



CSIRO

CSIRO LAND and WATER

FLAG Analysis of Catchments in the Wellington Region of NSW

By Trevor I. Dowling

Consultancy Report
CSIRO Land and Water, Canberra
March 2000



CSIRO

CSIRO LAND and WATER



FLAG Analysis of Catchments in the Wellington Region of NSW

Consultancy Report

Trevor I Dowling

CSIRO Land and Water, Canberra
Consultancy Report March 2000

Copyright

© 2002 CSIRO Land and Water.

To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO Land and Water.

Important Disclaimer

To the extent permitted by law, CSIRO Land and Water (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

EXECUTIVE SUMMARY

This consultancy was commissioned by the Department of Land and Water Conservation (DLWC), Wellington. It investigates the potential of wetness maps generated using the FLAG model to provide a useful addition to the DLWC toolkit. Outputs were produced at different spatial resolutions for DLWC to evaluate their usefulness, at the 'extension' scale, for first pass landscape evaluation, salinity risk assessment, demonstrating effects on catchment biodiversity as habitats change, cost determination (lost production / rehabilitation) of affected land and the cost effectiveness of the modelling approach.

The FLAG modelling approach has been developed for the rapid assessment of dryland salinity risk at a range of scales, which avoids the direct use of process models (Roberts, Dowling and Walker, 1997). It does however use process and local knowledge about the causality of salinity. It requires (a) elevation data at an appropriate resolution, which is available throughout Australia and (b) a training set of known discharge or salinity.

FLAG analyses were performed on three small areas at 10 and 25m DEM resolutions. Limited field checks suggested that both resolutions gave useful results. One of the relative wetness indices incorporating local lowness in the landscape (using the LOW filter) was consistently better in matching patterns on the ground and more aesthetic than the other based on plan concavity (CC filter).

To test the results over a wider area the analyses were also performed for the entire Little River catchment. This analysis also gave an indication of the ease of use and the robustness of the method over larger areas and more useful scales. From field assessments, with interpretation given by Allan Nicholson, the match with FLAG mapping was very good.

A second stage of the method that predicts salinity from a training set was run using a pre 1995 salinity map. The correlation between predicted and mapped salinity was poor. However, comparisons with the June 1999 salinity map showed a greater area of affected land and better agreement with the FLAG wetness index. The results would probably improve if the revised salinity map was available digitally.

FLAG is a fast and robust means for obtaining a highly visual rapid assessment of potential wetness, discharge and salinisation that can be used as a valuable first step in establishing salinity risk.

CONTENTS

1.	INTRODUCTION	1
	PURPOSE	1
	OBJECTIVES	1
	BACKGROUND	2
2.	METHODS	3
	2.1 GENERAL METHODS USED IN FLAG	3
	2.1.1 Stage 1 - Definition and calculation of indices	3
	2.1.2 Combination of indices	4
	2.1.3 Stage 2 - Calculation of discrete discharge or salinity maps.	10
	2.2 METHODS SPECIFIC TO THE WELLINGTON ANALYSIS	11
3.	RESULTS	13
	3.1 YAHOO PEAKS ANALYSES	13
	3.2 MUMBIL ANALYSES	14
	3.3 RYLSTONE ANALYSES	14
	3.4. LITTLE RIVER ANALYSES	14
4.	DISCUSSION	34
5.	CONCLUSIONS	36
	ACKNOWLEDGEMENTS	36
	REFERENCES	37

1. INTRODUCTION

Purpose

This report is the final stage of a consultancy for the NSW Department of Land and Water Conservation (DLWC) by CSIRO Land and Water (CLW). The broad objective is to provide wetness index maps of several areas of interest to DLWC (Fig. 1) using the methods encapsulated in the Fuzzy Landscape Analysis GIS (FLAG) model. The maps produced are to be evaluated by DLWC staff to assess their usefulness as additional visualisation tools in the department's extension "toolkit" and provide a valuable layer of information for interpretation.

Objectives

- Apply FLAG to several DLWC study areas at 10m resolution (the resolution at which the model was developed and is believed to provide optimal results)
- Apply FLAG to the same areas at 25m resolution (*i.e.* the widely available DEM coverage resolution for NSW provided by the NSW Land Information Centre) and compare the results to the 10m resolution analyses
- Apply FLAG to a substantially larger area than those above at 25m resolution.
- Field check and validate the results with DLWC staff (Allan Nicholson)
- Given sufficient time and appropriate training/validation sets, perform salinity outbreak predictions using FLAG
- Given sufficient time and availability of appropriate data from DLWC, provide an analysis of an urban salinity site
- Supply DLWC with documented maps and interpretation and discussion of the results.

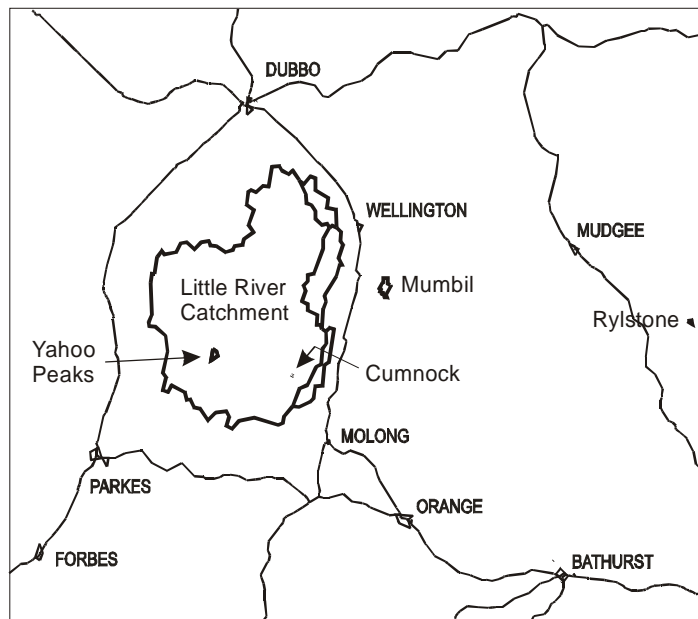


Figure 1. Location of study sites in the vicinity of Wellington, NSW.

Background

A DLWC requirement for salinity extension work is the efficient communication of hazards and solutions to landholders and communities. Officers currently use a variety of maps including soils, geology, and electro-magnetic induction (EM) when explaining scenarios. The wetness index maps provided by FLAG, indicative of potential groundwater discharge and salinity, are believed to be a valuable addition to the salinity extension kit. A number of models have been developed for wetness and salinity prediction, and some of these have been used with limited success. Commonly, these models require more input data than is generally available (necessitating intensive field data collection or estimation of parameters) and are computationally intensive. They include very detailed process based models with extensive data and processing demands (Dawes and Hatton, 1993), broad-scale statistical GIS methods (Bradd *et al.*, 1997), composite index models (Searle and Bailie, 1998) and time series remote sensing (Furby *et al.*, 1995). The main problem with the latter models is that the available data and used are often too coarse for the modelled processes.

Salinisation processes are generally well understood, but a quantitative method of risk assessment that will work for a range of situations and a range of scales using appropriate available data is needed. Elevation is the main data set that is ubiquitously available in Australia, usually at a resolution appropriate to the scale of the salinisation processes. The FLAG modelling framework was developed to assess dryland salinity risk at a range of scales that avoids the use of process models and requires only elevation data. Many of the parameters relevant to salinisation processes are intercorrelated with elevation (landscape position). These include rainfall, vegetation, soils, geology, geomorphology. Historical farming practices (tree clearing followed by ploughing) are also intercorrelated factors that have affected surface shape and runoff patterns. Groundwater levels often correlate well with topography (Salama *et al.*, 1993), causing salinity to occur in low areas, convergent areas and at breaks of slope. Thus, for a number of reasons we expect enhanced discharge and salinity to be related to topographic features and hence to elevation. The aim of FLAG is to explain as much as possible of the spatial pattern associated with groundwater discharge and salinisation using topographic data alone without separately addressing the processes.

The question arises: how much extra effort is required to explain greater spatial variation than a simple index based method like FLAG? A major difficulty in using spatially explicit process models is the need for extensive data to parameterise, calibrate and validate them. These data are not generally available except as surrogates or educated guesses. FLAG takes the alternative approach of trying to extract as much information as possible from elevation only. Elevation is a (the most) commonly available dataset and is correlated to varying degrees with parameters relevant to groundwater discharge and salinisation processes.

While other information is available, *e.g.* geology, soils, vegetation and climate, the spatial and temporal resolution is generally not adequate for the modelled processes. Costs involved in obtaining such data at a relevant scale are prohibitive, except in a select few study areas that have been subjected to detailed long-term research and monitoring. For this reason, many of the process-based models in use are considered to be research tools to gain process understanding. Some of this understanding has been incorporated into the assumptions of the simpler approach developed in FLAG. It is an attempt to move beyond process-based models towards an applied rather than theoretical framework.

2. METHODS

The methods employed in FLAG are described fully in Dowling *et al.* (1997), Roberts *et al.* (1997) and Laffan (1996). These general methods are summarised below, followed by a description of the methods specific to the application of the model at Wellington.

2.1 General methods used in FLAG

FLAG is a simple approach incorporating terrain analysis that uses a number of topographic indices (0-1 scale) that are derived from elevation data and combined in various ways. A Digital Elevation Model (DEM) is used to calculate the following grid-based topographic indices:

- Local lowness - relative to a smoothed topographic surface
- Plan curvature - related to convergence/divergence *i.e.* groundwater blockages and bottlenecks
- Contributing area – relative height in the landscape or study area (the area monotonically above each cell, *i.e.* analogous to a subsurface catchment that is not restricted by surface catchment boundaries).

The prerequisites for the FLAG analysis are a hydrologically sound DEM to derive wetness indices and a training set of actual mapped salinisation to derive predictions of discharge or salinity. A grid resolution of 10m was found to be most appropriate, being similar to the expected scale of processes and spatial extent (patch size) of salinisation.

2.1.1 Stage 1 - Definition and calculation of indices

FLAG, like all models, requires assumptions about the way reality has been conceptualised. The specific assumptions underlying FLAG are:

- Topography is the surface expression of all factors that have acted on a site over time including geology, soils, climate, vegetation and land use, often in an intercorrelated way. The first index is a set of high elevation points, called "HIGH", where the highest point in the study area was assigned 1.0, the lowest point was assigned 0.0, and all other points were scaled linearly according to their relative elevation (Fig. 2a).
- The water table conforms to the topographic surface except that it is smoother, and exhibits less total variation in relief than the ground surface. Thus, the water table is closer to the ground surface at low points in the landscape, and further from the surface at high points. The second index is a set of local low points, called "LOWNESS". LOWNESS is obtained by smoothing the DEM using a 130m x 130m (13 x 13 pixel at 10m resolution) moving window to calculate the average local elevation and then subtracting this newly obtained surface (SMOOTH) from the actual surface elevation (Fig. 2b). Locations in the landscape that are low relative to the surrounding points have positive values proportional to the difference in local elevation. LOWNESS is then normalised so that locations which are low in the local landscape are assigned high values in the set (maximum LOWNESS = 1.0); locations which are at or above the local landscape are assigned zero values. Because it is assumed that the water table conforms to the landscape, areas with high membership in the set LOWNESS are expected to be areas where the water table intersects the land surface, resulting in groundwater discharge and potentially waterlogging and salinity.

A parallel approach uses plan curvature (Zevenbergen and Thorne, 1987, available in ArcInfo 7.0 Grid), which fits a polynomial surface within a 3 x 3 pixel window (30m x 30m at 10m resolution), and uses the second derivatives of the surface as an estimate of CONVEXITY, or the complement CONCAVITY. Because the distribution of values in CONCAVITY exhibited an extreme peak with long tails, the CONCAVITY values were histogram equalized (monotonically rescaled to produce approximately equal numbers of points within each sub-range of values) rather than simply normalised (Fig. 2c). In analogy to LOWNESS, points which are in highly concave locations are expected to be closer to the groundwater level (run-on areas), while points in convex locations were expected to be relatively distant from the groundwater level (run-off areas).

