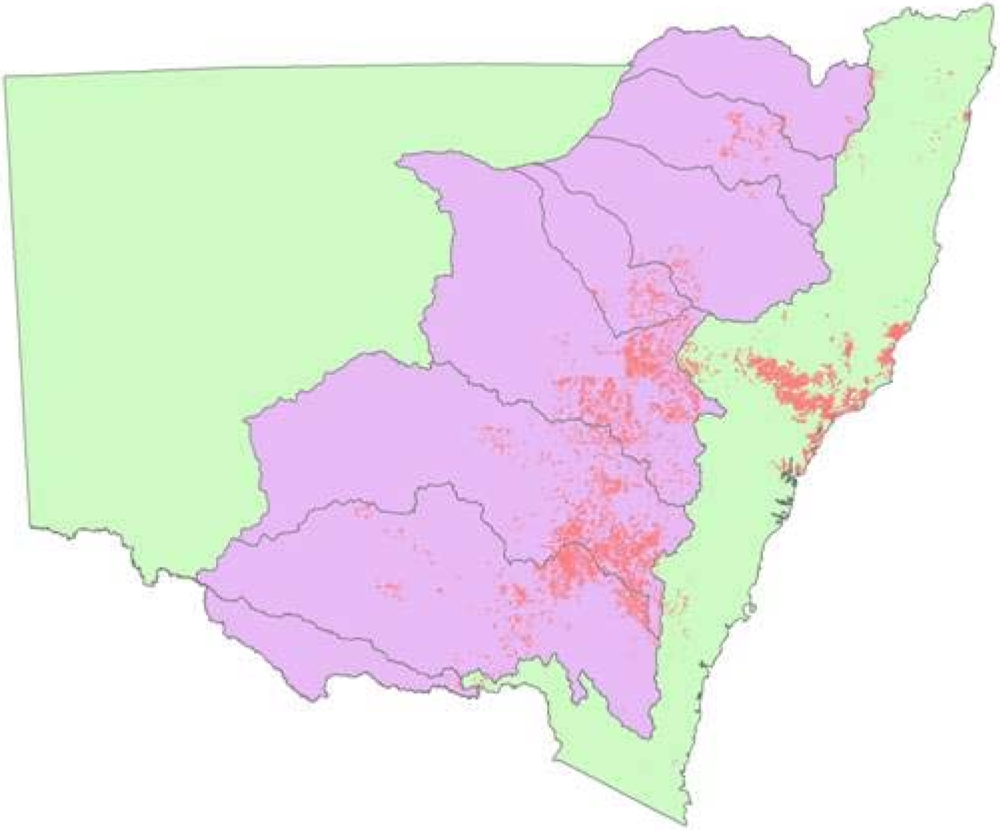
2. An appropriate buffer (based on the results of the seven study catchments) was applied to the ‘Outbreaks of Dryland Salinity’ coverage based on the classification in step 1. This buffer was scaled as a percentage of the current extent saline expressions within the known observed maximum and minimum extents. We assumed that all scalds within the 3rd-order catchments are at a similar stage in their ‘saline extent cycle’ and are similar in behaviour (saline scald extents) to the study catchment that represents that basin. For example, if the current extent is the same as the minimum observed at the representative study site, then an increase in area equal to the observed trends from the nearby study catchment is used to extrapolate a maximum areal extent. If the current extent is the same as the maximum observation, then a

reduction in area within the buffer is used to extrapolate a minimum areal extent. And if the current extent falls between the minimum and maximum, then the pro-rata proportions are used.

3. The maximum buffered extents of saline areas were then used to clip the grid of FLAG wetness values. The FLAG wetness was then increased or decreased on an area percentage basis, giving preference to the highest wetness values over lower wetness values. The aim of this process was to best match an observed saline extent with the FLAG wetness index, and by using the wetness index it allowed the scalds to expand or contract within a topographical influence. The use of the FLAG wetness index constrains the expansion and contraction of the saline areas within topographic features, as opposed to simply buffering the saline extents in a flat terrain. The result was a FLAG wetness representation of saline scalds in the 'Outbreaks of Dryland Salinity' map.

4. Using the percentage area change in minimum and maximum extents, the scalds were expanded or contracted to assess the bounds the salinisation areas may fluctuate within. Results are reported by region.

Figure 4: Current outbreaks of dryland salinity are shown in red. This study focuses on the areas in the purple catchments



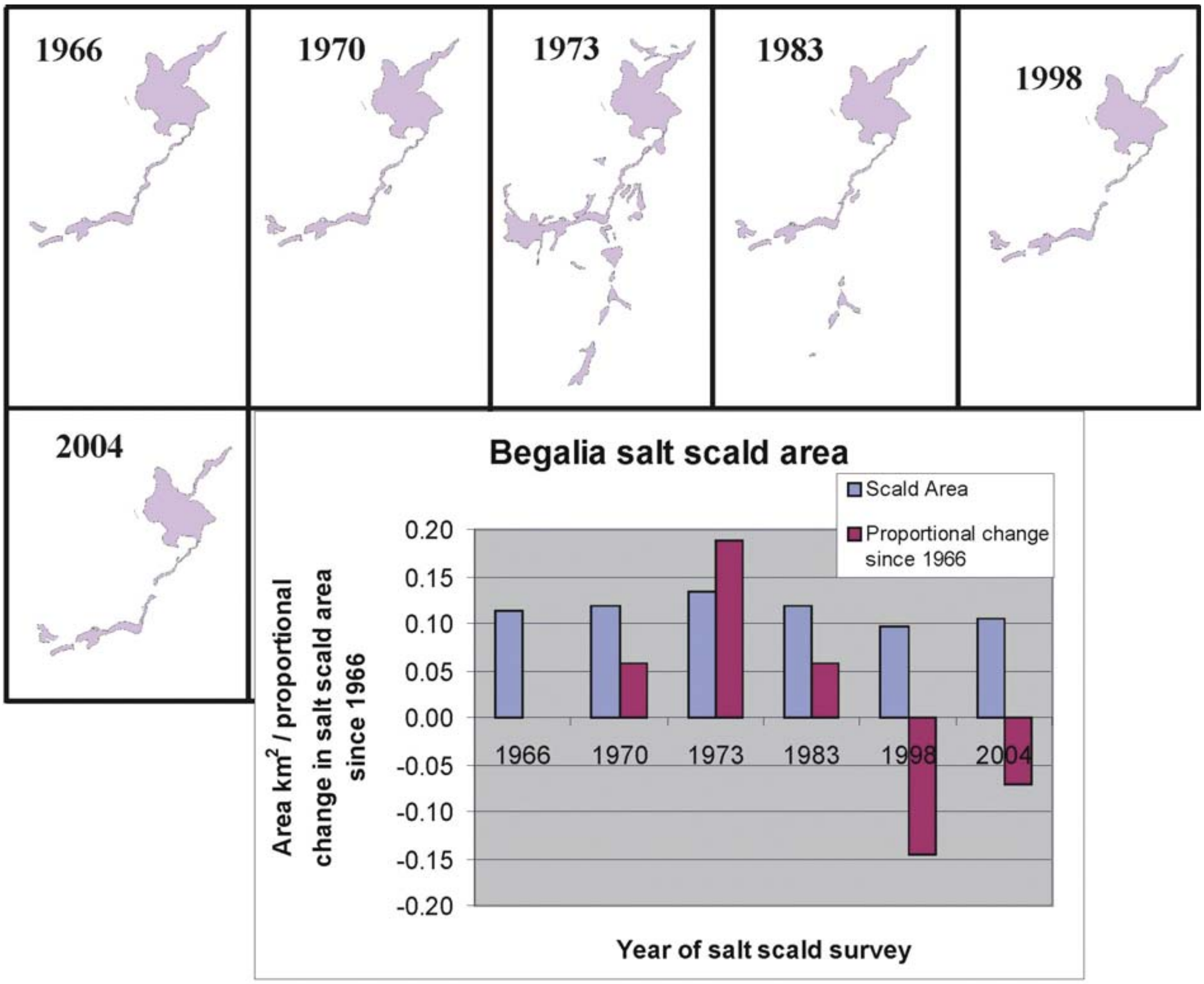
This data set is still being created, and the northern regions are less well mapped so far.

3 Results and Discussion

3.1 Study sites

The variation in saline extents in the seven study site catchments are presented as mapped polygons and a summary graph of the saline area over time, showing how the area has changed relative to the first mapped record. In the Begalia catchment, the maximum extent occurred around 1973 and the minimum around 1998 (Figure 5).

Figure 5: Saline area (salt scald) variation in the Begalia catchment



The Williams Creek catchment is very close to the Begalia catchment. Very similar oscillating patterns occurred, showing the maximum extent in 1973 and a reduction in scalding around 1997 (Figure 6). The major difference between the two catchments occurs in the amount of variation: Williams Creek has much more marked changes in saline area, showing almost a 100% difference in maximum and minimum extents. Localised site characteristics are most likely the reason for the difference in variation between the sites. As the overall oscillating patterns of saline extent variation are similar, this analysis has captured the major driver determining the saline outbreak severity, despite localised catchment conditions, including possible human effects (e.g. saline remediation works). Wattle Retreat, in a flatter catchment, also shows an oscillating pattern (Figure 7). The main difference is that the extent of the scalds peaked in the 1990s, and the current extent is at the minimum recorded.

