

Spatial Prioritisation of Revegetation Sites for Dryland Salinity Management: An Analytical Framework Using GIS

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ABSTRACT

To address the lack of analytical and modelling techniques in prioritising revegetation sites for dryland salinity management, a case study of the Hodgson Creek catchment in Queensland, Australia, was conducted. An analytical framework was developed, incorporating the use of spatial datasets (Landsat 7 image, DEM, soil map, and salinity map) which were processed using image processing techniques and a geographic information system (GIS). Revegetation sites were mapped and their priority determined based on recharge area, land use/cover and sub-catchment salinity. The analytical framework presented here enhances the systematic use of land information, widens the scope for scenario testing, and improves the testing of alternative revegetation options. The spatial patterns of revegetation sites could provide an additional set of information relevant in the design of revegetation strategies.

INTRODUCTION

Salinity is a major land degradation problem in Australia (National Dryland Salinity Program, 1999). The problem is caused by groundwater redistributing salts and accumulating these at the surface (DNR, 1997). High levels of salt in soils affect plant growth and crop yield, and can lead to the decline in water quality, habitat degradation, and damage to infrastructures (National Dryland Salinity Program, 1998; Murray-Darling Basin Commission, 1999). In Australia, it is estimated that about 2.5 million hectares of land is affected (National Dryland Salinity Program, 1999).

It is generally accepted that the main cause of dryland salinity (i.e. salinity in non-irrigated areas) is inappropriate clearing of deep-rooted perennial vegetation and its

replacement with shallow-rooted crops and pastures or with urban development (RIRDC, 2000; Stirzaker *et al.*, 2000). Studies have found marked associations between land clearing and outbreaks of watertable salting in hydrologically sensitive catchments (Bui 2000; DNR, 1997). Logically therefore, to mitigate dryland salinisation in heavily cleared areas, vegetation should be re-established to help restore the water balance in a catchment (Martin and Metcalfe, 1998).

One important task in revegetation planning for dryland salinity management is the need to map and prioritise revegetation areas in a catchment. This requires two questions to be asked: Which area should be planted? Which area should be planted first? Because the hydrologic and environmental processes involved in dryland salinity have a spatial dimension (e.g. groundwater recharge and discharge areas are spatially distinct), indiscriminate planting of trees is not desirable. Vegetation should be best planted based on the understanding of the hydrogeological system, climate and soils of the area being revegetated (Thorburn, 1999). Moreover, prioritisation will help to rationalise spending and deployment and allocation of input resources.

While there is nothing particularly novel about using GIS for mapping and suitability analysis, its application to revegetation for salinity management has been rarely exploited. Hence, the objectives of this study were to a) develop and evaluate a framework for mapping and prioritising revegetation sites associated with dryland salinity management and b) analyse the spatial patterns of revegetation sites and their possible implications to alternative revegetation strategies.

DRYLAND SALINITY AND THE REVEGETATION OPTION

Saline seepages and scalded areas usually occur in the discharge zone of a catchment. The discharge zones cover the landscape area where the net movement of water is out of the groundwater table (DNR, 1997). This zone is often characterised by relatively flat areas where weathering and erosion products accumulate. On the other hand, the recharge zones cover the areas where water enters and moves downward to the groundwater table. These areas are usually found on shallow, permeable soils located on upper slopes. The distinction between recharge and discharge zones is important: there are theoretical and practical implications (e.g. George *et al.*, 1999; Martin and Metcalfe, 1998) that are relevant to revegetation prioritisation.

Dryland salinity problems commonly result when woody vegetation is cleared from upper catchment slopes (Bui, 2000). When trees are removed, the increase in the deep drainage component of the soil-water balance usually results in an alteration of the catchment hydrologic regime (Williams *et al.*, 1997). This hydrological imbalance increases groundwater recharge and mobilises salt previously distributed in deeper subsoil and substrate layers (DNR, 1997). Therefore, revegetation and/or retention of existing vegetation must become a central strategy to combat salinity. When present in recharge areas, trees and high water use crops can reduce deep

drainage by using more water (through transpiration) to a greater depth and by intercepting more rain in the canopy than most pastures or crops (DNR, 1997).

Revegetation is generally a curative, rather than preventive, management option. It is potentially expensive (DNR, 1997), the effects on watertables are often localised (George *et al.*, 1999), and the benefits in controlling salinity can take a considerable period (e.g. 30 or 50 years). Thus, it is imperative that all stages of the replanting efforts (from initial site assessment to on-going maintenance and monitoring) should be carefully planned. To minimise costly failures, the mapping and prioritisation of revegetation sites is one aspect that needs focused attention.

Understanding the spatial pattern of potential revegetation sites could also help in the design and evaluation of revegetation strategies. Information about the landscape structure including size, shape, number, type and configuration of the various landscape elements such as remnant vegetation and deforested patches, are necessary inputs to sound decision-making (e.g. Forman and Godron, 1986). For example, Fedorowick (1993) developed a landscape restoration framework in deriving design alternatives that could benefit both agriculture and wildlife in a fragmented landscape in Canada. His design focused on adding patches and corridors, by considering their number, location, and connectivity.