- The contributing area for any point is given by the set of points connected by a continuous, monotonic uphill path. The concept of contributing area is of great significance in hydrologic modelling with emphasis on flows within a catchment boundary. It is assumed that for saturated sub-surface flow, all points that are connected by a continuous, monotonic uphill path would exert some hydraulic head on the location below, and thus contribute to potential discharge. This means that any number of topographic catchment boundaries may be crossed provided the subsequent points in the next catchment are higher. The "UPNESS" index is defined as the fraction of the total landscape monotonically uphill from each pixel following the assumptions given above. After calculating UPNESS for each pixel the set was normalised. A histogram equalisation of UPNESS is also calculated for use with the histogram-equalised CONCAVITY, called "UP-EQ" (Fig. 2d).

2.1.2 Combination of indices

Essentially, a given position in the landscape is the relative elevation of a point with respect to the points in its vicinity, which takes into account the shape of the land surface in the immediate vicinity of the point. This has been emphasised in the Australian landform classification of Speight (1990) but has been difficult to incorporate into algorithms.

FLAG employs a set of programs based on fuzzy set theory, which provides a mathematically rigorous framework for combining the indices. It assumes that likely sites for discharge and salinity were those low in the local landscape with high contributing area. Accordingly, we defined the set of pixels with high LOWNESS and high UPNESS as the minimum, or intersection, of LOWNESS and UPNESS. This is the fuzzy wetness index or filter termed "LOW" (Figs. 4a,c,e; 5a,c,e; 6a,c; 7a,c). Figure 3 illustrates the derivation of the LOW index. To improve the readability of the maps, LOW was normalised.

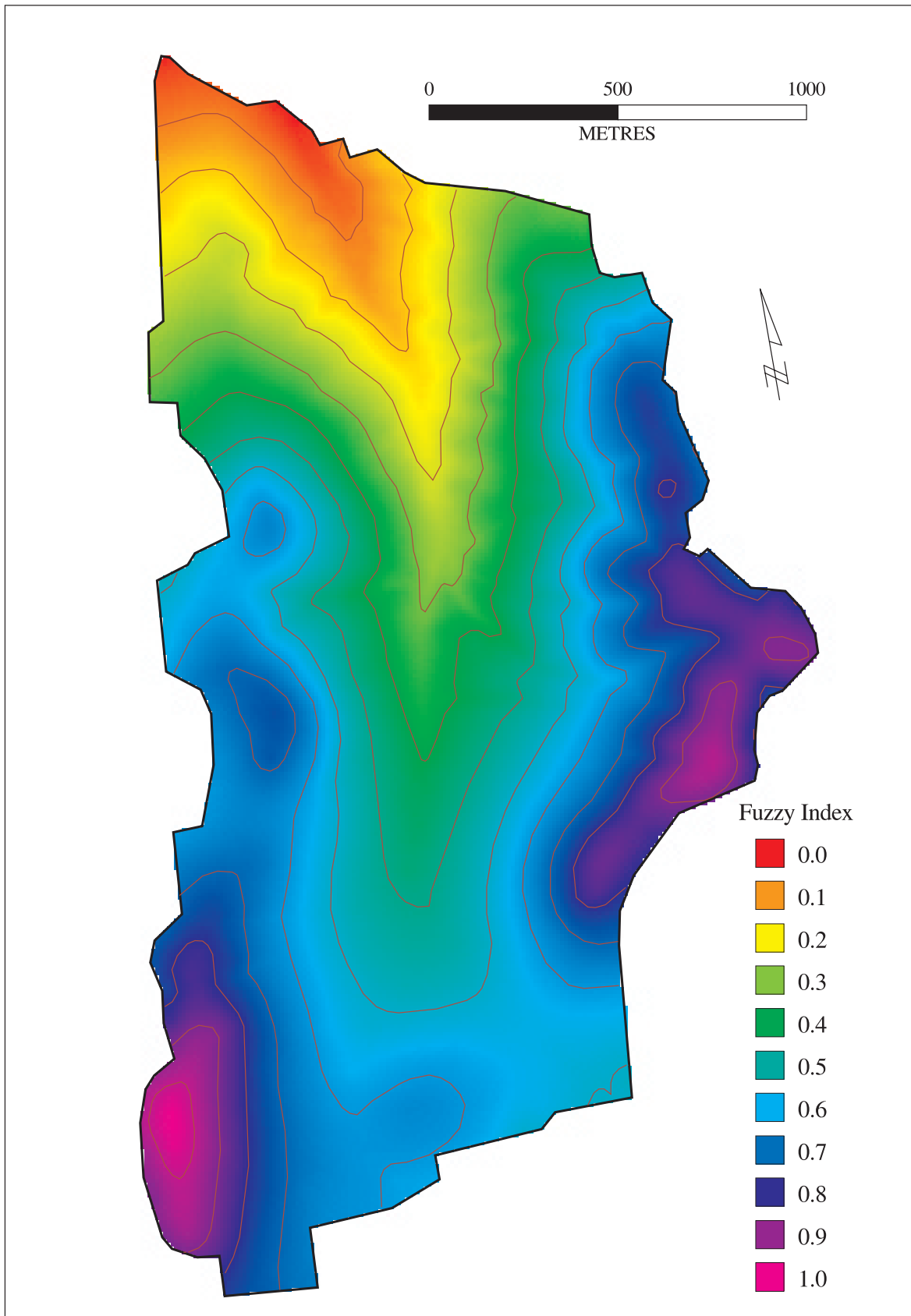


Figure 2a Yahoo Peaks Elevation index (HIGH) scaled from 0 (90m) to 1 (153m). Contours were derived from the DEM (5m interval).

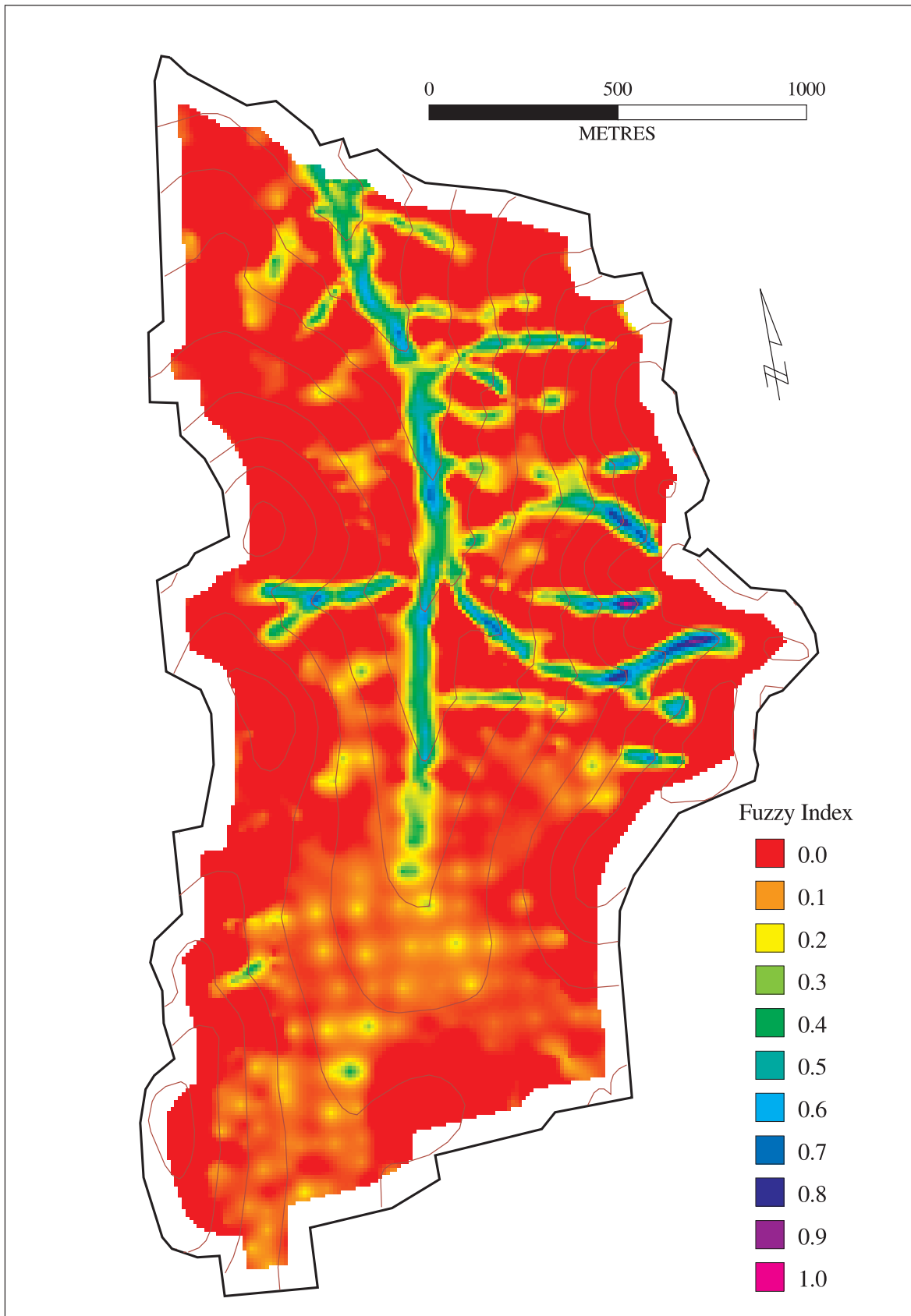


Figure 2b Yahoo Peaks LOWNESS index scaled from 0 (the least low) to 1 (the most low). Magenta represents areas that are locally lowest in the landscape. Contour interval is 5m.