Figure 6: Saline area (salt scald) variation in the Williams Creek catchment

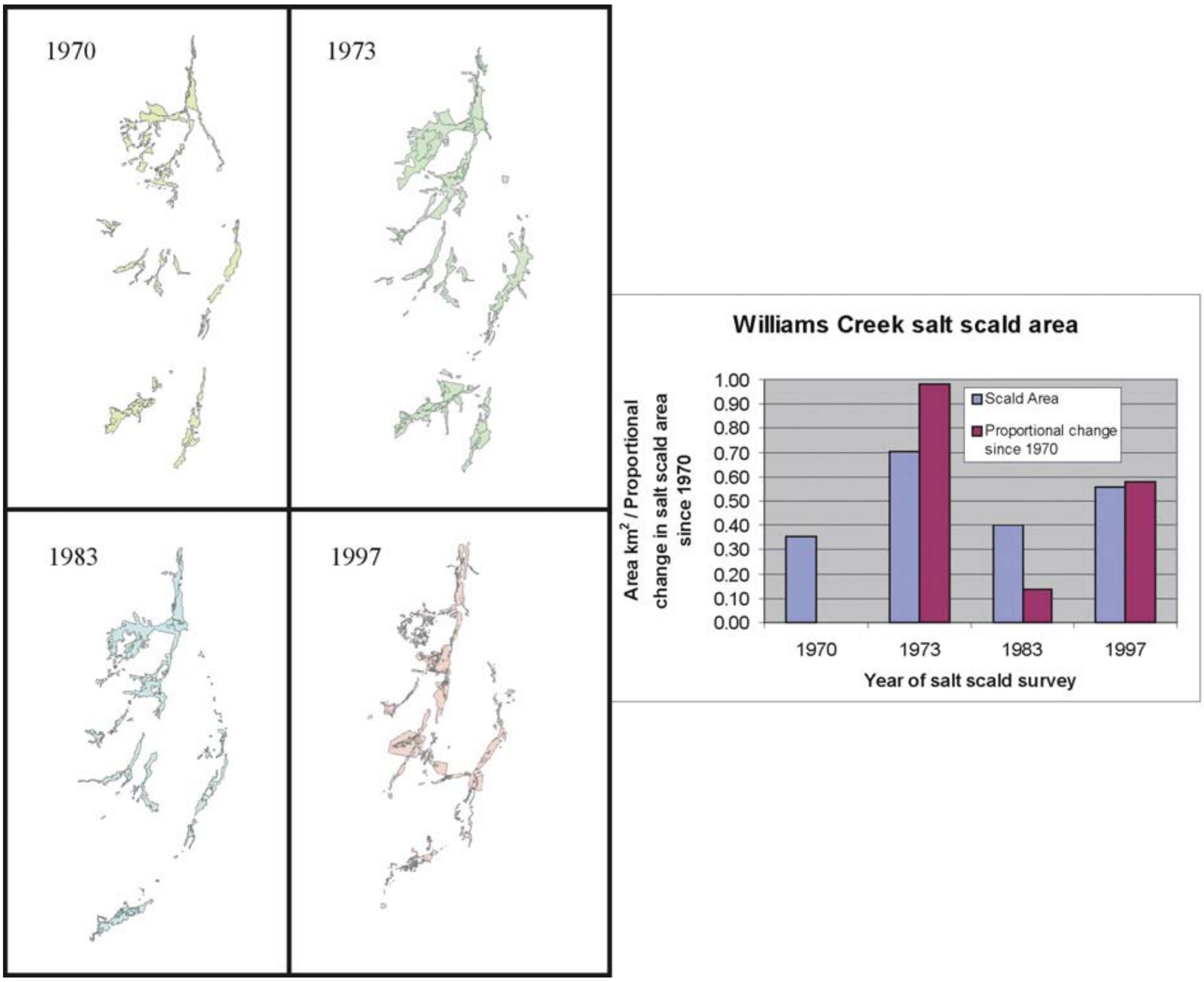
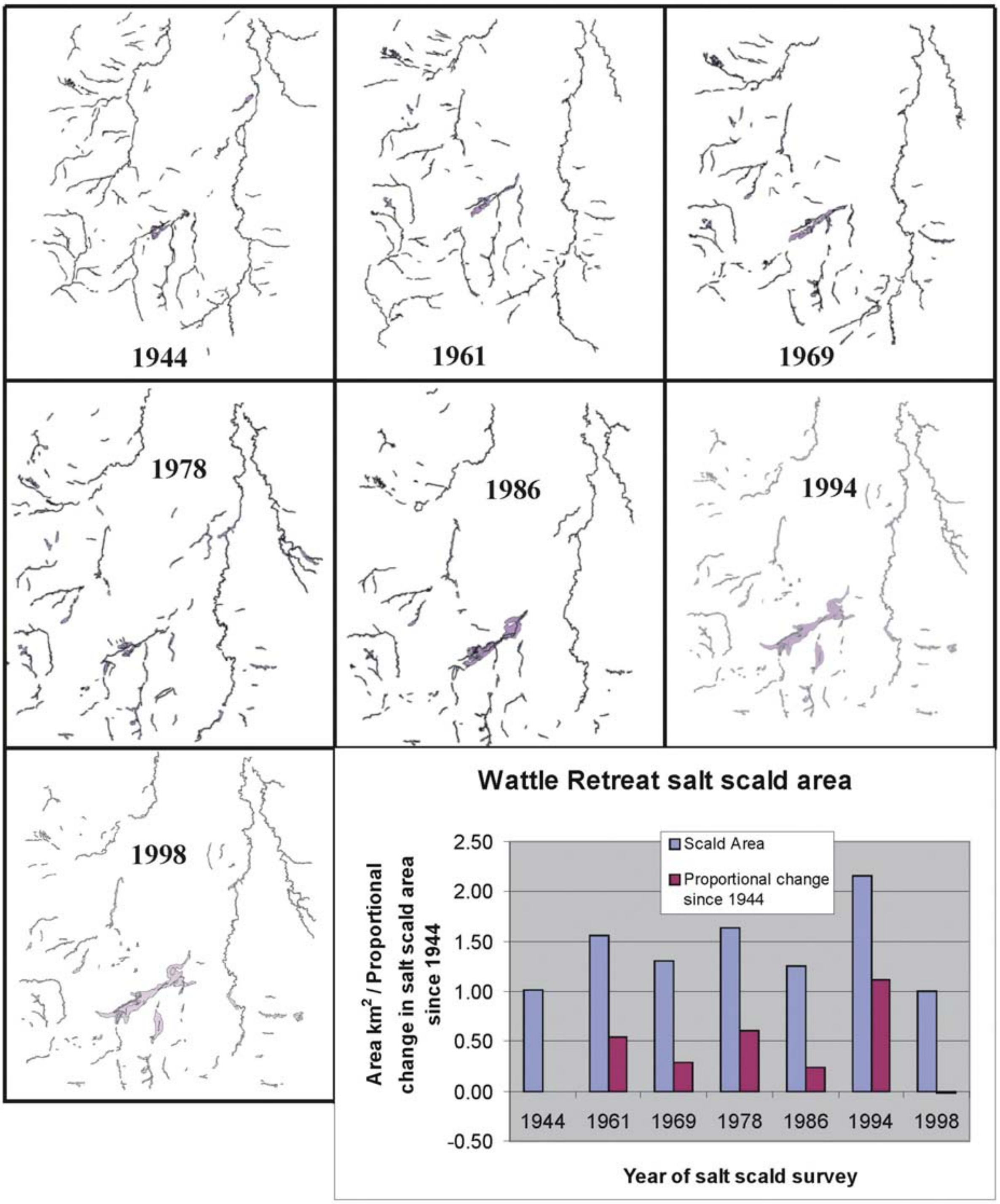


Figure 7: Saline area (salt scald) variation in the Wattle Retreat catchment



These three study catchments all showed general oscillating patterns, as described by Plowman (1999): ‘the saline areas appeared to oscillate in size from 1953 to 1994.’ However, the Cowra, Applewood, Mumbil and Box Hill catchments have shown a different response through time. The first three all showed an increase in saline extent until the early 2000s, when it appeared to be stabilising or starting to fall (Figures 8, 9 and 10). Box Hill, which is further north, also showed this trend, although the saline extent appeared to be declining more rapidly in the early 2000s (Figure 11). It can also be observed that the saline extent in Box Hill not only expanded and contracted, but also moved about. This may be the result of water tables breaking through one part of the landscape, then this area slowly blocking up and groundwater pressures causing the scald to break out in a another area.

The description of a generally increasing saline extent is similar to what Dominis (1999) described of Baldry: ‘the area of bare patches at the Baldry site generally increased in size from 1958 through to 1996’. On the basis of the two previous independent studies and the five new sites examined in this study, we conclude that in southern inland NSW (southern Lachlan, Murrumbidgee and Murray), the saline extent will show more oscillation (generally a 10-year cycle between peaks and troughs) then the mid and northern catchments of NSW. In the central and northern inland areas (mid and upper Lachlan, Central West, Namoi, Gwydir, and Border Rivers), the extent generally increased up until the late 1990s and early 2000s. This trend may be part of a larger oscillation that has 30- to 40-year cycles between peaks and troughs. Or it could be an indication that a new equilibrium in salt mobilisation out of the catchment from flushing processes has occurred since the major land use clearing in the early to mid 1900s.