METHODS

Study Area

The study area covers the Hodgson Creek catchment of the Murray-Darling Basin system in south-east Queensland, Australia (Figure 1). It is located south west of the city of Toowoomba, approximately 125 km from Queensland's capital city of Brisbane. The catchment has a total area of 80,854 hectares, with a human population of about 7,000.

[Figure 1, about here]

The climate in the catchment is predominantly sub-tropical, with summer dominant rainfall, i.e. about 70% of the annual rainfall occurs in the October to March period (DPI 1988). The average annual rainfall ranges from 659 mm in Pittsworth to 954 mm in Toowoomba. Over 70% of the catchment (mostly on the eastern and central parts) has soils that are derived from geologically recent basaltic intrusions (Willey, 1993). Alluvium comprises about 20% of the area, and the remainder has a sedimentary origin. Soil erosion has been identified as a severe land degradation problem in cultivated areas of the catchment. Approximately 61% of the catchment is under intensive cultivation (Carberry and Walker, 1993). Grasslands, remnant woodlands and revegetated areas comprise the rest, with settlement areas covering less than 1% of the area.

The catchment is affected by a number of forms of salinity, including seepage, scalding and irrigation salting (Carberry and Walker, 1993). The dominant form in the catchment is saline seepage, associated with clearing of native vegetation, overgrazing, and increasing areas of crop production (Carberry and Walker, 1993). The Kenmuir and Beauaraba soils, located on upper slopes, have been identified as the recharge zones, while the Waco and Irving soils predominate in the discharge zones.

Data Acquisition and Image Processing

The GIS database comprised of four primary data sets: (a) Landsat 7 ETM+ satellite imagery (to derive recent land use/cover), (b) digital elevation model (DEM) (to produce slope and sub-catchment boundaries), (c) agricultural management unit map (AMU) (interpreted map of soils and landscape position needed to delineate recharge and discharge zones), and (d) existing salinity outbreak map (needed to help prioritise revegetation sites). Other ancillary maps used to aid interpretation and analysis included the geology, land use (1988), land capability, cultivation, stream/drainage, and land cover (1991) maps.

With the exception of Landsat 7 image and the DEM, all primary datasets were sourced from the Queensland Department of Primary Industries (DPI) (Carberry and Walker, 1993). The DEM was produced by the local office of the Department of Natural Resources (DNR) and derived from both 1:10,000 and 1:25,000 contour and drainage data (Storey, 1999). The source data used to built this DEM has a positional accuracy of ± 12.5 m (horizontal) and ± 2.5 m (vertical), while the AMU soil map has an estimated horizontal accuracy of 20 m. The positional accuracies of all maps used in this research are sufficient for the goal of this catchment-scale (approximately 1:50,000) study.

The study used a 43 km x 34 km orthorectified image subset acquired on 5 March 2000. All of the visible and non-thermal infrared bands, including a Normalised Differenced Vegetation Index (NDVI) image, were included in a supervised image classification (Apan *et al.*, 2000). Sample training areas for each land use/cover class were selected based from ground survey and ancillary datasets. Signature evaluation relied on statistics and graphical methods to examine the spectral properties of sample classes. A maximum likelihood algorithm was employed, with classes set to different a priori probabilities based on the class area estimated from auxiliary data (Richards, 1993).

Two complementary approaches were implemented to assess the results of image classification: visual checks and using error/confusion matrix. Visual checks depended on qualitative visual comparison of the raw and the classified image. On the other hand, error/confusion matrix involved a quantitative approach to compare a classified image (187 sample pixels) with that of ground reference data. All image processing tasks used the GRID module of ARC/INFO 7.2.

GIS Processing and Modelling

A flowchart of the GIS processing and modelling steps applied to both primary and derived layers is shown in Figure 2. All datasets were clipped to the extent of the catchment boundary, and then converted into raster data format (30m x 30m grid cell size) to facilitate GIS analysis. The project utilised the GIS software ARC/INFO 7.2 and ArcView 3.2 with Spatial Analyst extension.

[Figure 2, about here]

The mapping of the recharge zones (i.e. where water enters and moves downward to the groundwater table) and discharge zones (i.e. where the net movement of water is out of the groundwater table) was adopted from the techniques developed by Bui (2000). The information on soil-landform relationships, parent material, soil thickness, depth to bedrock, topographic position, and soil types was interpreted based on pedogenic principles. Potential recharge zones were assumed to correspond to map units with high permeability and drainage areas. Conversely, potential discharge zones were assumed to correspond to soil map units with low permeability and poor drainage located in low spots of the landscape. The rest of the soil map units were accepted to be transmission areas. The interpretation and reclassification tasks were aided by geology, drainage and vegetation maps, including soil survey reports by Thompson and Beckmann (1959) and Macknish (1979).