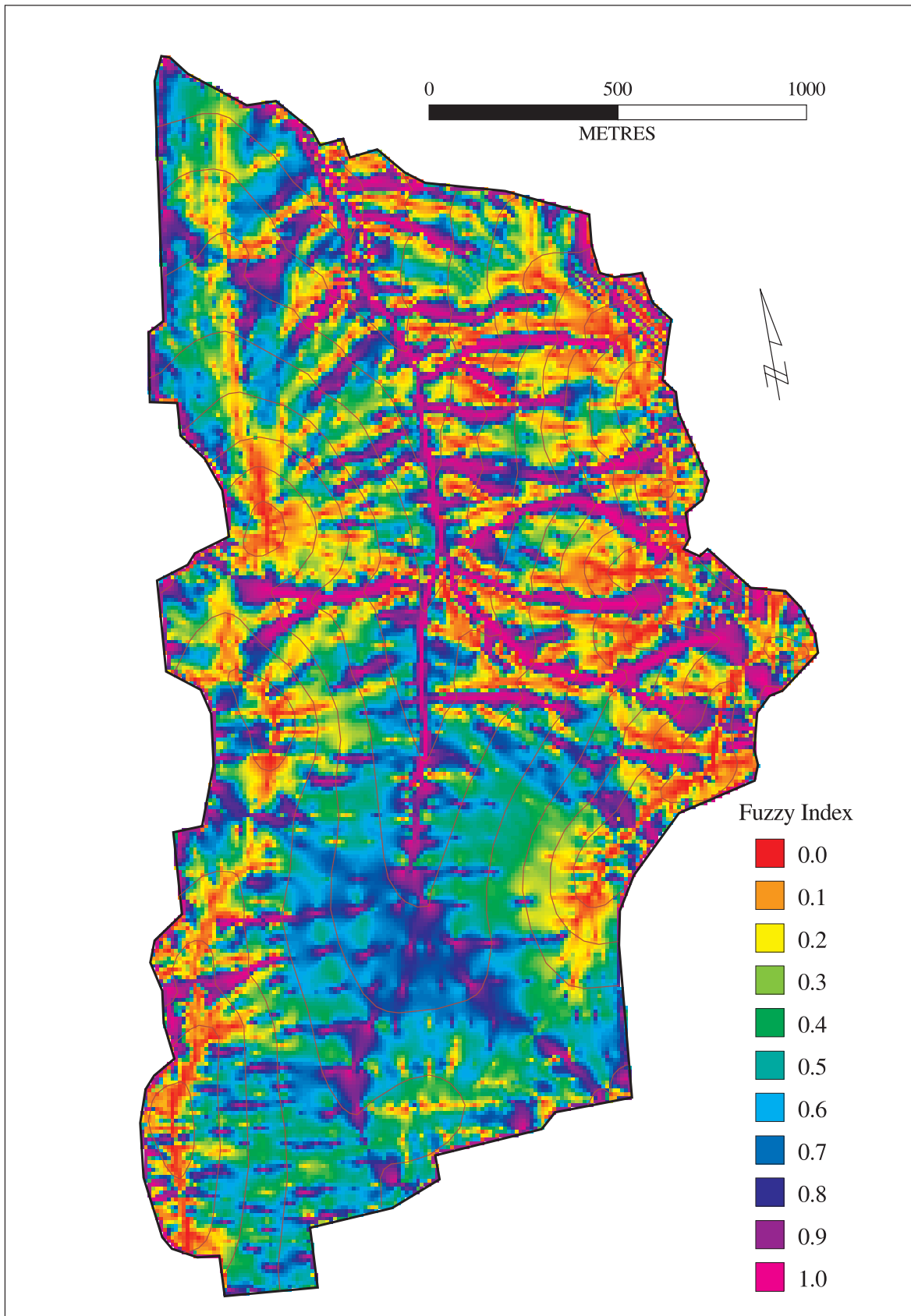


Figure 2c Yahoo Peaks CONCAVITY index scaled from 0 (the least concave) to 1 (the most). Magenta represents areas that are highly convergent in the landscape. Contour interval is 5m.

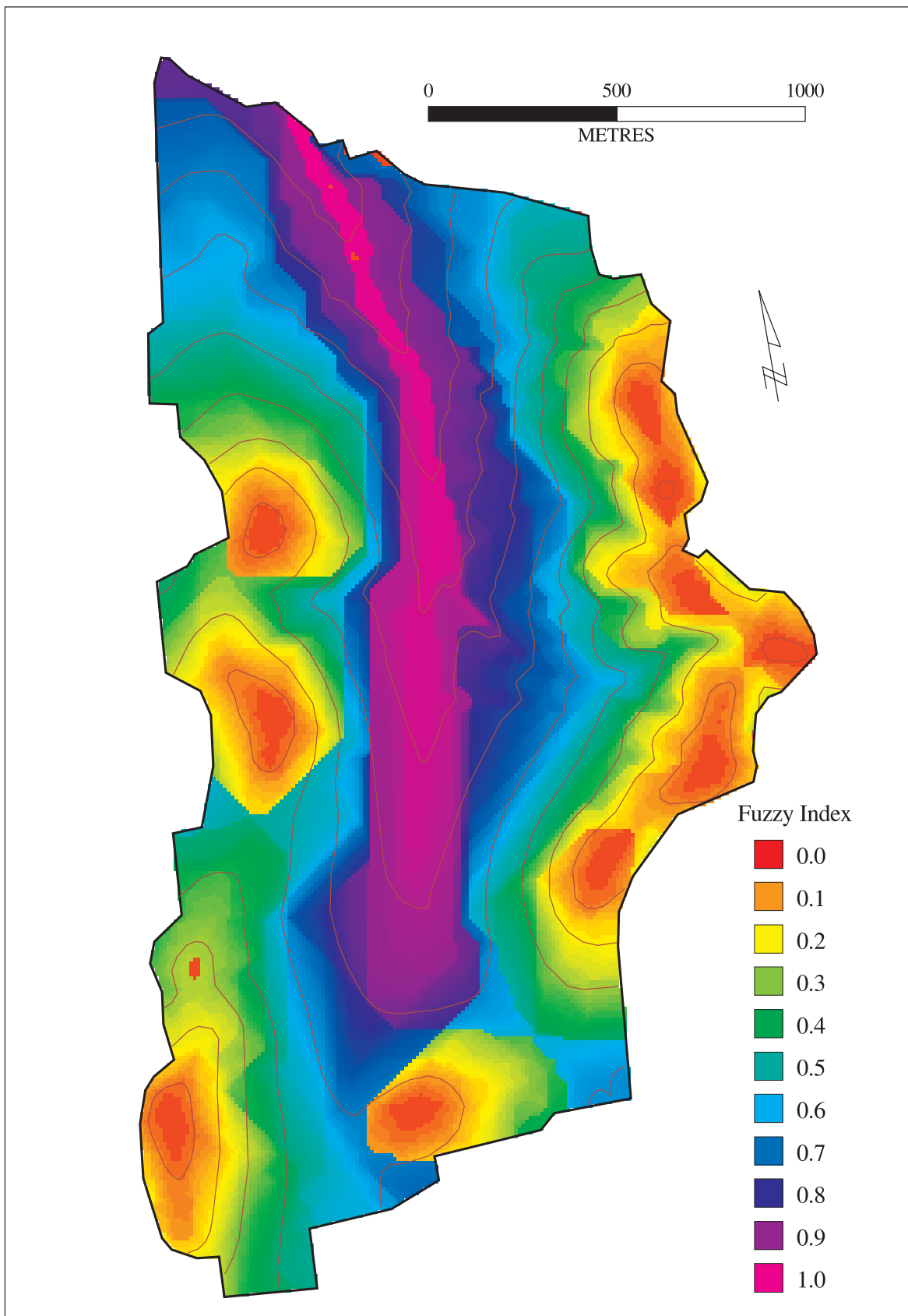


Figure 2d Yahoo Peaks UPNESS index (UP-EQ) scaled from 0 (least contributing area) to 1 (most area). Magenta patches represent areas where there is most piezometric head in the landscape. This map has been histogram equalised for visual clarity and compatibility with the CC-EQ index. Straight lines are artefacts of the current algorithm. Contour interval is 5m.

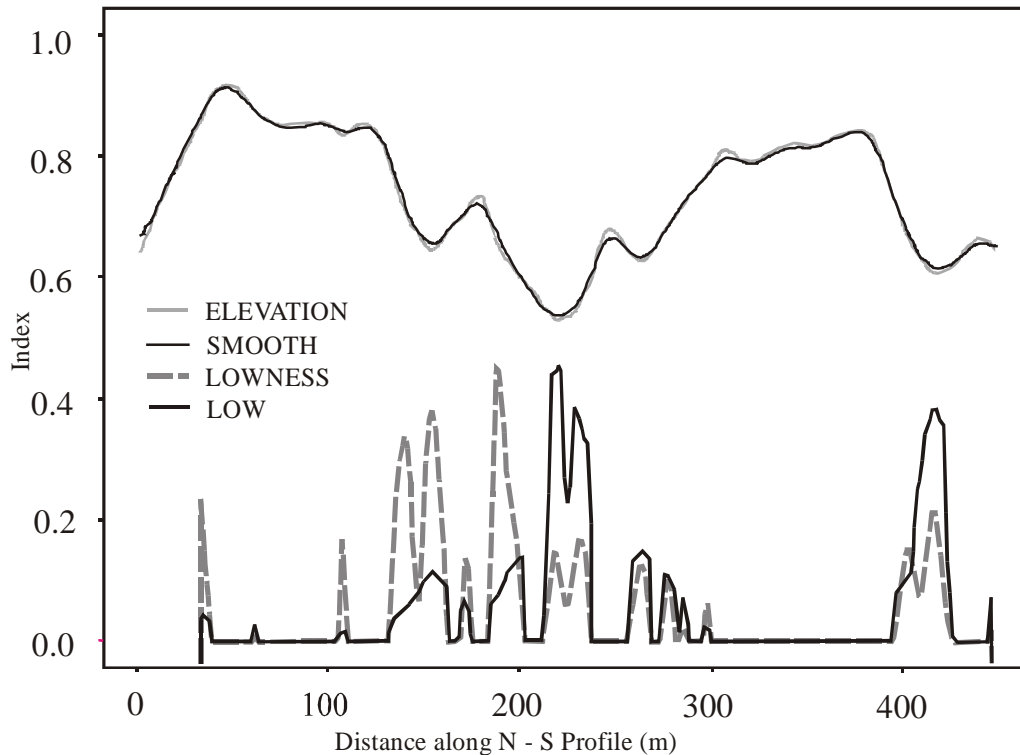


Figure 3. Profile view (north to south) midway across the study area showing how LOWNESS is derived from the smoothed elevation and the effect of its combination with UPNESS to obtain the LOW index. Areas that are locally very low (LOWNESS index) that are high in the landscape are moderated by the effect of UPNESS and areas of lesser local lowness that are also very low in the overall landscape are emphasised.

In a parallel operation, it was assumed that sites likely to have discharge and salinity are those with high plan concavity and high contributing area. Accordingly, the set of pixels with high histogram-equalised concavity and high histogram-equalised UPNESS was defined as the intersection CC-EQ and UP-EQ. This is an alternative fuzzy wetness index or filter termed “CC” (Figs. 4b,d,f; 5b,d,f; 6b,d; 7b).

The two indices LOW and CC are interpreted as predictors of relative surface soil wetness. High relative soil wetness is correlated with discharge. Waterlogging is a subset of the discharge area. The spatial coincidence of waterlogging and discharge is related to low slope or geological / geomorphological impediments. Salinity will occur only in waterlogged areas, the extent and severity depending primarily on discharge fluxes, salt concentrations and evaporation rates.

2.1.3 Stage 2 - Calculation of discrete discharge or salinity maps.

The second stage of FLAG is concerned with evaluation and prediction. Most maps are of a discrete (present/absent) type, for example, a salinity map shows sharp boundaries when in reality gradations usually occur. To develop and evaluate the predictive model, ground-truth data on the actual spatial distribution of salinity and groundwater discharge are required to scale it to local conditions. This can be obtained from field-mapping, drilling, water chemical analyses (bore or stream), air photos, satellite imagery, electromagnetic traverses and local knowledge. Uses and limitations of training areas for FLAG are considered in detail elsewhere (Laffan 1996).

Fuzzy maps can be converted to discrete maps by determining a threshold value (termed alpha-cut or α -cut) where all values greater than or equal to *alpha* are promoted to a value of 1.0 and all values less become 0.0. Any numerical value between zero and one can be chosen for the threshold, according to the purpose of converting a fuzzy index to a discrete index. The method used in FLAG to optimise the selection of a threshold value is based on the use of a training area and is one of many possibilities.

The fuzzy indices LOW and CC are continuously scaled between 0 and 1 whereas the ground truth maps of discharge and salinity are binary. The appropriate threshold (or α -cut) is not known *a priori*. There are several possible ways to evaluate the performance of the predictions, depending on the characteristics desired of the predictor. We developed a procedure using statistics obtained from a contingency table of predicted versus actual to establish the appropriate alpha cut values from training area information (Roberts *et al.*, 1997).

There are many possibilities of combining these statistics to evaluate the alpha cut predictions. The one used, termed POWER, is defined as:

$$power = \left[\frac{a}{(a + b + c)} \right]^{0.5}$$

where a = cells correctly predicted saline, b = cells incorrectly predicted saline and c = cells incorrectly predicted non-saline.

POWER weights errors of commission and omission equally, and ignores the correct negative predictions, which dominate the totals, but are relatively uninformative. Note that POWER has been rescaled, by taking its square root, to improve the readability.

Statistics are calculated for each of the binary maps (19 in total) and plotted as a function of the α -cut threshold. A map generated by grouping all values below the optimum power and all those above is the final (binary) map of predicted salinity or discharge.