Figure 8: Saline area (salt scald) variation in the Cowra catchment

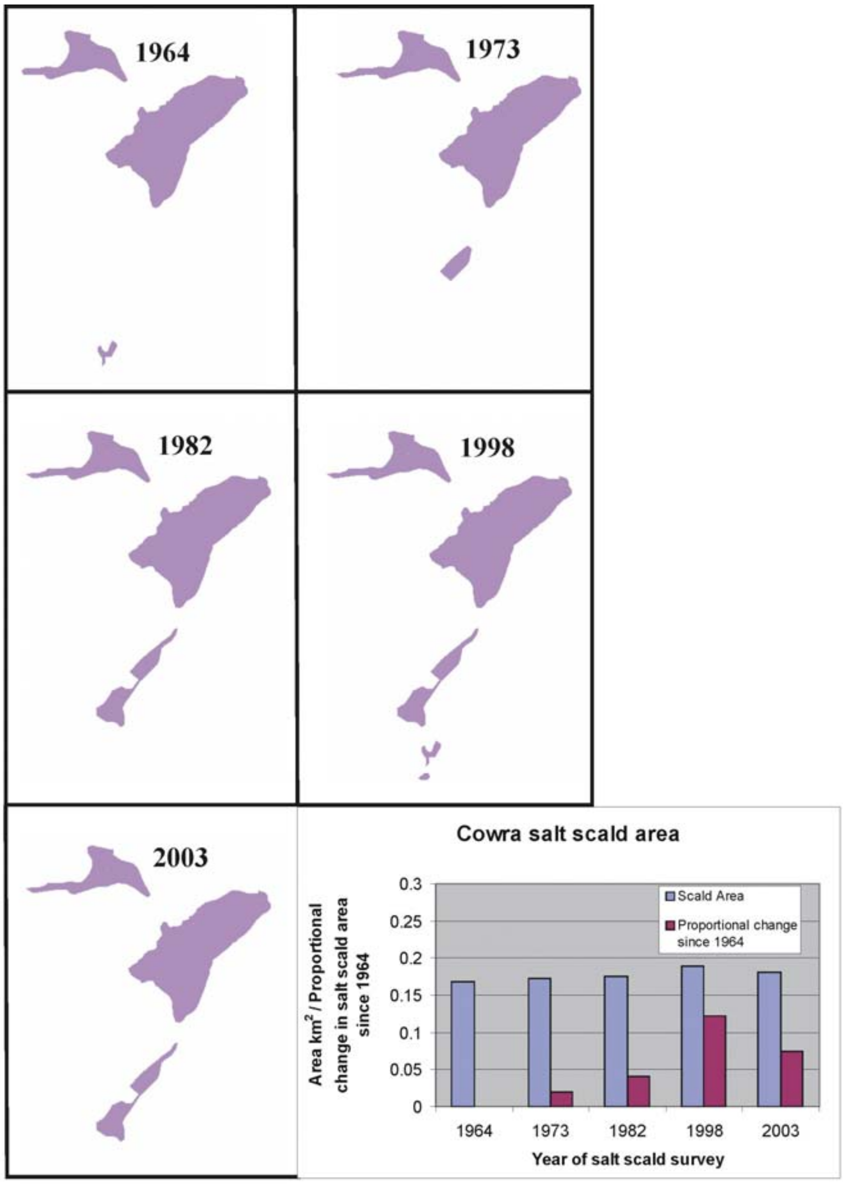


Figure 9: Saline area (salt scald) variation in the Applewood catchment

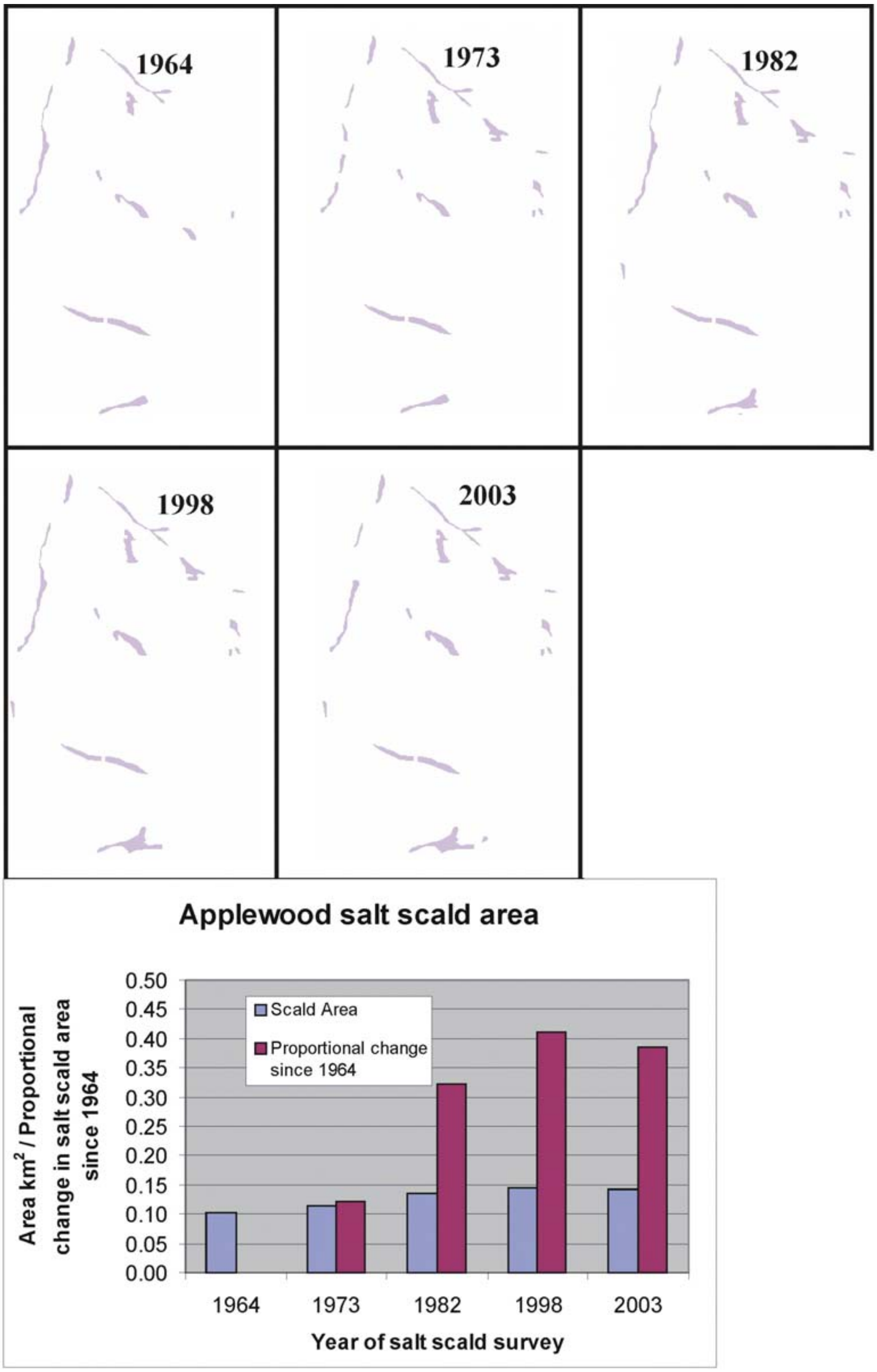


Figure 10: Saline area (salt scald) variation in the Mumbil catchment

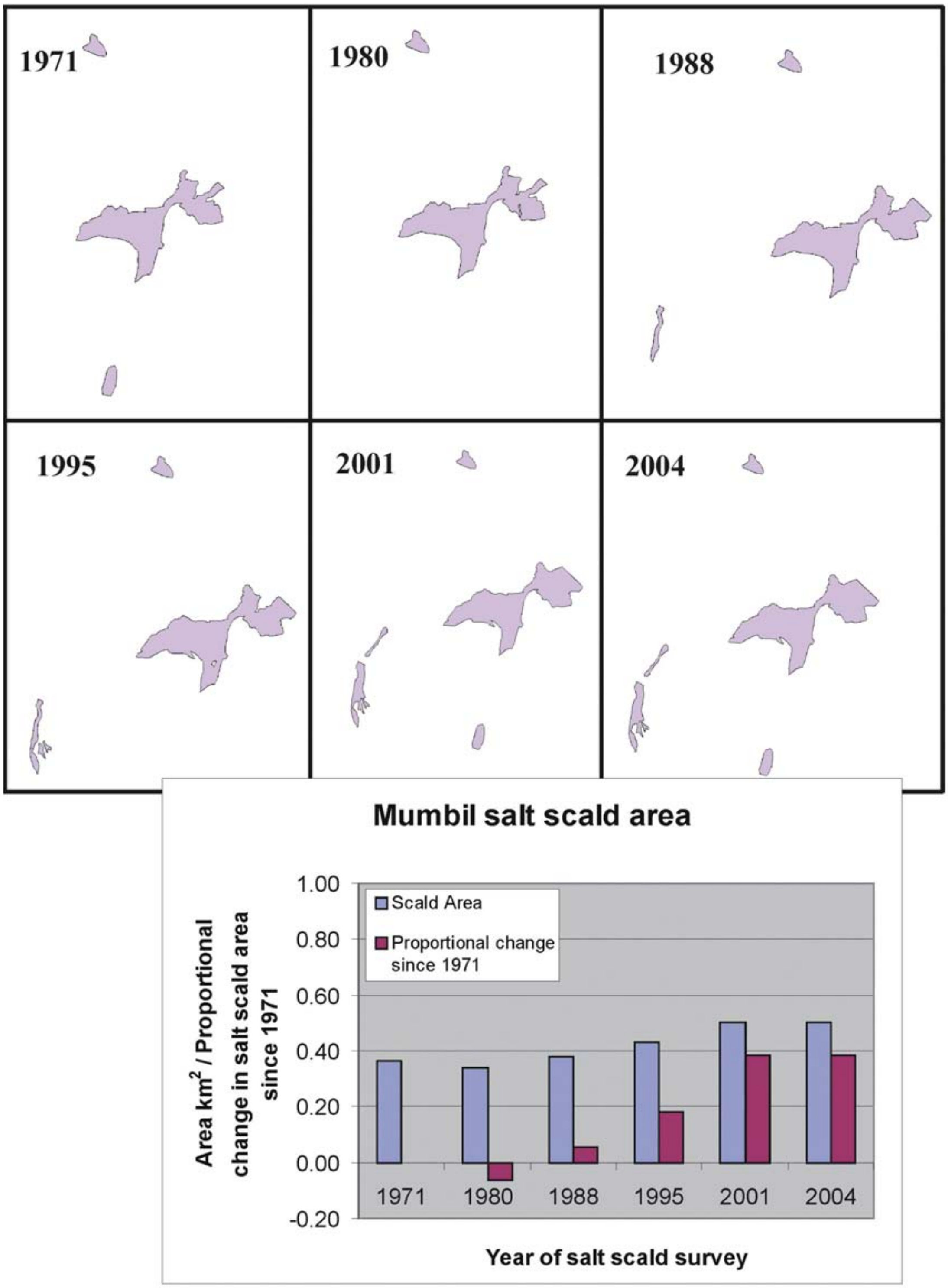
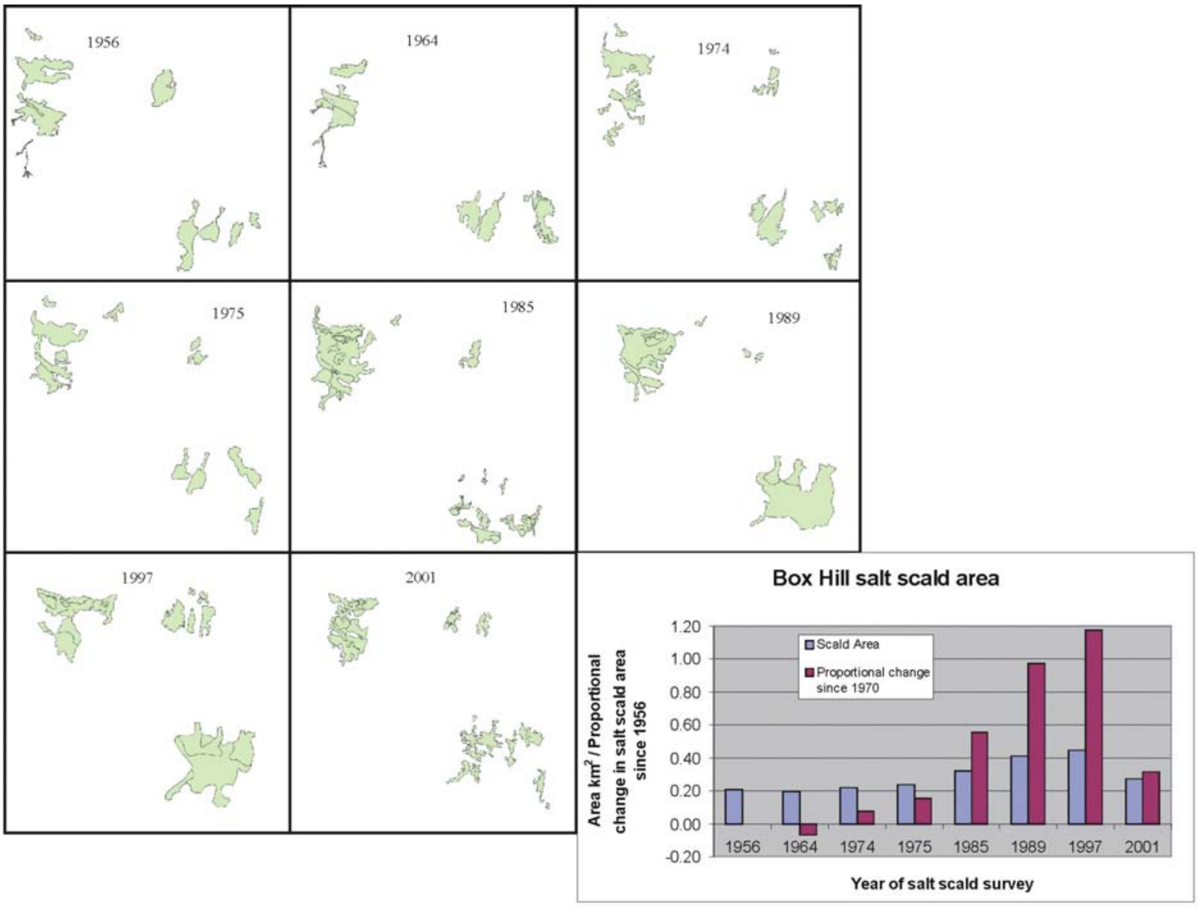


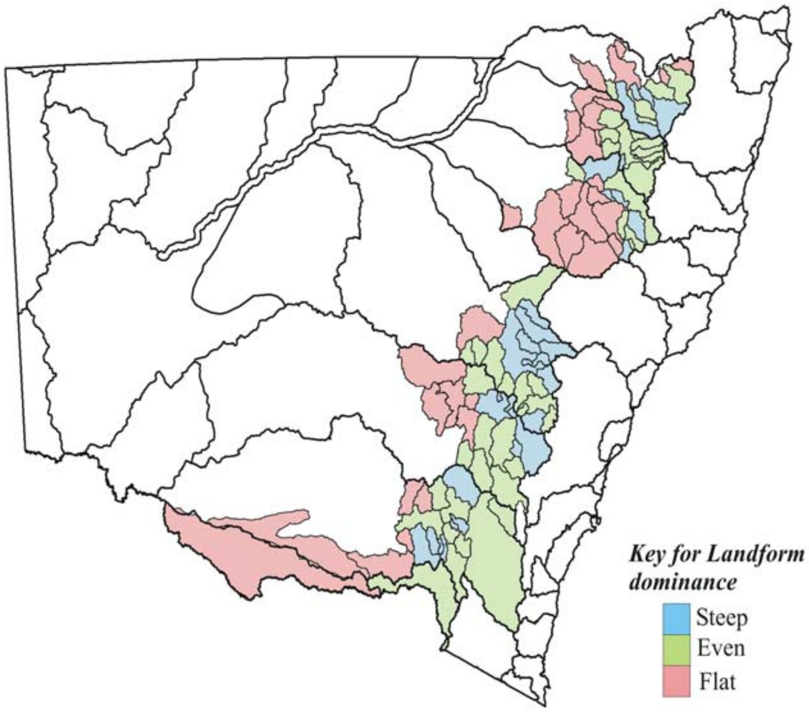
Figure 11: Saline area (salt scald) variation in the Box Hill catchment



3.2 Landform classification within the NSW Murray–Darling Basin and scald buffering

The study catchments used for this Salinity Audit were classified by their dominance of landforms (Figure 12). We used a 150-m buffer for determining the minimum and maximum extents of salinity outbreaks in catchments dominated by steep slopes, 250 m in catchments classified as having an even dominance of landforms, and 575 m in flat catchments.

Figure 12: Landform dominance in the 3rd-order catchments used in the NSW MDB

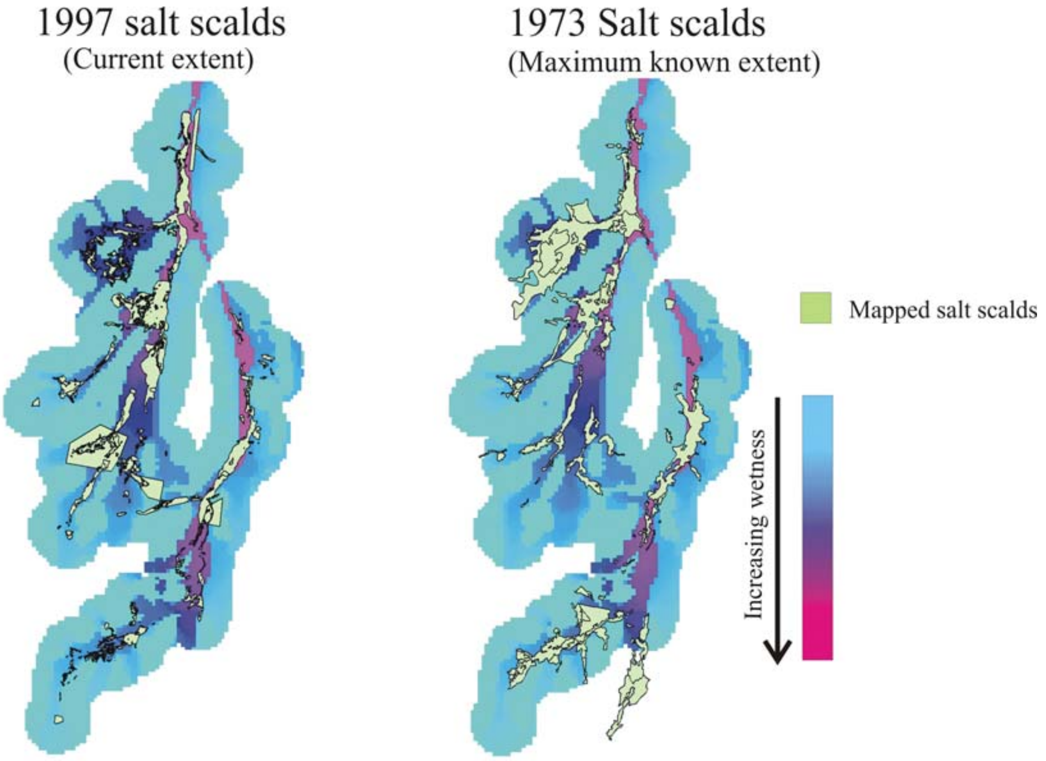


The seven study catchments were classified with the following landform dominance:

- Williams Creek (south)—**steep**
- Begalia (south)—**even**
- Wattle Retreat (south)—**flat**
- Cowra (middle)—**flat**
- Applewood (middle)—**steep**
- Mumbil (middle)—**even**
- Box Hill (north)—**even**

A clipped 150-m buffered wetness index from the FLAG model of the Williams Creek scalds is shown in Figure 13. The FLAG wetness image is shown by the blue to magenta background within the buffered area, and mapped scalds are light green. The 150-m buffered maximum extent captures most of the saline extent variation, but new expressions of scalds do not always get captured in the buffering process, as shown by the lower right-hand corner of the 1973 maximum extent image. This is because the representation of Williams Creek scalds is taken from the 2000 coverage of salinity from the ‘Outbreaks of Dryland Salinity’ coverage, to which the buffer is applied. The FLAG wetness representation of this scald will closely match the area, but the shape of the modelled scald will vary, as the method used places preference on the highest wetness values (magenta) over lower wetness values (blue). Therefore, the scalds are represented as being in about the right location and of about the right size.