This study refined Bui's (2000) methodology by incorporating slope information in estimating the final recharge and discharge boundaries. Because some portions of the soil map units corresponding to recharge areas were found in flat areas where drainage is poor, the slope information was used to clip these poorly drained areas. Thus, soil units typically associated with recharge zones but located on valley floors and with less than 3% slope were classified as transmission or discharge zones.

The DEM provided the slope and the sub-catchment boundary layers. The sub-catchment boundary layer, generated using ArcView's Hydrologic Modeling extension, aimed to subdivide the study area into smaller sub-catchments so that the relative extent (area) of salinity outbreaks per sub-catchment could be quantified. As one of the revegetation prioritisation criteria, the spatial extent of salinity in each sub-catchment was determined by overlaying the sub-catchment boundary layer with that of the salinity map (Figure 2).

To produce the revegetation map with classes of "high", "moderate" and "not" priority, the following selection criteria were implemented:

- high priority – includes recharge zones associated with pasture/grassland.

Revegetation for salinity management is typically located either in the recharge or discharge zones. While solely focusing on recharge zones may be impractical for various reasons (see for example, Thorburn, 1999), addressing the problem of

reducing groundwater recharge (rather than discharge) is often more important (e.g. George *et al.*, 1999; Martin and Metcalfe, 1998). In Western Australia, George *et al.* (1999), concluded that the probability of achieving reduced water levels by revegetation of the discharge zones was lower and the magnitude of the response smaller than revegetation in the recharge zone. Moreover, studies have shown that vegetation planted in discharge areas accumulate salts in the root zone which limit transpiration and growth of plants (Thorburn, 1999).

The planting of deep rooted, perennial native species in recharge zones associated with pasture/grassland could be expected to make a significant difference to long-term salinity risk in these areas. Moreover, because of slope and soil attributes, many of these areas are not well suited for annual cropping. Hence, revegetation of either native tree species or commercial timber species are more likely to be considered a feasible and economic option for these sites.

- moderate priority – includes recharge zones currently being used for cultivation or settlement. This covers the non-pasture/non-grassland recharge zones. As cropping is the dominant land use in this category, selective tree planting within the constraints of sustainable agricultural systems (rather than monoculture tree plantations) is the most likely option for salinity management.
- not priority – includes discharge and transmission zones or lands with bodies of water (e.g. lake, dam, stream, etc.).

The high priority areas were further ranked into three classes “high-1”, “high-2”, and “high-3” based on the areal severity (i.e. spatial extent) of salinity in each sub-catchment. This ranking was determined through GIS by attribute querying of the recharge and pasture/grassland areas followed by overlaying the results by the combined sub-catchment boundary layer and salinity map. The priority classes were determined by ranking and reclassification (using an equal interval technique) based on the total area affected by salinity per sub-catchment (Figure 2).

The measurement of spatial patterns of identified revegetation sites (i.e. combined high and moderate priority areas) involved the use of a landscape pattern analysis program, Patch Analyst (Grid) 1.1 extension (Rempel *et al.*, 1999) to ArcView. The program generated landscape structure indices pertaining to area, number of patches, patch density, patch size, patch shape and nearest neighbour distance. These indices were analysed and their significance assessed in relation to alternative revegetation strategies. In the present framework, however, the spatial pattern analysis of revegetation sites was not used as a determining factor of the prioritisation process. Instead, it was employed as a post-prioritisation tool to further analyse the revegetation sites, and how the information could be potentially used in the design and evaluation of revegetation strategies.

Validation

The validation of results is often difficult for a multi-criteria GIS-based land suitability assessment. The accuracy of the model is only as good as the soundness of the selection criteria used and the accuracy of the input maps. While map accuracy can be assessed with relative ease, the direct evaluation of the criteria's merits is more complicated. For this study, the ideal approach would be to a) select priority sites classified by the model, b) revegetate the corresponding sites, and then c) compare their relative successes in preventing salinity outbreaks. However, this will require considerable time and resources to implement. Thus, this study placed the validity of its results entirely on the sound scientific underpinnings (from both theoretical and practical knowledge base) of the decision criteria used. For instance, the prioritisation of recharge areas over discharge areas is based from a study (George *et al.*, 1999) that compares the effects of revegetation to the magnitude of groundwater level reduction.

The map accuracy assessment focused on testing the attribute accuracy of the resulting prioritisation maps. A total of 32 sample pixels (30m x 30m) under "high priority" class were generated using ArcView's simple random sampling program. Then, cross-tabulation technique allowed the assessment of the pixels' agreement with field survey information that produced a "percentage correct" value (number of correct pixels divided by number of total pixels multiplied by 100). Each sample pixel was judged as "correct" if it satisfied the criteria set for high priority class: "the area is in recharge zone and the land use/cover is pasture or grassland."

RESULTS

The Landsat 7 ETM+ image was classified into four land use/cover types: woody vegetation (7,277 ha; 9% of the catchment), pasture/grassland (22,880 ha; 28%), crops (50,170 ha; 62%), and settlement (325 ha; less than 1%). These class definitions were adopted, after modification, from the SLATS project (DNR, 1999). As woody vegetation is often spectrally distinct from bare soil and agricultural crops, mapping these land cover features is readily achieved using Landsat 7. However, high spectral confusions were observed between a) crops vs. grassland, and b) woody vegetation vs. some agricultural crops in black soil areas. These conditions necessitated the use of a spatial masking (eg. "cut-and-paste") technique that used reliable ancillary datasets.