2.2 Methods specific to the Wellington analysis

Datasets for the nominated areas were clipped and relative wetness indices (for the LOW and CC filters) calculated using the methods described in Stage 1. Two model calibrations need to be considered by the user, in order to adapt the model to the landscape being studied. The first one is to determine the dimensions of the smoothing window used to calculate the LOW index, which is a reflection of the wavelength of the landscape (ridge-gully separation). Preliminary sensitivity analysis on the 10m DEM used to develop the method (near Young, NSW) indicated that a reasonable window size was 130m x 130m. The second one is a threshold value used to determine UPNESS for each cell and allows general control over the size of the areas included. It specifies how much higher a neighbouring cell must be in order to be counted in the UPNESS tally. If the threshold is negative it allows UPNESS to include lower cells, which may be useful in limited circumstances. Normally threshold will be set to zero except for scenario testing and some special cases. For this work, only smoothing window dimensions were varied in order to cover an approximate 130 x 130m area. Details are listed below in the relevant sections.

Plan concavity is a measure of convergence/divergence of the landscape and had a fixed processing window of 3 x 3 cells. Based on the development work, the 10m resolution was expected to give reasonable results relevant to the scale of the process of interest. At 25m resolution however, the 3 x 3 processing window represents 75 x 75m and this was not expected to give results comparable to the 10m resolution, given that this generalisation may be representing other processes operating at a different scale.

The sites were inspected after the analysis with the exception of Rylstone which was the most remote location. Each map was visually assessed, relying on the expert knowledge and interpretation of Allan Nicholson.

The second stage of FLAG (salinity prediction) was attempted using the pre-1995 map of salinity (unsourced) produced by DLWC and used by Bradd *et al.* (1997). There was no correlation between the training set and the predicted wetness index generated by the model. Equally poor statistics were generated using the same training set in a different study, leading to the assumption that the training set was inadequate. On this basis further salinity prediction was abandoned. A revised edition, June 1999, existed but was unavailable in digital format in the required timeframe.

10m resolution:

Point elevation data was available for 3 sites (Fig. 1), Yahoo Peaks (279 Ha.), Mumbil (769 Ha.), and Rylstone (200 Ha.). Data, initially surveyed by DLWC and previously used for joint CSIRO - DLWC projects, was obtained from CSIRO Land and Water project archives. Reliability was assumed since the data had already been processed and used for generating DEMs within Topog (Dawes and Hatton, 1993) for hydrological modelling.

Boundaries were defined by the limits of the survey points, which did not always completely cover the catchment. DEMs were interpolated using ANUDEM (Hutchinson, 1989). Time did not permit more than two iterations of ANUDEM to generate the best DEM.

The FLAG analysis was undertaken using the following 'standard' settings derived from the study site for the developmental work near Young, NSW:

- smoothing window 13x13 (130m x130m)
- concavity window 3x3 (30mx30m)
- UPNESS threshold 0.0

25m resolution

DEMs generated by NSWLIC for all NSW were clipped to approximate study areas and provided by DLWC through Greg Summerell at the Wagga Research Centre.

Study area boundaries defined for the 10m analyses were transformed to UTM projection to allow direct comparisons between resolutions. This was approximate due to constraints in the orientation, lack of survey control and extent of survey data.

The analysis settings were kept close to those of the 10m analysis where possible:

- smoothing window 5x5 (125m x125m)
- concavity window 3x3 (75mx75m)
- UPNESS threshold 0.0

3. RESULTS

The results include a large number of figures due to the requirement to supply all maps in order for DLWC to assess the relative merits of each filter type and resolution. Maps of salinity prediction were not generated because of the poor statistics obtained from the digitally available pre 1995 salinity training set. The results are organised as follows:

Yahoo Peaks - LOW and CC filters for each resolution (Figs. 4a,b,c, d) plus the area clipped from the Little River analysis which shows the effect of a more regional 'UPNESS' or uphill contributing area (Figs. 4e, f).

Mumbil - LOW and CC filters for each resolution (Figs. 5a, b, c, d) plus the same area clipped from a 25m analysis using an extended DEM, again to see whether a regional effect could be modelled (5e, f).

Rylstone - LOW and CC filters for each resolution (Figs. 6a, b, c, d).

Little River - LOW and CC filters for the 25m resolution (Figs. 7a, b) plus an alternative ArcInfo linear stretch for the LOW filter highlighting the wetter areas (Fig. 7c) that is easier to interpret.

In each of the smaller study areas the 25m analysis resulted in more generalised maps that included artefacts associated with abrupt changes in slope or highly crenulated contours due to the coarser grid resolution.

3.1 *Yahoo Peaks analyses*

Fig 4a,b show the differences in the 10m analysis, between the fuzzy relative wetness indices derived from the LOW and CC filters respectively. The general pattern is reasonably similar in both despite the detail that is apparent in the CC map.

A number of regularly spaced anomalies in the southern end of the catchment highlight a major problem interpolating from regularly spaced, rather than well selected, survey points.

An artefact of the implementation of the smoothing window is a shrinking of the area by the size of the smoothing window (Figs. 4a,c). This occurs when the smoothing window encounters 'no data cells' contributing to the calculation of a cell, which automatically deems that cell 'no data' as well.

The fuzzy relative soil wetness index is in broad agreement with vegetation distribution observed on the ground, where scalds and salt tolerant species are evident in the main gully and many small patches predominantly on the eastern side of the catchment (Figs 4a, c). A line joining the green/yellow boundary in these gullies coincides with a N-S aligned dyke. It also forms the boundary between the alluvium floor of the valley and granite/aplite to the north-east and conglomerates to the central-east sections of the map. More gullies and salt affected areas are predicted (in greens and yellows) on this map than appear on the site. Evidence of previously salinised areas has been hidden by extensive tree planting and gully restoration that has taken place after the area was surveyed for elevations.

The LOW wetness index (Figs. 4a,c,e) predicted a high wetness index mostly agreeing with the area ground-truthed as waterlogged or salt affected. The concavity filter (CC, Figs. 4b,d,f) produced very similar results although the extra detail and speckle, caused partly in the interpolation of the DEM, tends to detract from the interpretability. The LOW index for the study site that was clipped from the Little River analysis, shows a considerable loss of detail (down to practically 1 contiguous area) due to the domination of the UPNESS index.

3.2 Mumbil analyses

Again the LOW wetness index (Figs. 5a,c,e) was preferable to CC (Figs. 5b,d,f) for interpretation. The 10m analysis gave very good results, particularly in depicting a number of saline seeps in the northern valley, although instances could be found where the 25m and regional test was in better agreement with actual wetness. Vegetation differences were more difficult to interpret because of the dryness and harvesting operations of mid December.

The catchment was relatively small but geologically complex. It contains at least three geological units with shales predominant in the catchment, basalt capped hills in the west and a dominantly limestone hill situated in the northern part. Three fractures (or faults) traversed the entire catchment in a N-S direction. All of these geological units were expressed in the topography and the analysis results reflected the geology.

3.3 Rylstone analyses

This site was not checked but some significant differences in spatial distribution can be seen (Figs. 6a-d) which are attributable in part to generalisation of the DEM but more dramatically to the relocation of watercourses, most likely due to errors in the source data. From a subsequent field inspection, Allan Nicholson reported that there was a good agreement between the observed conditions on the ground and predicted wetness index, particularly in the western end of the catchment.

3.4. Little River analyses

The LOW index identifies narrow areas of higher wetness in this landscape, which conform to the pre-1995 salinity map, although the extents are very different. The June 1999 salinity map has similar narrow areas of salinisation but longer in extent and more numerous. It agrees significantly more with high values of the wetness index and the inclusion of incipiently saline land would improve the result further. An important point to note is that the June 99 salinity map includes saline areas that are expanding upward and outward to the perimeter of the catchment and on geologies (conglomerates) previously thought to be fresh water discharges. Inspection of many sites indicated that the FLAG wetness index was a very reasonable representation of discharge and saline areas. The CC wetness index, as in the previous examples, was more difficult to interpret and appeared to be more useful in highlighting broad landscape or geological differences. On the other hand, the default ArcInfo linear stretched version of the LOW index (Fig 7c) was easiest to read because of the resulting combination of colours a simplification of the detail seen in Figure 7a.

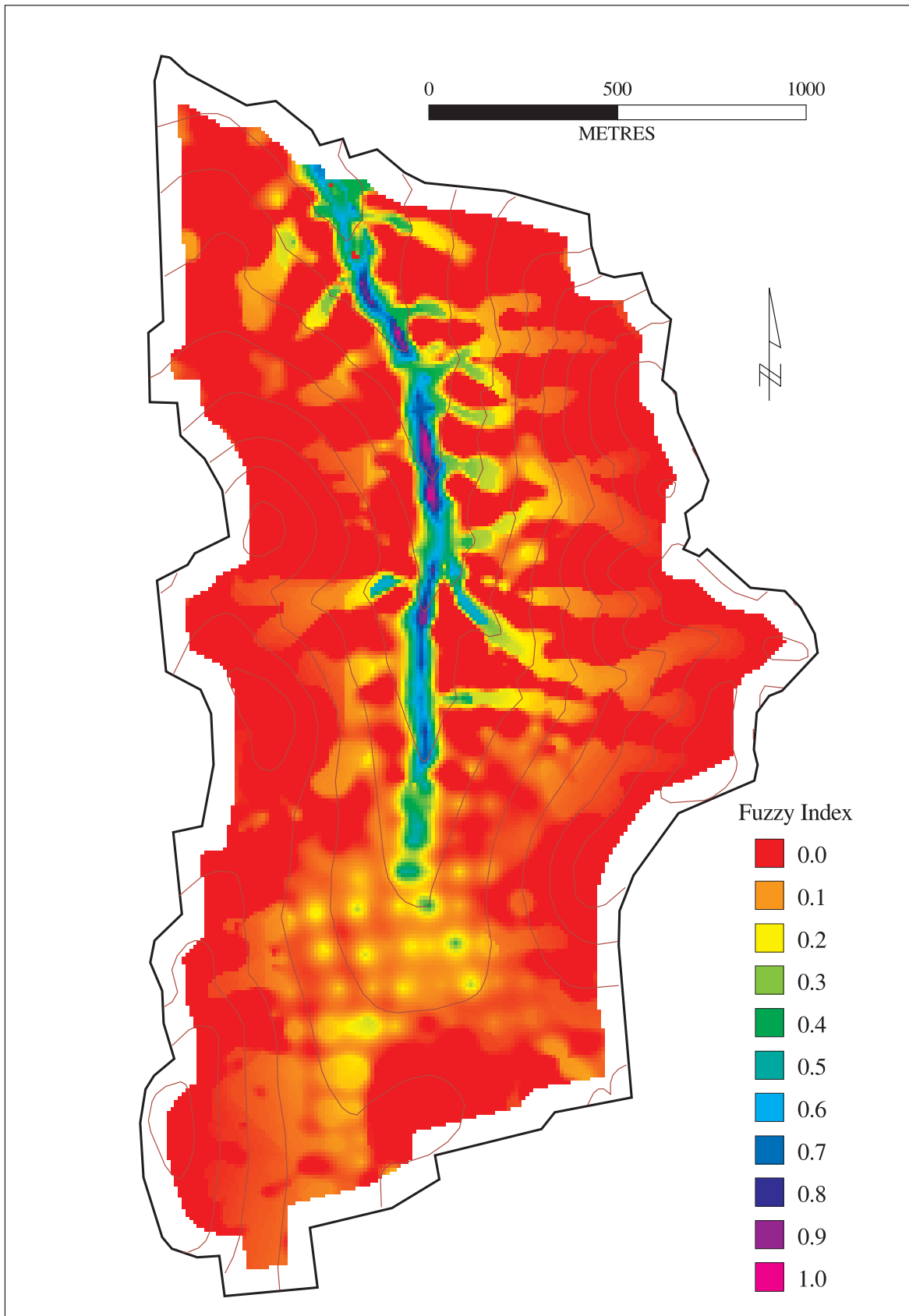


Figure 4a Yahoo Peaks 10m wetness index calculated using the LOW filter. Small values (red) indicate driest while large values (magenta) are wettest. Contour interval is 5m.