Figure 13: FLAG wetness index for the Williams Creek scalds, showing observed current and maximum known extents



3.3 Current, predicted minimum and maximum salt scald extents

We used the Begalia, Williams Creek and Wattle Retreat study sites and the work of Plowman (1999) and Wagner (1986) to determine the trends in saline extent in the southern NSW catchments.

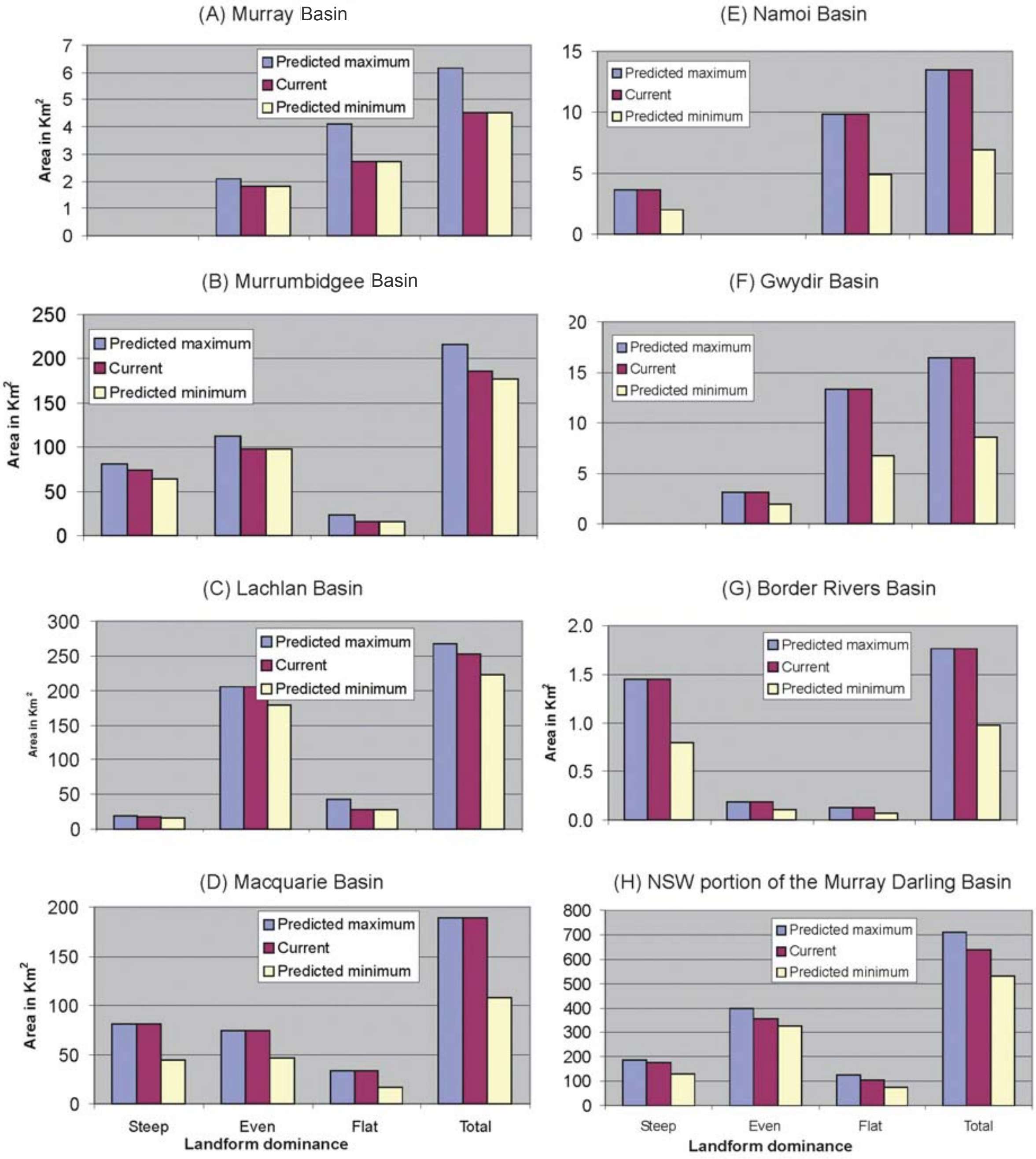
In the Murray region, the area classified in the 'Outbreaks of Dryland Salinity' (DNR 2004) as saline was minimal (Figure 14a). Spiers (2002) reported that many areas in the upper catchment are waterlogged but not saline on account of the high rainfall, which flushes salts away. In the even and flat landform-dominated catchments, the predicted minimum extent is equal to the current extent of scalding. No saline areas occurred in steep landform-dominated catchments. The overall maximum extent of salinity is predicted to be about 25% greater than the current situation (i.e. 2000 saline conditions).

In the Murrumbidgee and southern Lachlan, the current saline extent in the steep landform-dominated catchments is between the predicted minimum and maximum extents. In the even and flat landform-dominated catchments, the predicted minimum extent is equal to the current extent of scalding. The Lachlan catchment also has a higher instance of scalds in the even landform-dominated catchments (Figures 14b, c).

For the mid to northern NSW catchments, we used the Cowra, Applewood, Mumbil and Box Hill study sites and the work of Dominis (1999) to determine the trends in saline extent. All five sites indicate that the current extent of salinity is close to the maximum extent observed and may be starting to stabilise or fall. The mid to northern extents of the Lachlan have been adjusted to make the current extent equal to the known maximum extent. In the Macquarie, most scalds occur in the steep to even landform-dominated catchments, and the current extent is equal to the known maximum extent (Figure 14d). The extent of the minimum predicted extent of scalds is close to a 50% reduction in all basins in mid to northern NSW (Figures, 14d, e, f, g). This magnitude of difference is most likely driven by the observed general increase in size of the scalds. In the Namoi region only steep and flat landform-dominated catchments occurred. The steep landform-dominated catchments reflect landscapes such as the Liverpool Ranges, and the flat landscapes are found in the Liverpool Plains. In the Namoi, Gwydir and Border Rivers, the saline mapping is incomplete, and this is therefore reflected in the low extents of salinity (Figures 14e, f, g). The Gwydir is dominated by even and flat landform-dominated catchments, and the Border Rivers has a higher occurrence of currently mapped scalds in the steeper landform-dominated catchments.

Based on the current mapping from the 'Outbreaks of Dryland Salinity' (DNR 2004), the current extent of scalds in the NSW portion of the MDB is 644 km^2. The predicted minimum extent is 530 km^2, and the maximum is 711 km^2 (Figure 14h).

Figure 14: Saline areas for current and predicted minimum and maximum extents for each landform type within each basin. The NSW MDB is the sum of all basins



4 Conclusions

This methodology for estimating land salinisation has given a lower estimate of the maximum extent of known dryland salinity areas in the NSW portion of the MDB. Our estimate is half that of Littleboy *et al*. (2001), who were attempting to model areas affected by water tables within 2 m of the ground surface, whereas our methodology is restricted to known surface expressions of salinity. An added strength of our methodology is that it provides estimates of the potential variability of salt scald size. It does not predict new areas of salinisation, but simply examines the topographic constraints around the discharge sites that contain expansion and contraction of scalds through different recharge regimes. The maximum and minimum expansion and contraction observations were restricted to a 30- to 40-year time frame (late 1960s to 2000s). The work of Wagner (1986) indicated that before the 1950s, salt scalds were a relatively rare occurrence. After 1950, Wagner found a rapid increase in the number of scalds in the Southern Tablelands, which coincides with a major climate shift. The impact of this climate shift on fractured-rock groundwater levels has been explored by Rančić *et al*. (2008). Therefore, the fluctuations in discharge site extent analysed in this report fall within the context of the period of greatest known expressions.

Recurring land salinisation patterns between catchments grouped in the south of the State and in the centre to the north of the State indicates that this analysis captures landscape processes refelcting the major driver determining scald severity, despite localised catchment conditions, including human effects (e.g. saline remediation works, different seasonal effects). The remediation works in some of the catchments studied made a significant visual impact on saline areas when the aerial photography mapping was occuring , which would bias any mapping. This could potentially impact the estimated extents of expansion and contraction of scalds more significantly than the overall recurring land salinisation patterns. The results indicate that catchments in the south of the State showed an oscillating pattern in salinisation area throughout the 30 to 40 years of observations by aerial photography. Scalds in catchments in the middle and north of the State have been continually increasing in area, and may be starting to cycle back to a reduction in size now.

Management of saline discharge sites should target known expressions of salinity, because Berhane (in prep.) showed that there are site-specific reasons why discharges tend to remain in the same landscape position but fluctuate in area. Hydraulic conductivity and recharge are the main drivers of seepage face dynamics. Unless a major change in recharge regime across the State similar to that induced in the 1947–48 climate shift, or widespread clearing, occurs, it is unlikely that major new scalds will develop widely. Therefore, targeted salinity management as opposed to general widespread homogeneous actions can be recommended. Targeted management of recharge areas connected to the existing discharge sites will maximise investment returns, especially in upland areas where dryland salinity is contained within local groundwater systems.