The estimated accuracy of the classified image is 86% (percentage correct), with a kappa index of agreement of 0.78. This relatively good accuracy can be attributed to the following reasons: (a) the number of classes used is relatively low (i.e. four) and hence, should limit spectral confusion, (b) the spectral separability of woody vegetation and bare soil is high, and (c) the spatial masking of possible confusion areas should have minimised misclassification from the automated approach. For the attribute accuracy assessment of the prioritised revegetation map, 27 out of 32 model

sites (84%) agreed with the ground truth observations. It means that only 5 sample pixels were found erroneous—violating the criterion that pixel values should correspond to both recharge zone and pasture/grassland cover types.

A total of 16,127 ha (~20% of the catchment) was identified as priority sites for revegetation to reduce long term salinity risk in the catchment. Of this area, 10,690 ha (~13% of the catchment) was identified for high priority revegetation, and a further 5,497 ha (~7% of the catchment) as moderate priority (Figure 3). Within the high priority area, 7,685 ha (~10% of the catchment) received the highest importance ranking (high-1) based on the extent of existing salinity outbreaks within the relevant sub-catchments (Figure 4). A further 1,223 ha (~1.5% of the catchment) of the high priority areas received the lowest importance ranking (high-3) with the remainder (1,782 ha; ~2% of the catchment) receiving the intermediate importance ranking (Figure 4).

[Figure 3, about here]

[Figure 4, about here]

The landscape pattern calculations using Patch Analyst (Grid) showed that the revegetation sites include a high number of small patches. There were 758 patches <1 ha in size, which is approximately 72% of the total number of patches (Figure 5). Despite this high number, the total area covered by these small patches is relatively insignificant with these patches comprising only 1% of the total revegetation area (Figure 5). On the other hand, the total area of the patches >500 ha in size (although only 5 in number) totalled 8,292 ha (51% of the total revegetation area). This reflects the contiguous (i.e. not fragmented) nature of the revegetation sites identified. The mean patch size is 15.3 ha, while the patch density is 6 patches per 100 ha. The mean nearest neighbour distance, the average edge-to-edge distance from a patch to the nearest neighbouring patch, is 55 m.

[Figure 5, about here]

DISCUSSION

The set of GIS-based techniques developed in this study has provided a systematic and rational framework for the revegetation mapping of dryland salinity sites. Using the catchment as the spatial unit of management, the relevant “selection criteria” expressed as map layers were organised and processed in a raster GIS. While this work focuses on planting recharge areas, the generic procedures and datasets developed here could also be applied to revegetating discharge zones or identifying other priority areas within the catchment. A key feature is that the suite of GIS operations involved in this study constitute the core functionalities of major raster-based GIS software and hence, the modelling approach is replicable.

Up-to-date land use/cover information is necessary for revegetation planning and management. At the basic level, a dichotomous classification (woody vegetation vs. non-woody vegetation) of the target area is needed. Deriving land use/cover information at this level is readily achievable using multi-spectral data from satellite imagery (e.g. Tuomisto *et al.*, 1994; Apan, 1997). More often however, non-woody vegetation areas should be further categorised into finer thematic details (e.g. pasture/grassland, crops/cultivation, settlement, water, etc.) so that specific areas for revegetation can be identified. It is in this level of detail that mapping from satellite imagery alone is insufficient, due to high spectral overlaps of some land cover features in the agricultural landscape (e.g. crops vs. pastureland covered by grasses). The use of ancillary data and spatial masking technique is indispensable to map land use/cover at this level of detail.

There are no preferred prioritisation options for all situations: it depends on the management objectives of revegetation and the site factors. The first level of prioritisation (i.e. based solely on recharge zones and land use/cover), will be of benefit where limited salinity outbreak information is currently available. This level of prioritisation, assumes that the salinity outbreaks are dispersed or uniformly distributed in the catchment. However, where information about the location and severity of salinity is known, the second level of prioritisation (ie. based on sub-catchment salinity occurrences) should provide a greater level of detail to improve the decision making processes associated with salinity management.

The modelling approach developed here is flexible: prioritisation schemes based on other criteria could be formulated to produce alternative priority classes. For example, prioritisation of revegetation sites could be based on (a) the distance of the recharge areas to known salinity outbreaks (distant vs. proximal to salinity) (b) suitability to preferred production systems (e.g. agroforestry vs. monoculture plantations) and (c) the value of the land (e.g. urban residential vs. cultivation). In all cases, information on the recharge/discharge zones and current land cover information are necessary inputs to processing.