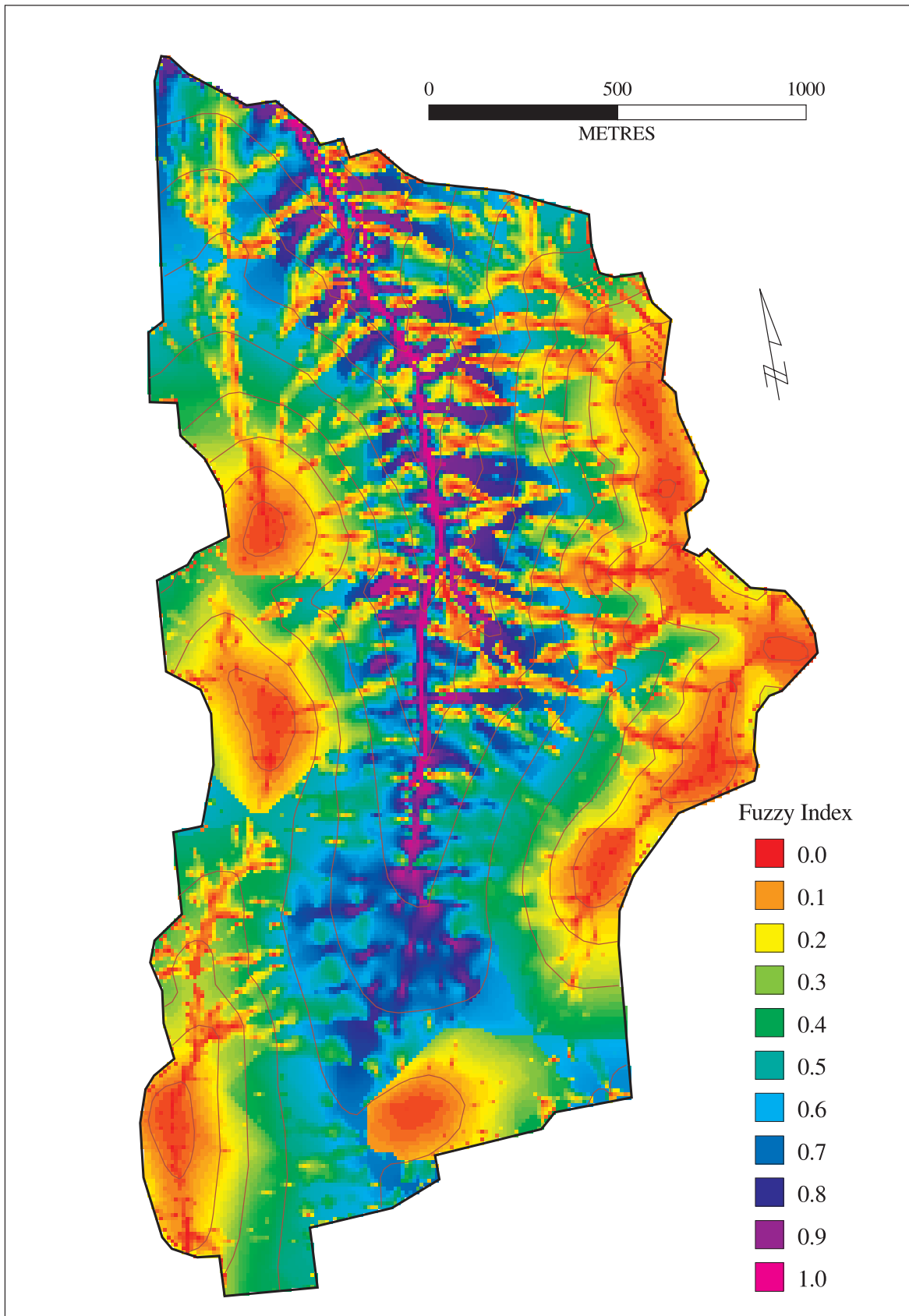


Figure 4b Yahoo Peaks 10m wetness index calculated using the CC filter. Small values (red) indicate driest while large values (magenta) are wettest. Contour interval is 5m.

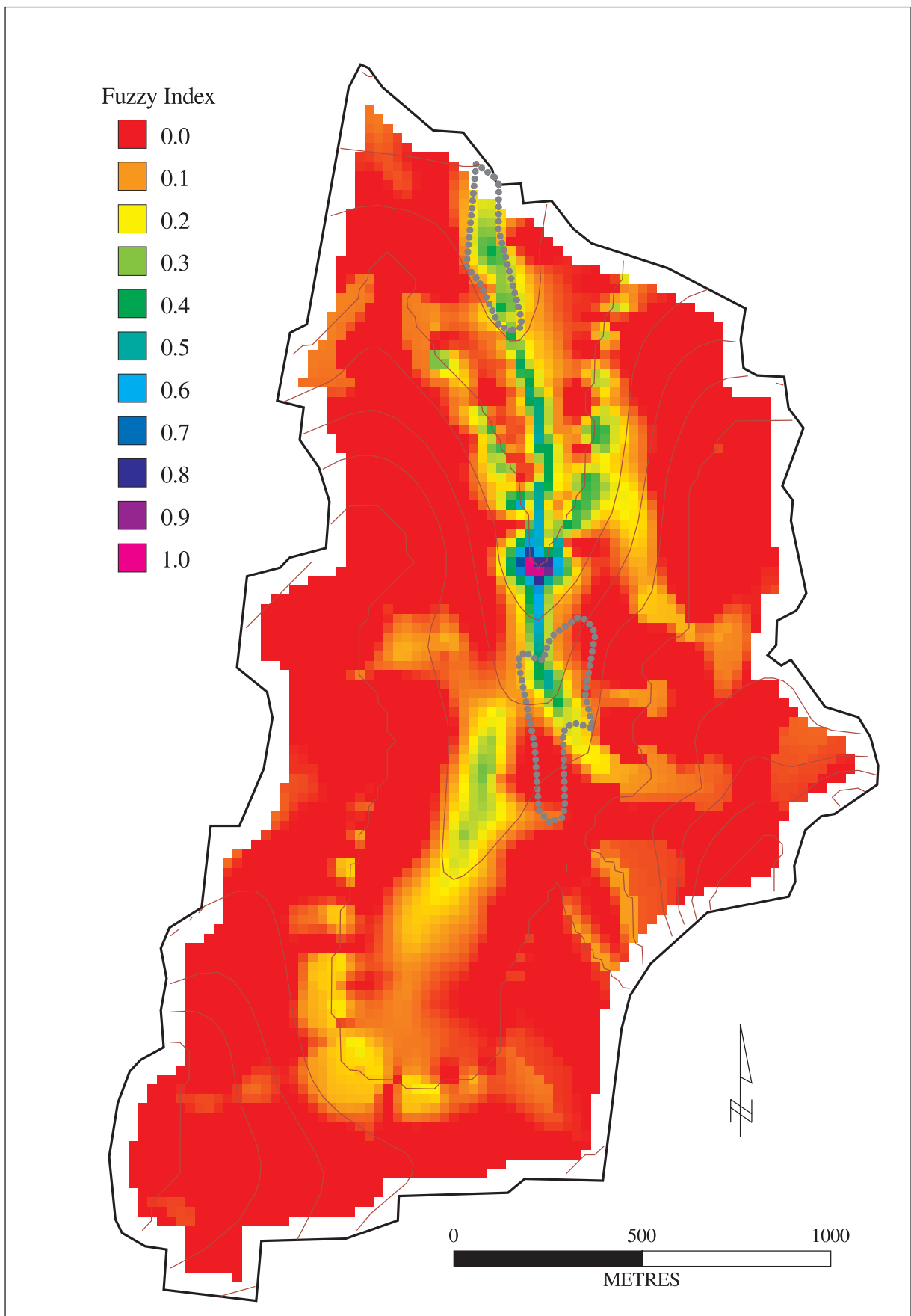


Figure 4c Yahoo Peaks 25m wetness index calculated using the LOW filter. Small values (red) indicate driest while larger values (magenta) are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

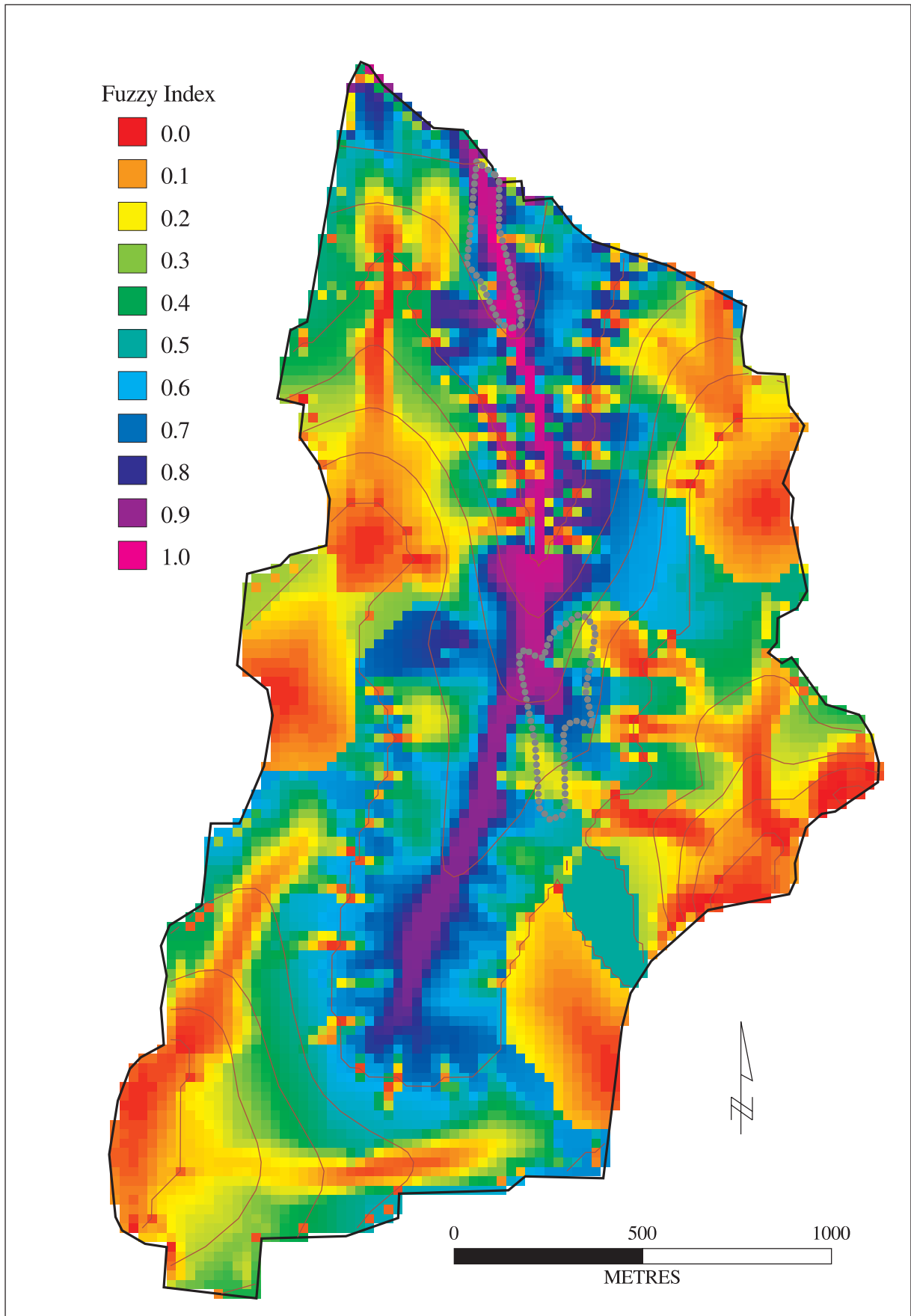


Figure 4d Yahoo Peaks 25m wetness index calculated using the CC filter. Small values (red) indicate driest while larger values (magenta) are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