Harvey *et al*. (2008) showed a cyclic component in stream salinity trends. This cyclic pattern does not appear to have a convincing link to the variations in salt scald expressions shown in this report. Differences in the scale or measurement frequency (e.g. gauging stations at the end of a catchment compared with scald expressions in a subcatchment), spatial differences in salt stores, and elevation and climatic gradients would all contribute to this difference, as the stream measurements are a response of the whole catchment, including fresh and saline tributaries. The buffering effects of a landscape in concentrating, storing and discharging saline waters into a stream network would also contribute to these differences.

5 Recommendations

1. For better representation of NSW saline areas, mapping of the ‘Outbreaks of Dryland Salinity’ (DNR 2004) needs to be completed.

2. More study catchments for determining expected trends and buffer widths would be desirable to give more examples of trends.

3. Discharge sites should be managed for erosion prevention within the potential spatial extent of scald expansion and contraction. Developing an understanding of scald extents can be achieved through viewing historical aerial photos, or undertaking soil (texture, salinity) or electromagnetic surveys. The current climate is dry, and scald sizes are generally reduced. Therefore, fencing out a current scald will most likely not account for increases in scald size if a high recharge regime recurs.

6 References

Anon (2004) Mapping soil salinity using satellite imagery. www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/water-gw-salinity-mapping

Beale, G.T.H., Beecham, R., Harris, K., O'Neil,l D., Schroo, H., Tuteja, N.K., Williams, R.M. (2000). Salinity predictions for NSW rivers within the Murray–Darling Basin. Centre for Natural Resources, NSW Department of Land and Water Conservation, Sydney.

Beale, G.T.H., Gilmore, R., Simons, M., Realica, S., Nanadakumar (2001). NSW Coastal Rivers Salinity Audit—Predictions for the Hunter Valley. Centre for Natural Resources, NSW Department of Land and Water, Sydney.

Caccetta, P.A. (2000). Mapping and monitoring land use condition change in the south-west of Western Australia using remote sensing and other data. CSIRO Leeuwin Centre, Floreat, Western Australia.

DNR (2004). Outbreaks of Dryland Salinity (map). NSW Department of Infrastructure, Planning and Natural Resources, Sydney.

Dominis, M. (1999). Dryland Salinity in Baldry Central West NSW, 1958 to 1999. Honours dissertation, University of Sydney.

Dowling, T.I. (2000). FLAG analysis of catchments in the Wellington region of NSW. Land and Water Consulting Report 12/00, CSIRO, Canberra. http://www.clw.csiro.au/publications/consultancy/

Evans H., Kiiveri, T. (1998). Monitoring Land Condition in the Upper Blackwood and Franklin–Gordon Catchments. LWRRDC Project, CSIRO, Canberra.

Freeze, R.A., Cherry, J.A. (1979). Groundwater (Prentice Hall: Englewood Cliffs, NJ, USA).

Furby, S.L. (1998). Mapping Dryland Salinity in Selected Catchments Across Australia. LWRRDC Project (CDM2), CSIRO, Canberra.

Furby, S.L., Wallace, J.F., Caccetta, P., Wheaton, G.A. (1995). Detecting and monitoring salt affected land. CSIRO Mathematical and Information Sciences and Agriculture Western Australia, Perth.

Harvey, F., Koen, T., Miller, M., McGeoch, S. (2008). 2006 Stream EC trends for inland NSW. Department of Environment and Climate Change NSW, Sydney.

Kirkby, S.D. (1996). Integrating a GIS with an expert system to identify and manage dryland salinisation. *Appl. Geogr.* **16(4)**, 289–303.

Laffan, S.W. (2002). Using process models to improve spatial analysis. *Int. J. Geogr. Info. Sci.* **16(3)**, 245–257.

Lawson, S. (1989). Dryland salinity project: Williams Creek drilling completion report. Technical Report T.S. 88.017. NSW Dept Water Resources, Sydney.

Lawson, S. (1994). Dryland salinity studies ‘Wattle Retreat’ Cootamundra, a review of 5 years of hydrological modelling. Technical Report 94/12. Department of Water Resources internal report.

Littleboy, M., Piscopo G., Beecham R., Barnett P., Newman L., Alwood N. (2001). Dryland salinity extent and impacts, New South Wales. National Land and Water Resources Audit, Technical Report: http://audit.ea.gov.au/ANRA/land/docs/state/NSW/NSW_DrylandSalinity_summary.html

Lytton, L., Punthakey J., Williams R.M. (1994). Dryland salinity project, Boxhill Groundwater Study 1989–1993. Technical Report T.S. 94.085. NSW Dept Water Resources, Sydney

MDBCMC (1999). The Salinity Audit of the Murray–Darling Basin: A 100-Year Perspective. Murray–Darling Basin Commission Ministerial Council, Canberra.

NSWLIC (1999). State wide digital elevation model data. NSW Land Information Centre, Bathurst, NSW.

Plowman, M.M. (1999). The nature of change of dryland salinity: a case study in the Spring Creek catchment, NSW. BSc dissertation. University of Sydney.

Rančić, A., Salas, G., Kathuria, A., Johnston, W., Smithson, A., Beale, G., Ackworth, I. (2008). Climatic influence on shallow fractured-rock groundwater systems in the Murray–Darling Basin, NSW. Department of Environment and Climate Change NSW, Sydney.

Roberts, D.W., Dowling, T.I., Walker, J. (1997). FLAG: a Fuzzy Landscape Analysis GIS method for dryland salinity assessment. Land and Water Tech. Report 8/97. CSIRO, Canberra. http://www.clw.csiro.au/publications/technical/technical97.html

SKM (1999). Projections of the Ultimate Salt Load from Victorian Dryland Catchments to the Murray River, Summary of Methods and Results. Department of Conservation and Natural Resources and Sinclair Knight Merz Pty Ltd, Melbourne.

Smith, J.W. (1979). The Geology of the Gundaroo-Nanima area, New South Wales. MSc dissertation. Australian National University.

Spiers, P. (2002). Dryland Salinity Mapping in the Murray Catchment 2002. NSW Department of Land and Water Conservation, Sydney.

Spiers, P., Woodgate M. (2004). User Guide—Salinity Mapping Methods in the Australian Context, Land and Water Australia. CSIRO, Canberra.

Summerell, G.K. (2004). Understanding the processes of salt movement from the landscape to the stream in dryland catchments. PhD dissertation, University of Melbourne.

Summerell, G.K., Beale G.B., Miller M.L., Dowling T.I. (2003). DLWC-FLAG modelling of soil wetness hazard in upland NSW: a user manual to access and interpret soil wetness maps. Centre for Natural Resources, NSW Department of Land and Water Conservation, Sydney.

Summerell, G.K., Dowling, T.I., Wild, J.A. and Beale, G (2004) FLAG UPNESS and its application for determining seasonally wet and waterlogged soils. Australian Journal of Soil Research 42 155-162.

Summerell, G.K., Miller, M., Beale, G., Emery, K., Lucas, S (2005a). Current and predicted minimum and maximum extents of land salinisation for the upland NSW portion of the Murray–Darling Basin. MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand (Ed. Andre Zerger & Robert M. Argent), Melbourne.

Summerell, G.K., Vaze, J., Tuteja, N.K., Grayson, R.B., Beale, G., Dowling, T.I. (2005b). Delineating the major landforms of catchments using an objective hydrological terrain analysis method. *Water Resour. Res.* **41**, 1-12

Summerell, G.K., Tuteja, N.K., Grayson, R.B., Hairsine, P.B. and Leaney, F (2006) Contrasting Mechanisms of salt delivery to the stream from three different landforms in South Eastern Australia. Journal of Hydrology 330/3 681-697.

Van Bueren, M., Price, R. (2004). Key findings from 10 years of Australia's National Dryland Salinity Program. Land and Water Australia, Canberra.

Wagner, R. (1986). Dryland Salinity in the South East Region. Unpublished report, Department of Conservation and Land Management, Yass, NSW.

Walker, G., Evans, R., Hatton, T., Gilfedder (1999). Salinity Audit of the Murray–Darling Basin Ultimate Salt Loads Reports, Quality Assurance Review. Report to the Murray–Darling Basin Commission. CRC for Catchment Hydrology, Canberra.

Wild, J.A.., Summerell, G., Grant, S., Miller, M and Young, J (2005) An infrastructure hazard map derived from soil landscape mapping with digital landform analysis. In Morrison R, Quin, S and Bryant E.A. (eds) Planning for Natural Hazards, how can we Mitigate the Impacts? Proccedings of a Symposium, University of Wollongong, 2-5 February 2005. pp79-87.ISBN : 1 74128 115 6 http:/www.uow.edu.au/science/eesc/geoguest/index.html

Woolley, D., Bish, S., Bradd, J., Dwyer, J., O'Neill, D., Williams, R.M. (1999). Murray–Darling Basin and Drainage Strategy: Groundwater Derived Saltloads in NSW. Centre for Natural Resources, CNR99.004. Department of Land and Water Conservation, Sydney.

Appendix A: Case study in the Mona Vale catchment to determine depth-to-groundwater relationship with FLAG UPNESS index

The Mona Vale catchment is a subcatchment of the Kyeamba catchment, within the Murrumbidgee region, on the South Western Slopes near Wagga Wagga. The soil types, groundwater piezometers and catchment boundary are shown in Figure A1. The catchment is located on highly fractured metasediments. Groundwater levels were monitored between 1991 and 2000 (Figure A2). Linear regressions of depth to water table during a wet period and a dry period against the UPNESS index were done as per Summerell *et al.* (2004). Results showed the relationships between depth of water table and UPNESS (Figures A3 and A4).