The analytical framework advanced here could also produce estimates of the costs of revegetation relevant to policy formulation or funds generation. GIS could produce a map layer of revegetation sites categorised into types of replanting treatment needed (i.e. either tree plantation, agroforestry, perennial pastures, etc.). As respective areas could be calculated for each treatment, and the cost per unit area could be estimated, the total costs could be determined. Lastly, the framework could also be extended to other problem areas or strategic actions related to dryland salinity management. An example would be an assessment of existing woody vegetation areas in terms of their importance to dryland salinity prevention, so that appropriate conservation measures could be deployed. By mapping woody vegetation areas in recharge zones, the “high priority conservation areas” can be identified.

Due to the complex issues involved, it is difficult to assess the implications of the spatial patterns of revegetation sites to the costs of establishment and maintenance.

For instance, it is not easy to compare the cost of revegetating fragmented sites to that of contiguous blocks due to many incriminating site factors. More in-depth studies are needed. However, if the benefits of the “economy of scale” hold true for revegetation projects, revegetating dominantly contiguous sites (like the Hodgson Creek catchment) is expected to be more cost-effective and profitable than fragmented sites. This assumes that the ownership of these large tracts of revegetation sites is confined to one or only few individuals (or corporations), or by a cooperative of many land owners.

With regards to revegetation methods and production systems, the presence of many small-sized revegetation patches may favour the adoption of natural regeneration methods, agroforestry and small-scale tree farms. Small patches interspersed with natural forest or woody vegetation may encourage natural regeneration and regrowth due to favourable biological conditions relating to seed dispersal, animal movement and foraging, edge effect, and microclimate. Revegetation sites dominated by small patches (e.g. 1-5 ha) may also favour the implementation of an individual-based (or a family-based) approach to revegetation, as opposed to the community- or corporate-run large tree plantations. For areas with large tracts of revegetation sites (as in the case of the Hodgson Creek catchment), the community- or corporate-based approach may be considered more appropriate. Normally, community organisations and corporations usually have the resources or organisational capability to engage in such a big undertaking as tree planting of large areas.

Contiguous large tracts of revegetated lands may have greater potential impact to reduce or control soil salinity than the small-sized lands. Thorburn and George (1999) believed that unless a very large area of the catchment is planted, water tables are unlikely to fall significantly. They also viewed that typically small, localised plantings, selected without knowledge of the catchment hydrology, are unlikely to reclaim most of the existing saline land and prevent new outbreaks. In some circumstances, however, small tree plantings may lower water tables and reduce salinity if they have been strategically placed (e.g. interception belts on perched aquifers) (Thorburn and George, 1999). Thus, there is a need to identify these strategic sites to maximise the benefits of replanting small-sized patches. GIS has the potential to model these sites using DEM, geology, groundwater, and soil information.

CONCLUSIONS

As revegetation is increasingly becoming a high priority for the control and prevention of dryland salinity, analytical techniques and decision support tools to enable more effective revegetation planning are needed. Critical components of the planning process include both the ability to identify revegetation target areas and to prioritise these areas based on a range of landscape features. This study has developed an analytical framework that incorporates the use of selected spatial datasets and processed using GIS-based techniques. This framework relies on the use

of current land use/cover information, as well as the location and boundary of groundwater recharge and discharge areas. A hierarchical approach to prioritising the revegetation areas based on sub-catchment salinity occurrences has also been presented.

The framework presented here enhances the systematic and rational use of land information. This framework provides scope for scenario testing (i.e. locating revegetation sites and their prioritisation) and the generation and testing of alternative treatment options, including the derivation of supplementary information such as revegetation cost estimates.

The spatial patterns of revegetation sites could provide additional sets of information relevant in the design of revegetation strategies, particularly the cost of establishment and maintenance, revegetation methods or production systems, and the potential impacts on the reduction or control of soil salinity. However, more studies are needed to develop an understanding of the ramifications of the spatial patterns of revegetation sites and the key aspects of revegetation alternatives.