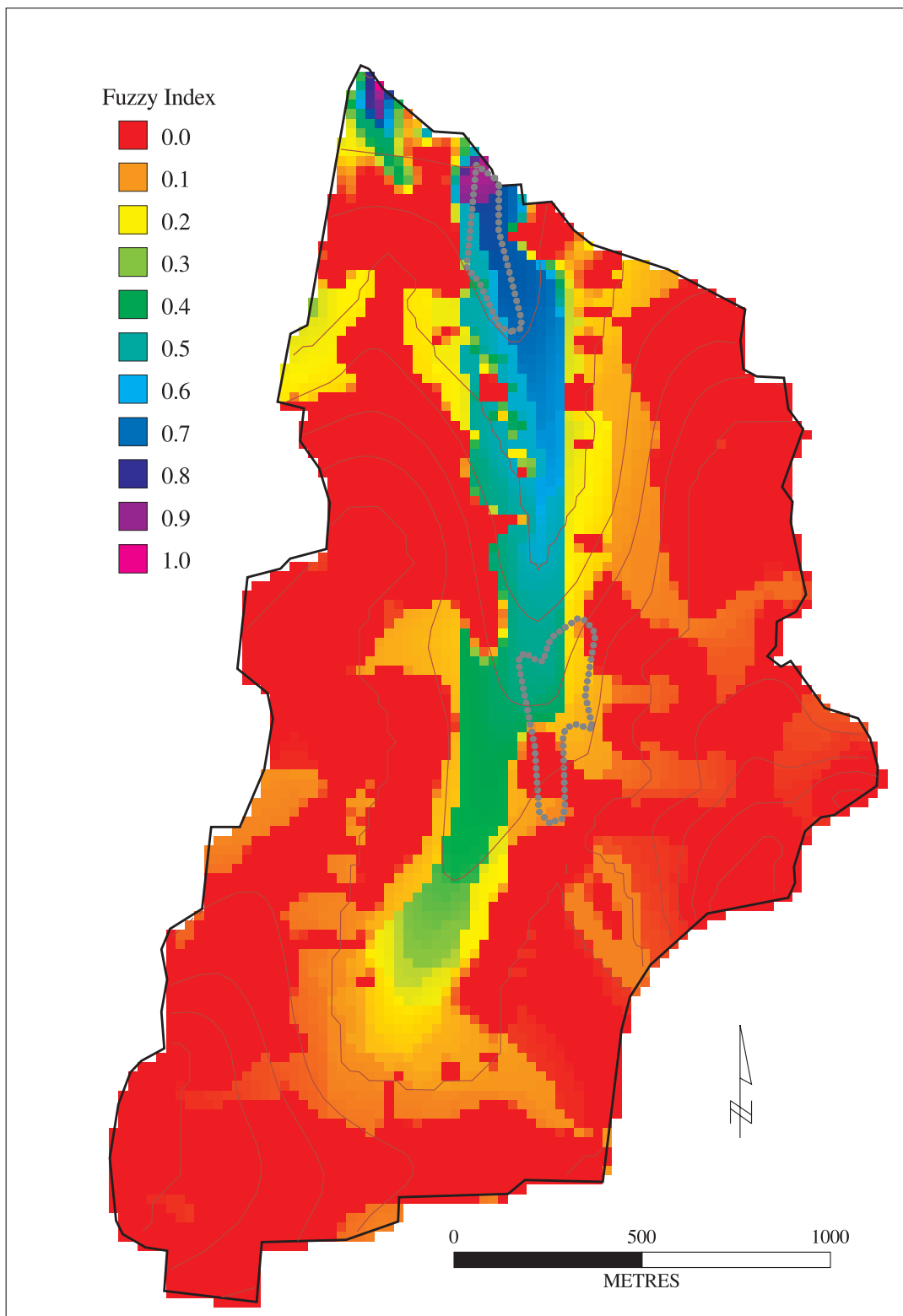


Figure 4e Yahoo Peaks 25m wetness index (subset of the Little River analysis (Fig. 7a) using the LOW filter. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

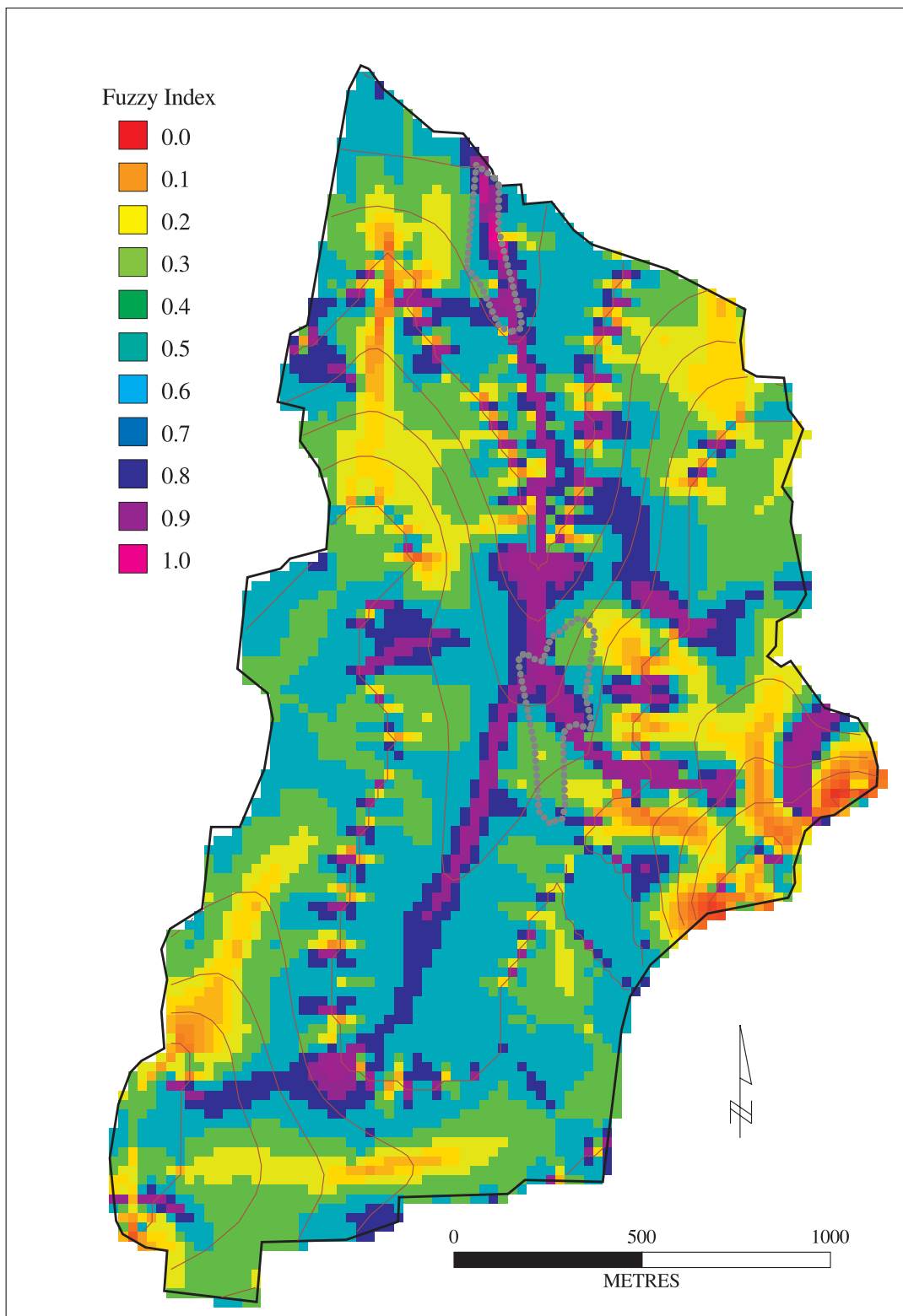


Figure 4f Yahoo Peaks 25m wetness index (subset of the Little River analysis (Fig. 7b) using the CC filter. Small values indicate driest while large values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

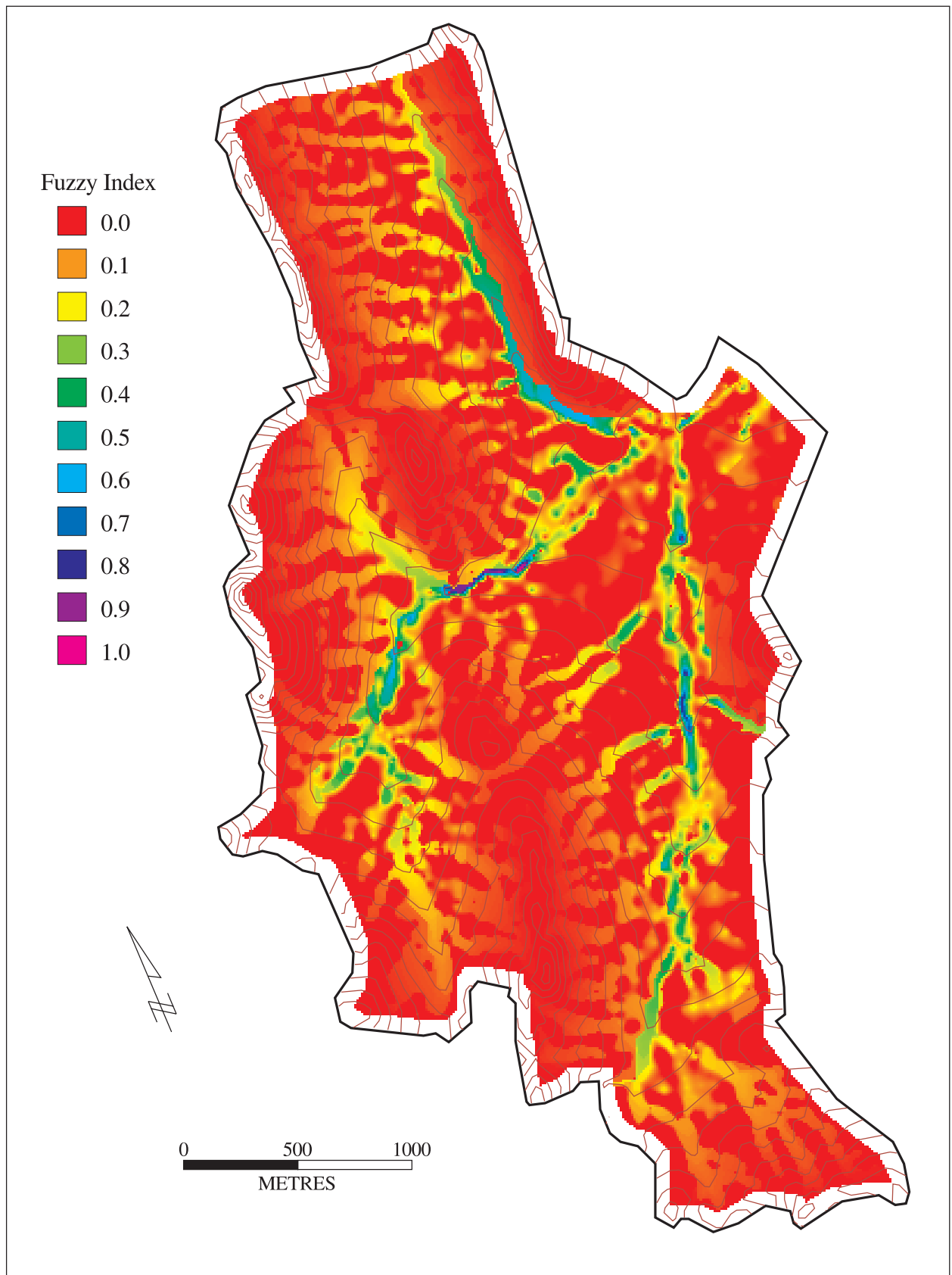


Figure 5a Mumbil 10m wetness index calculated using the LOW filter. Small values indicate driest while larger values are wettest. Contour interval is 5m.