Figure A1: The Mona Vale catchment (black boundary, derived from the 25-m DEM) overlying the major soil types and land uses within the catchment

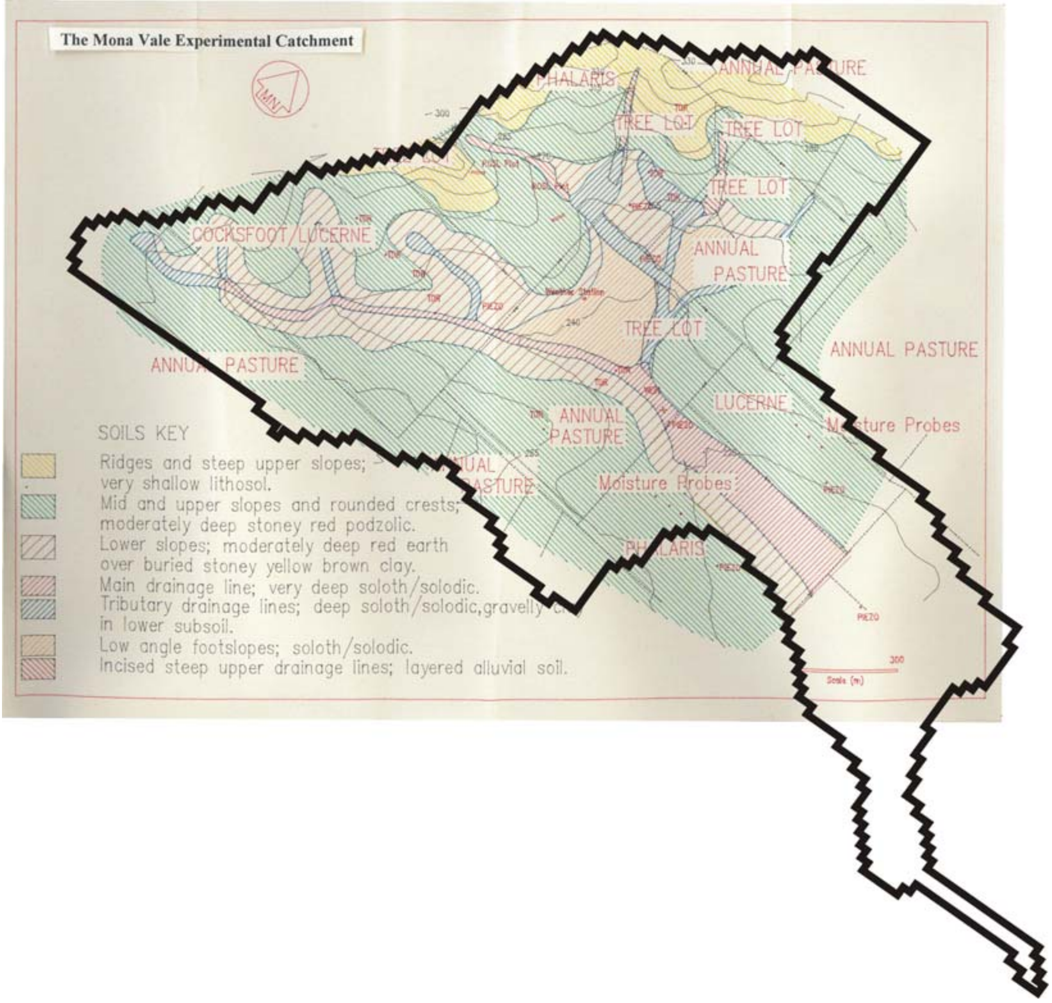


Figure A2: Bore hydrographs of the Mona Vale catchment from 1991 to 2000. Groundwater responded to climate by rising during the wet 1993 and falling during the dry 1997

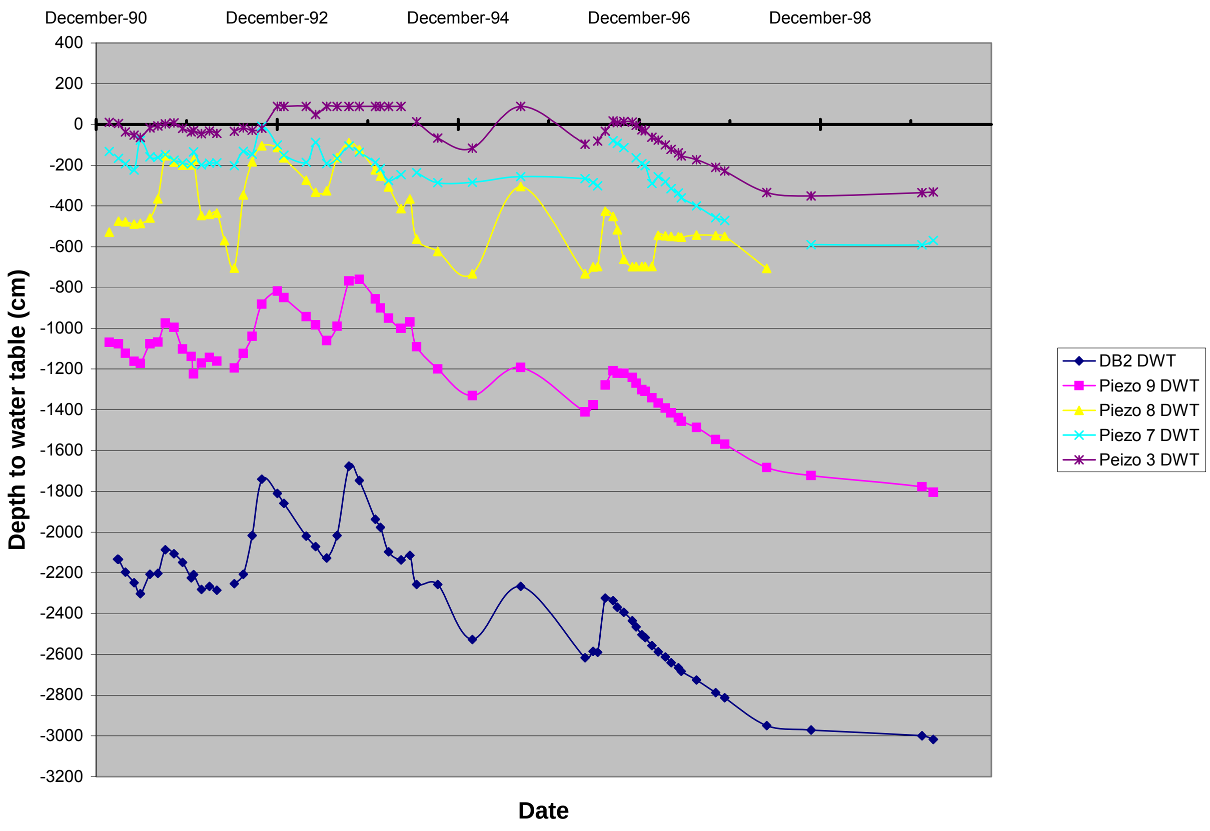


Figure A3: Relationship between depth to groundwater and UPNESS during a wet period when the water tables were high

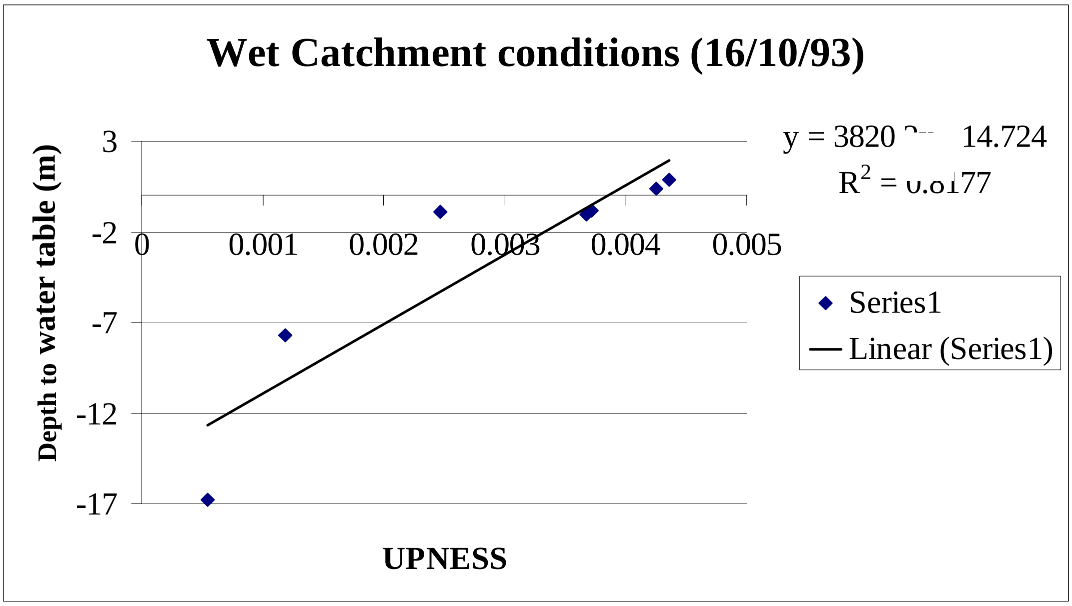
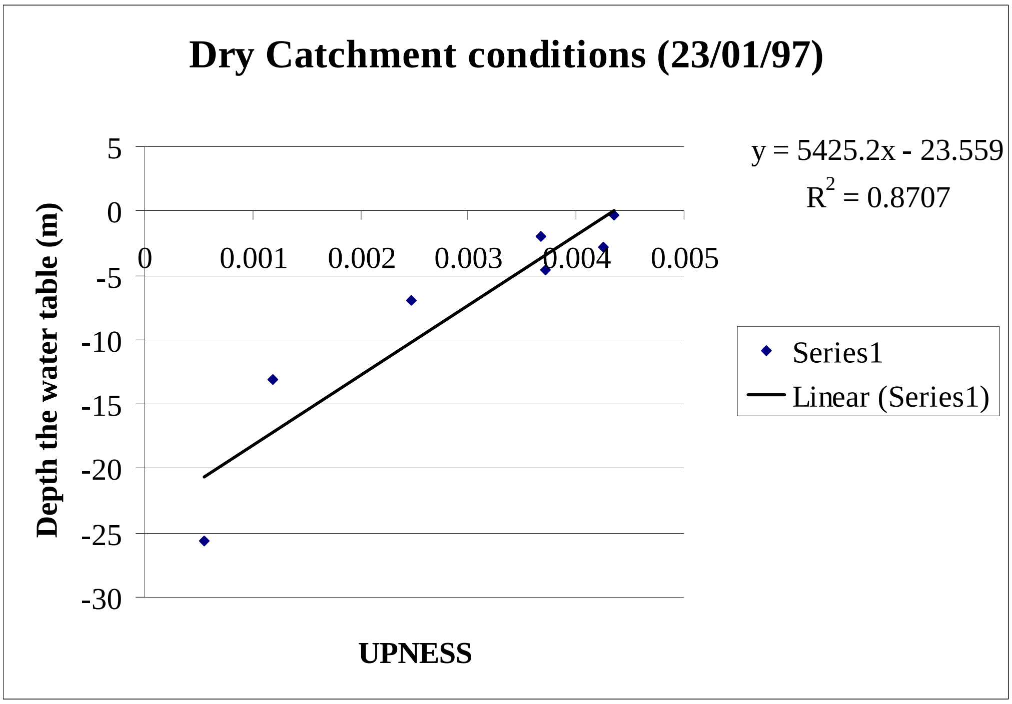