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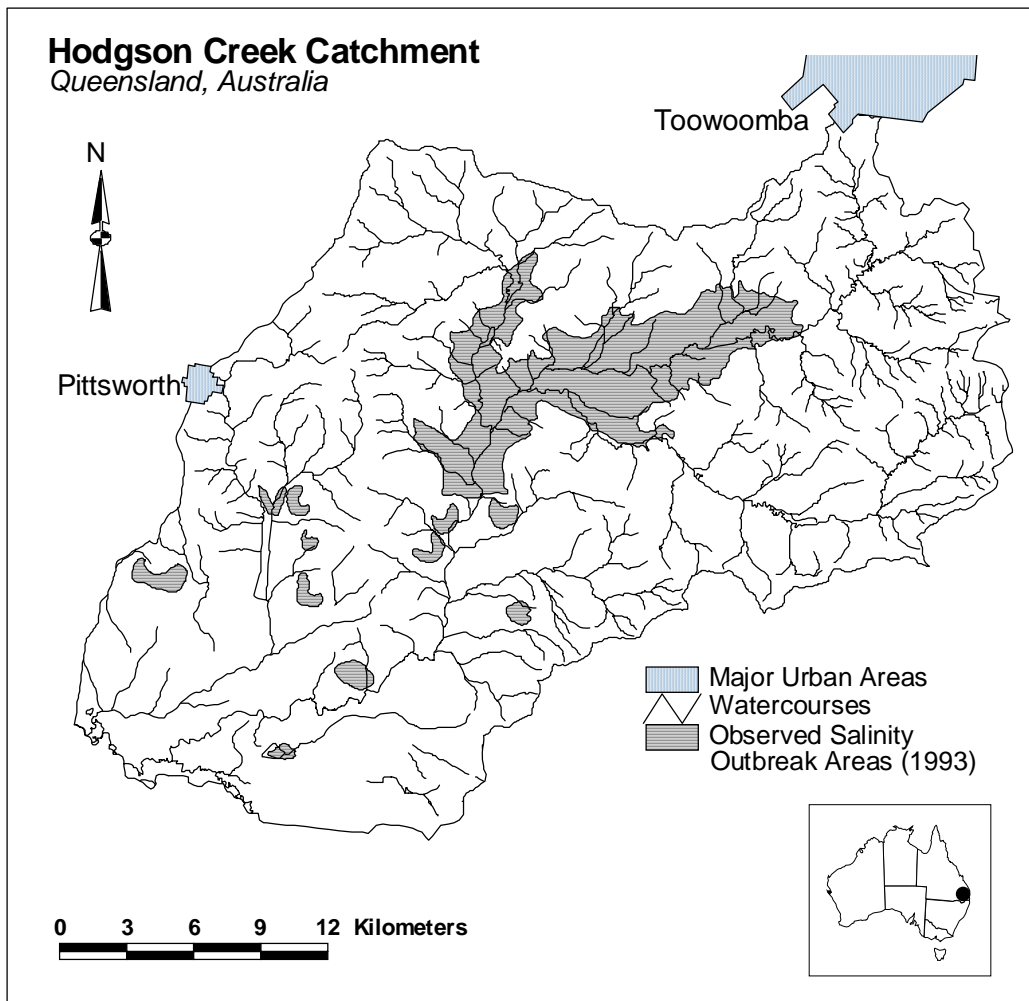


Figure 1. Location map of the study area showing salinity outbreak areas.

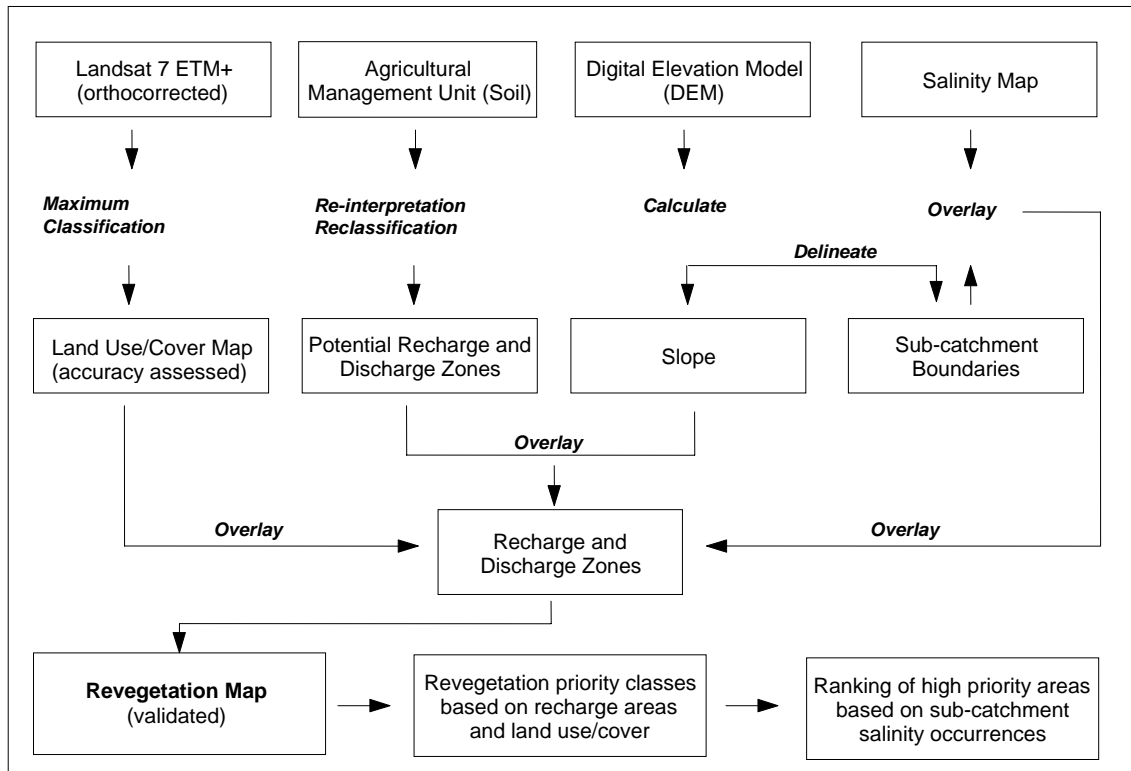


Figure 2. Flowchart of GIS processing and modelling for mapping and prioritising revegetation sites for dryland salinity management.