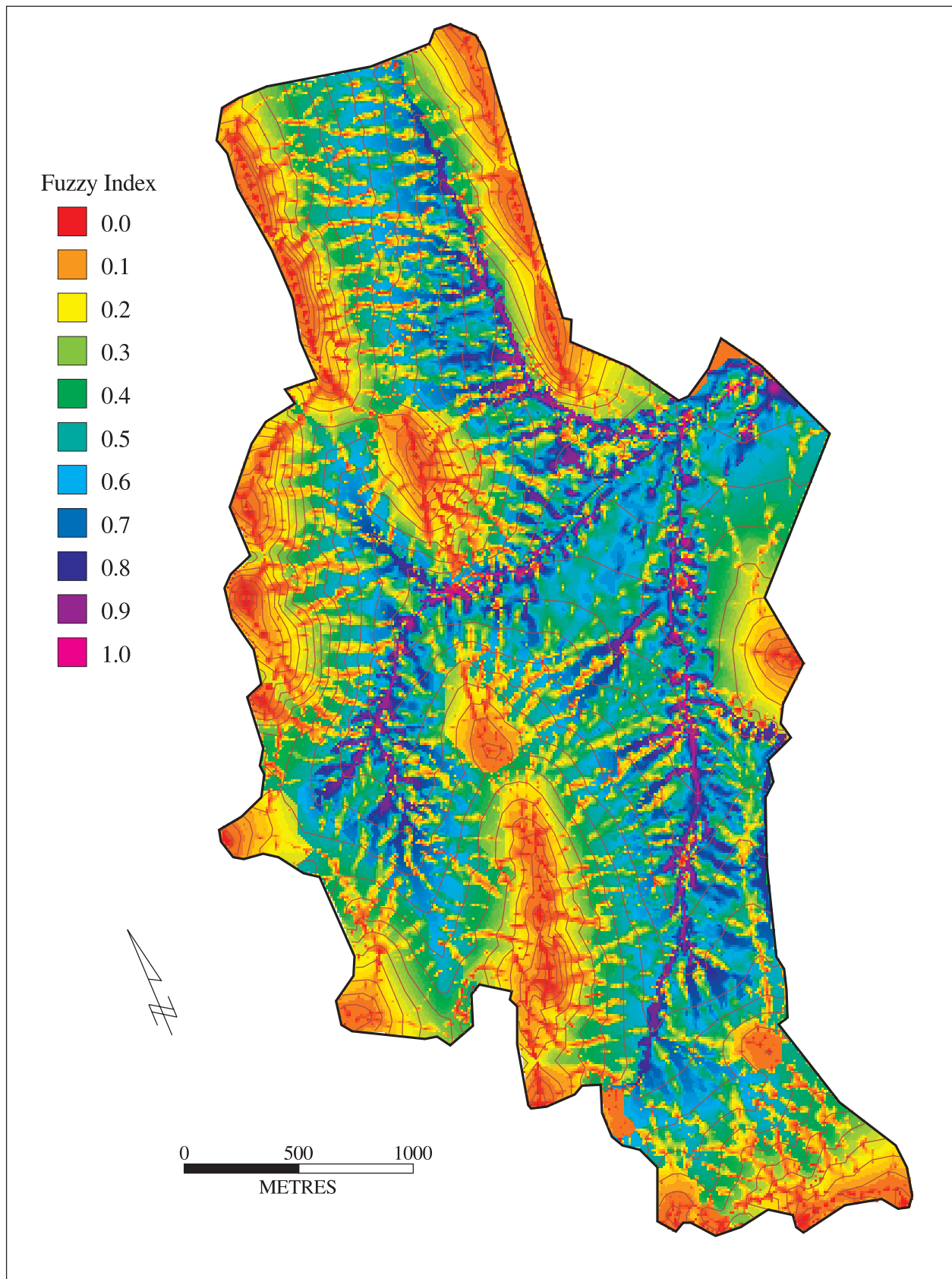


Figure 5b Mumbuil 10m wetness index calculated using the CC filter. Small values indicate driest while larger values are wettest. Contour interval is 5m.

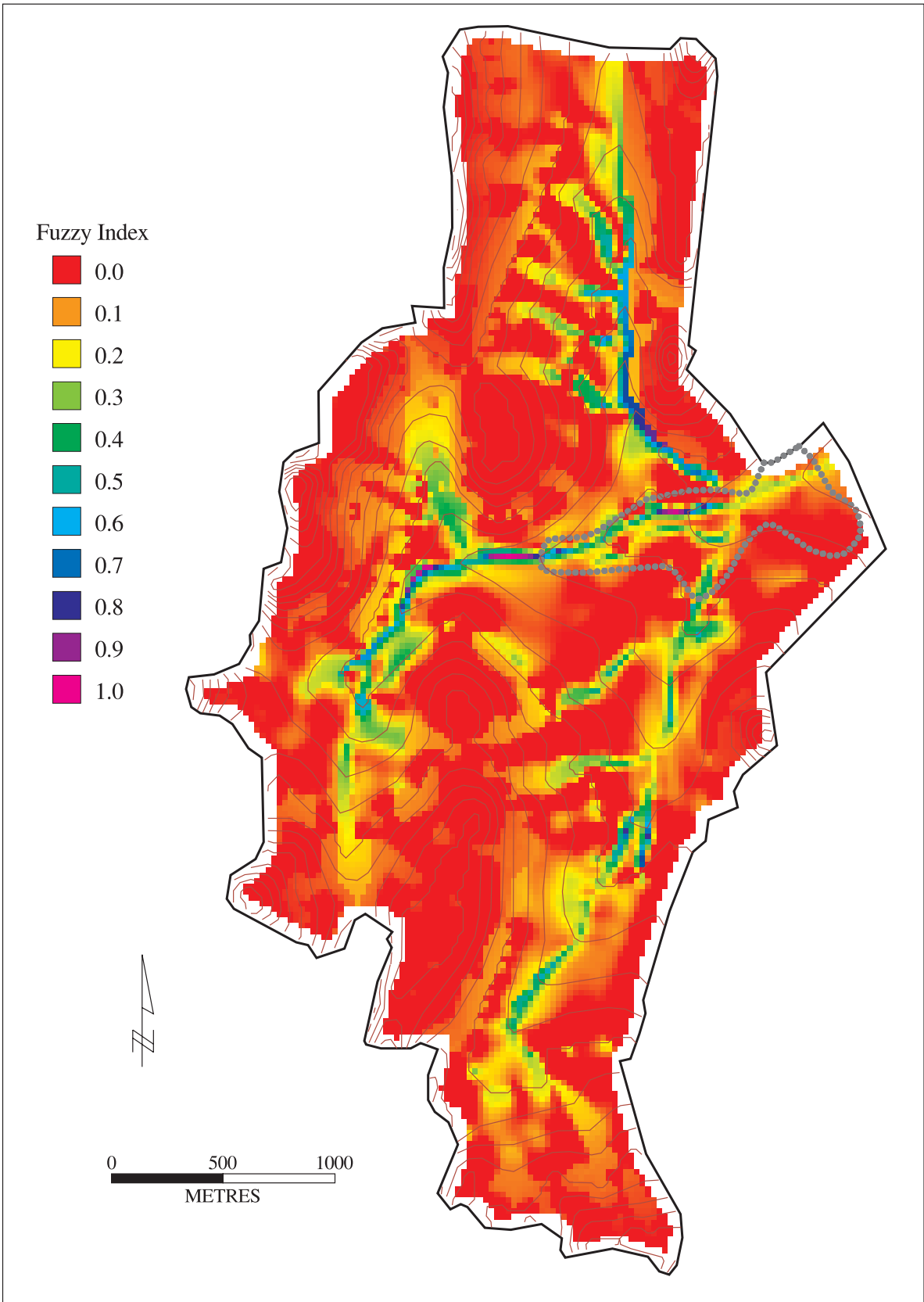


Figure 5c Mumbil 25m wetness index calculated using the LOW filter. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

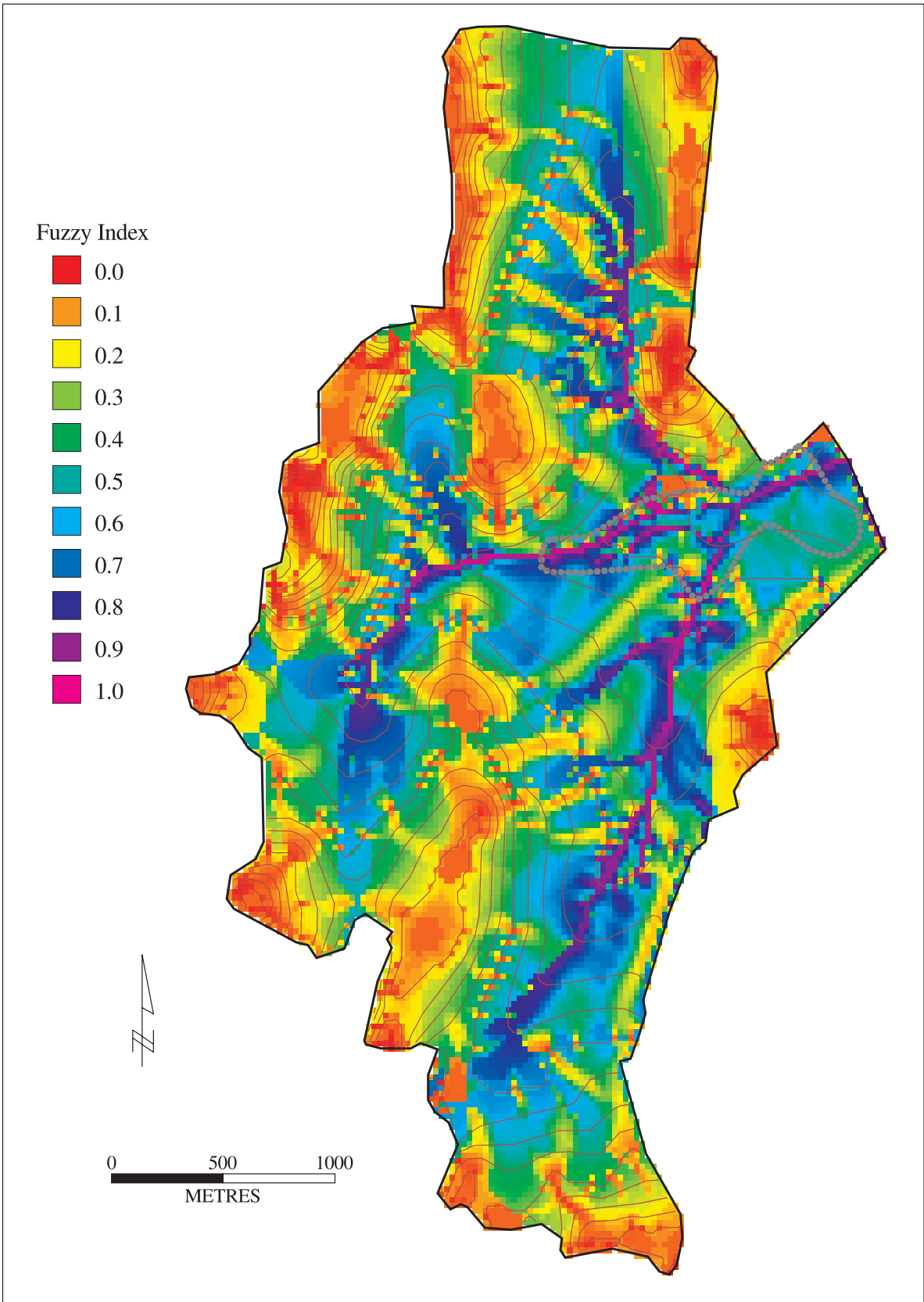


Figure 5d Mumbil 25m wetness index calculated using the CC filter. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