Figure A4: Relationship between depth to groundwater and UPNESS during a dry period when the water table was low



The transect in the Mona Vale catchment runs from the hillslope to the valley floor. The groundwater surface tends to reflect a non-linear smoothed-elevation surface with the greatest depth to water table on the hill tops, and the least at the break of slope and on valley floors. Therefore, a power function was used to better reflect the relationship between UPNESS and depth to water table (Figures A5 and A6). From this relationship, an UPNESS value at 2 m below the ground surface was determined as potentally salinised and used to define the spatial extent of water tables capable of discharging water and salt to surface soils by capillary flux in the soil. An UPNESS value of 0.0037 was determined as the dry climate extent and a value of 0.0015 as the wet climate extent. Figures A7 and A8 show the modelled influence of water tables within 2 m of the land surface under both wet and dry conditions as determined from the UPNESS index. Comparing the modelled results to the mapped soils shown in Figure A1 (specifically the valley fill drainage line areas) indicates that not only does the method match the piezometric groundwater head, it also sensibly defines the topographical extents.

Figure A5: Power relationship between depth to groundwater and UPNESS during a wet period to better represent the groundwater relationship with the land surface across a hillslope

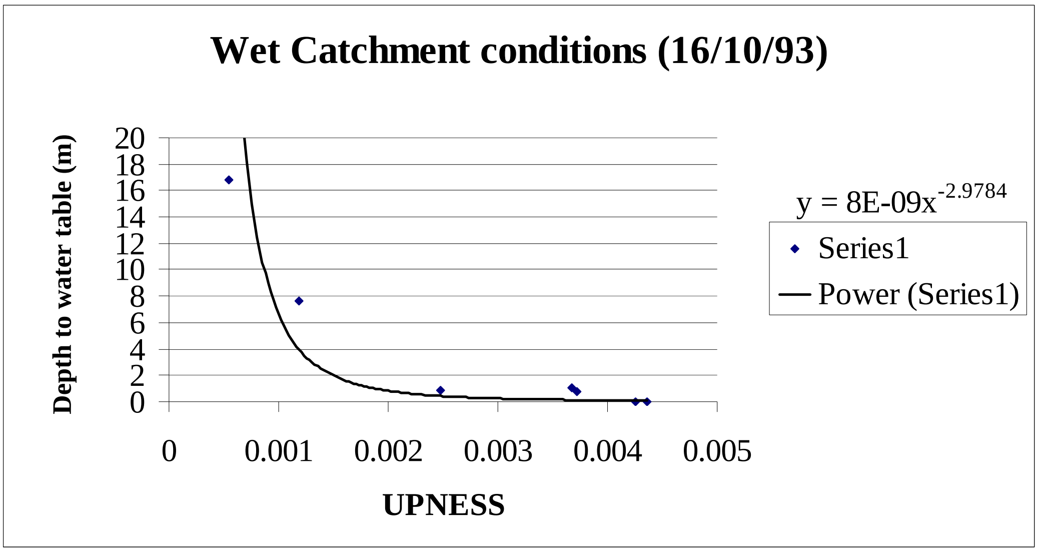


Figure A6: Power relationship between depth to groundwater and UPNESS during a dry period to better represent the groundwater relationship with the land surface across a hillslope

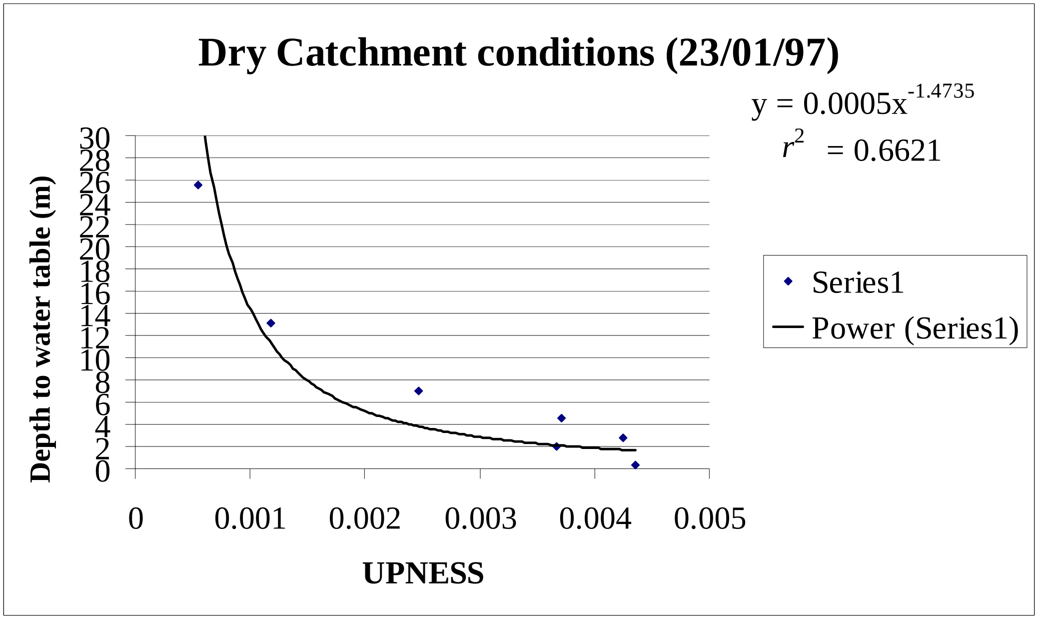


Figure A7: Wet catchment conditions: water table within 2 m of surface based on UPNESS classification 0.0015

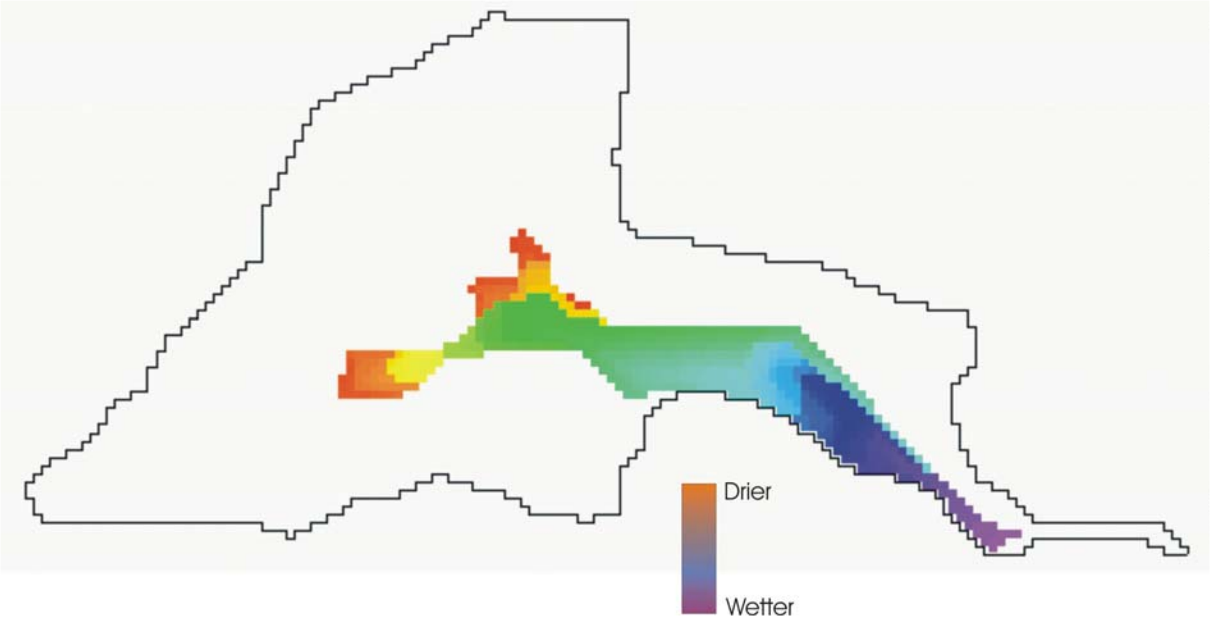


Figure A8: Dry catchment conditions: water table within 2 m of surface based on UPNESS classification 0.0037