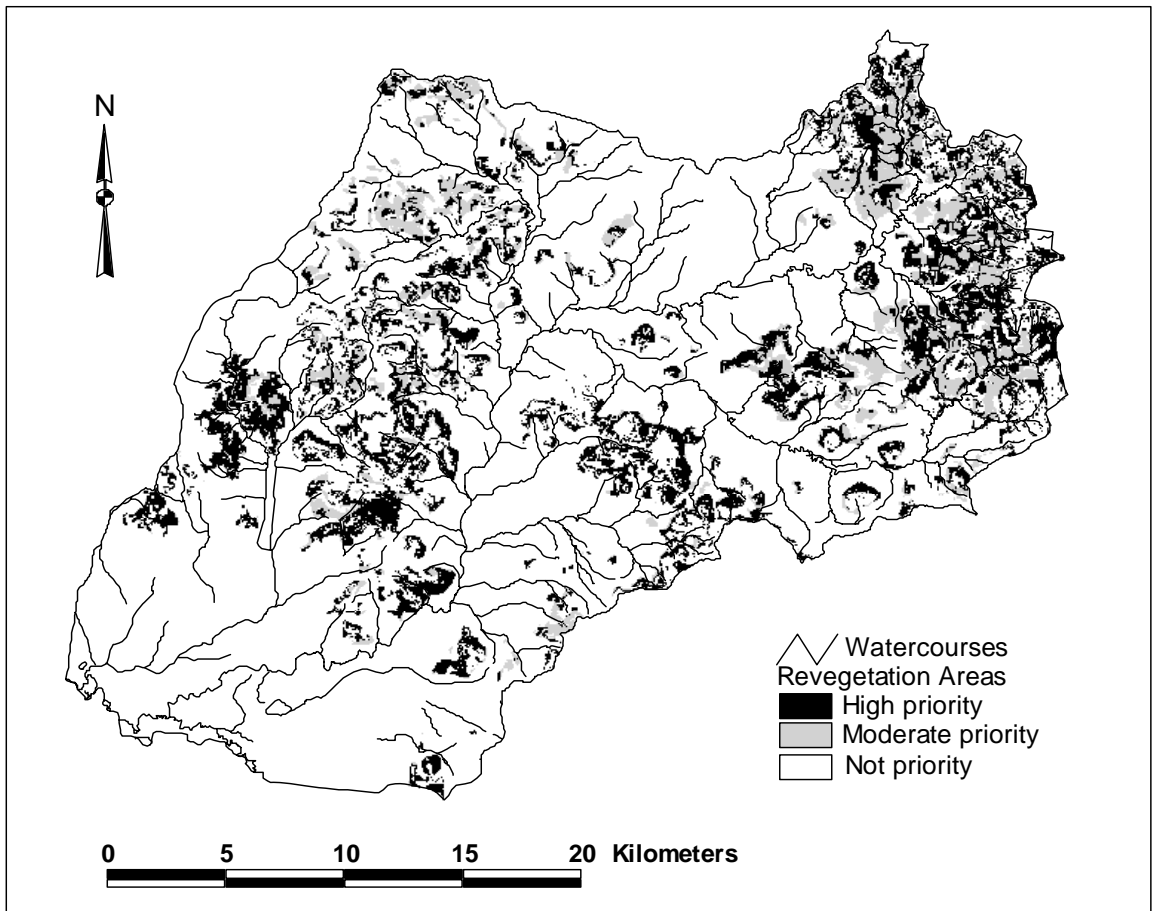


Figure 3. Revegetation areas and priority classes.

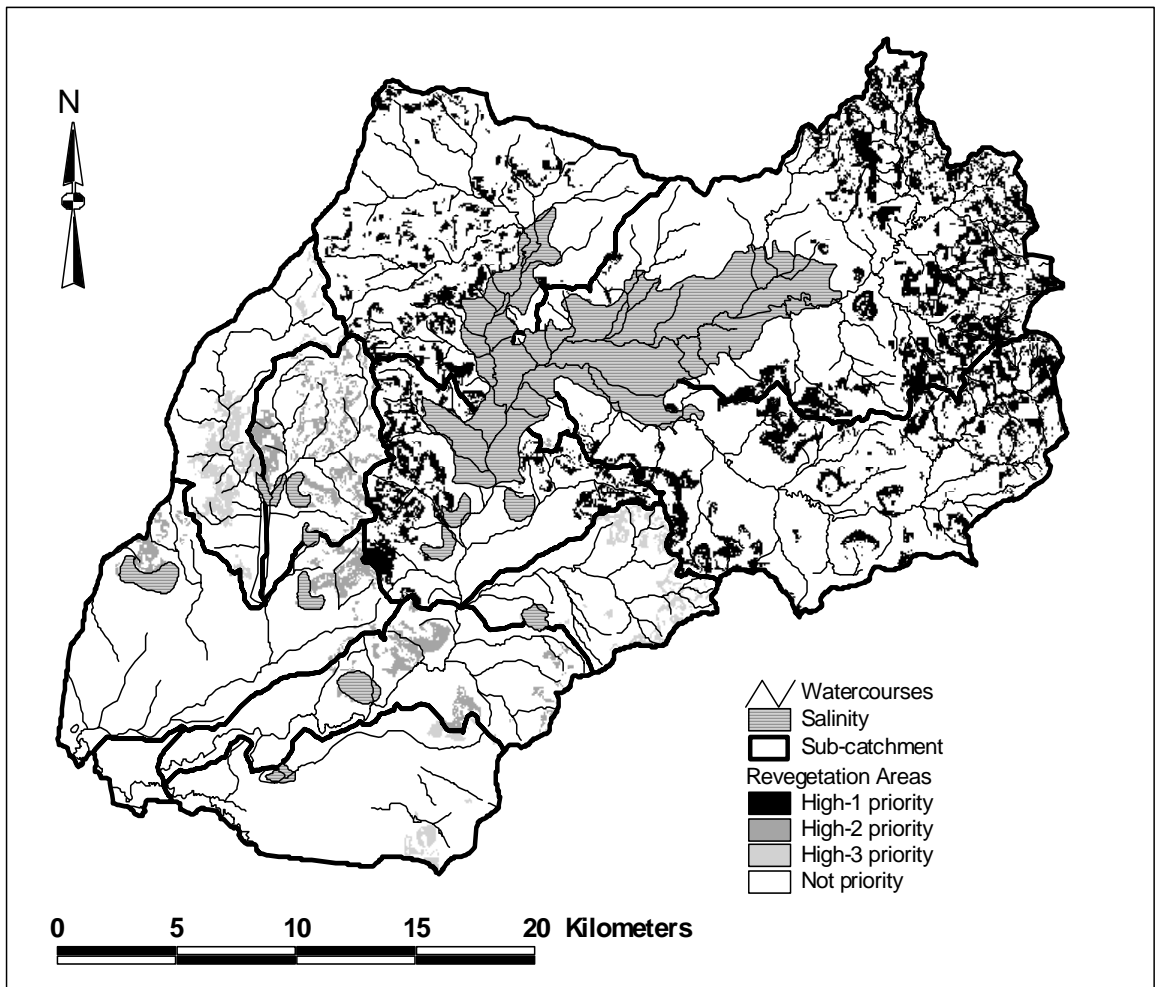


Figure 4. High priority revegetation areas and ranking based on sub-catchment salinity.

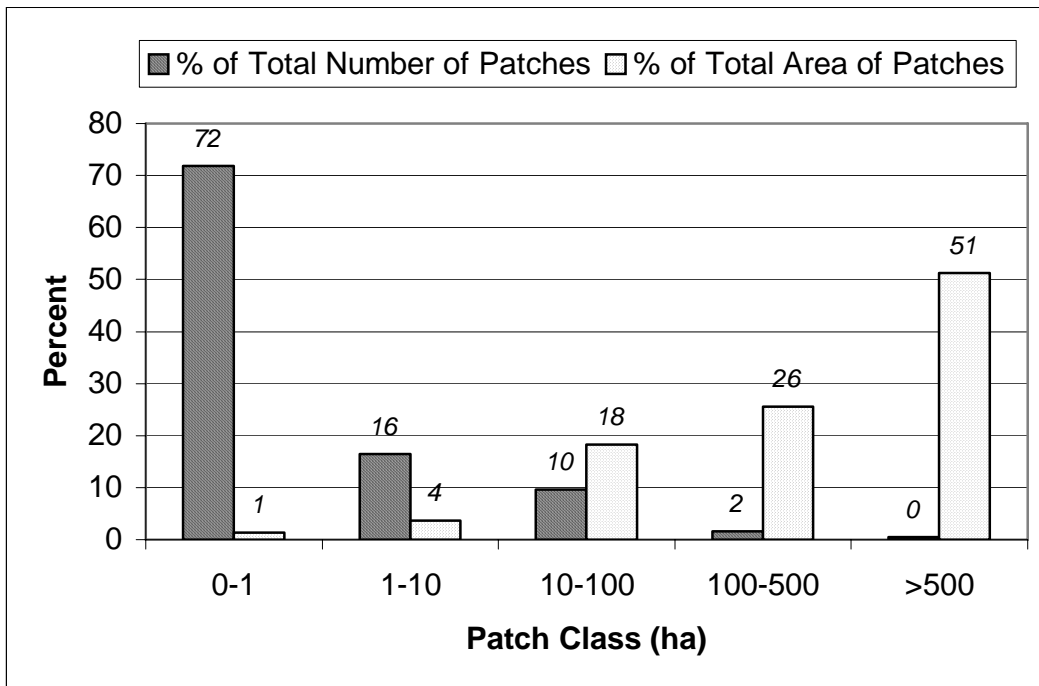


Figure 5. Percentages of total number and total area of revegetation patches.