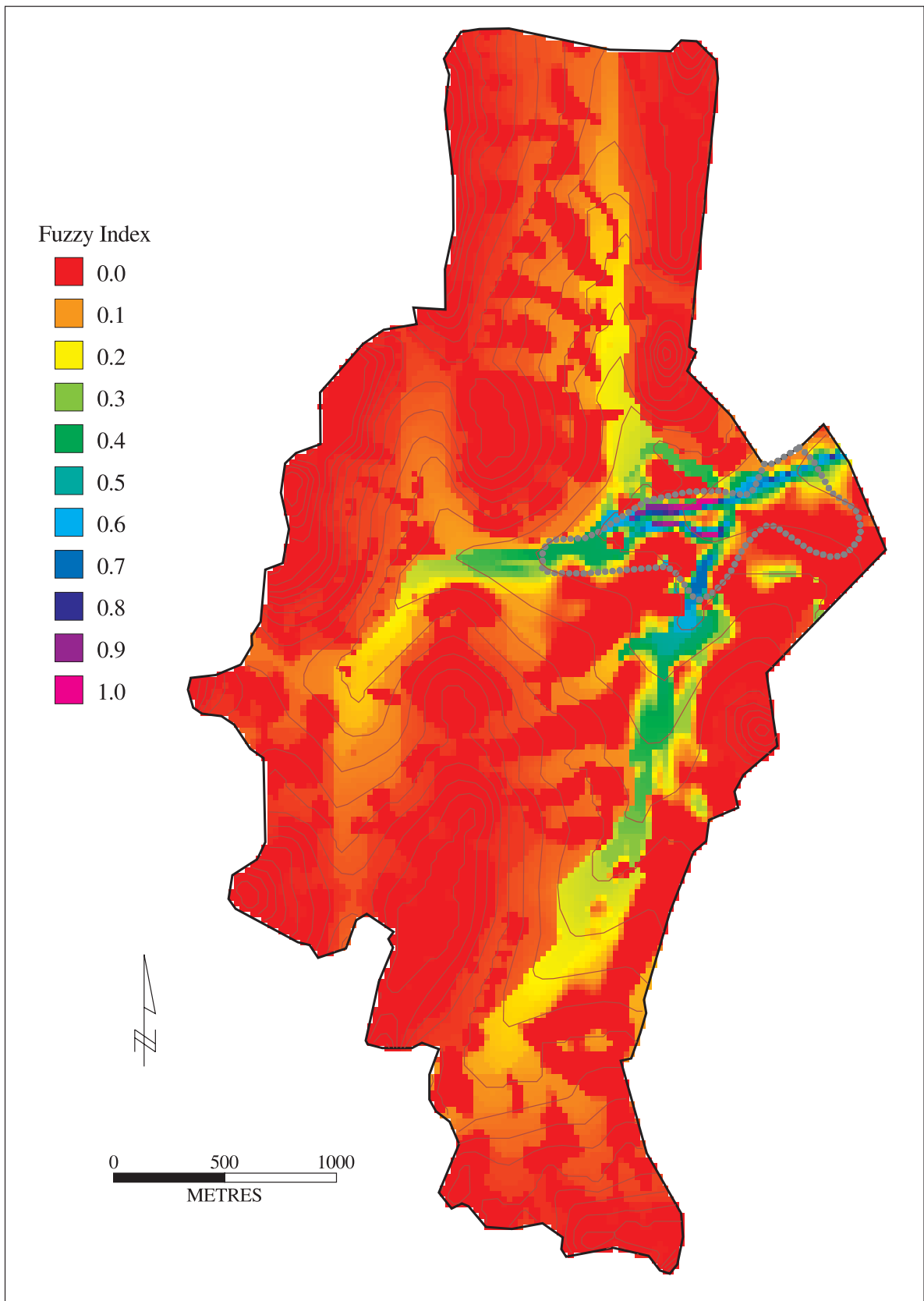


Figure 5e Mumbil 25m wetness index calculated using the LOW filter on a larger area (to simulate regional effects) then clipped. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

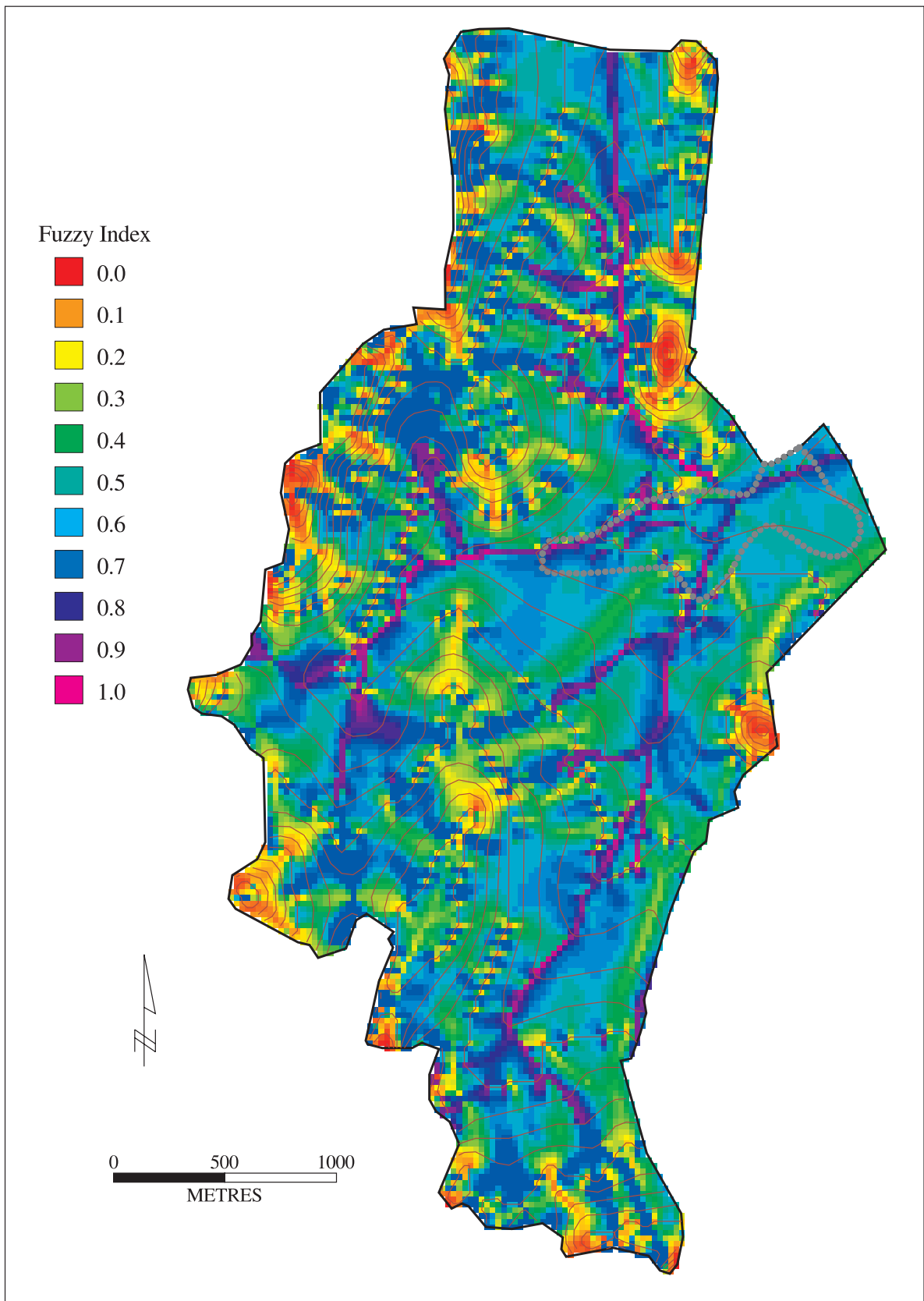


Figure 5f Mumbil 25m wetness index calculated using the CC filter filter on a larger area (to simulate regional effects) then clipped. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

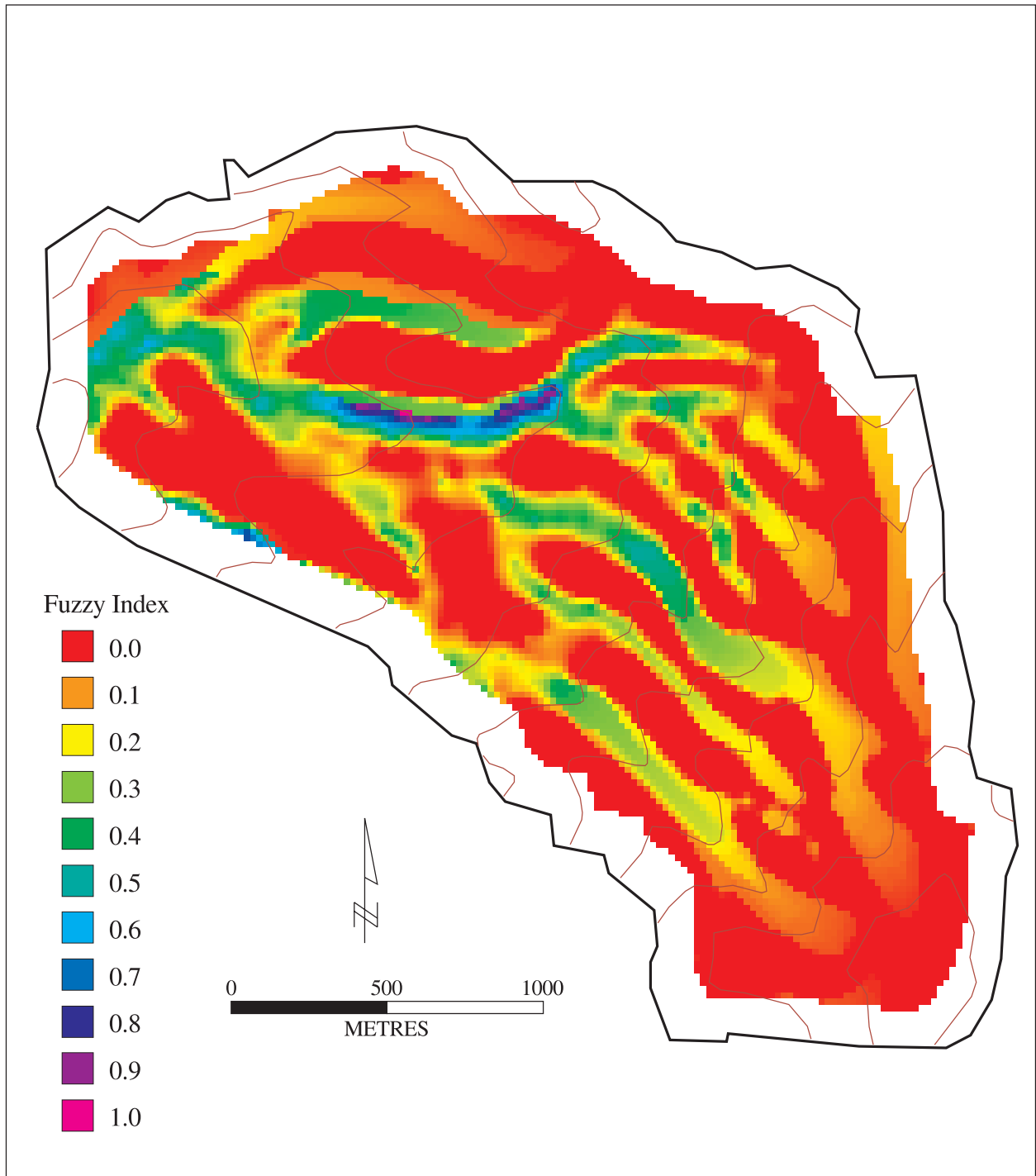


Figure 6a Rylstone 10m wetness index calculated using the LOW filter. Small values indicate driest while larger values are wettest. Contour interval is 5m.

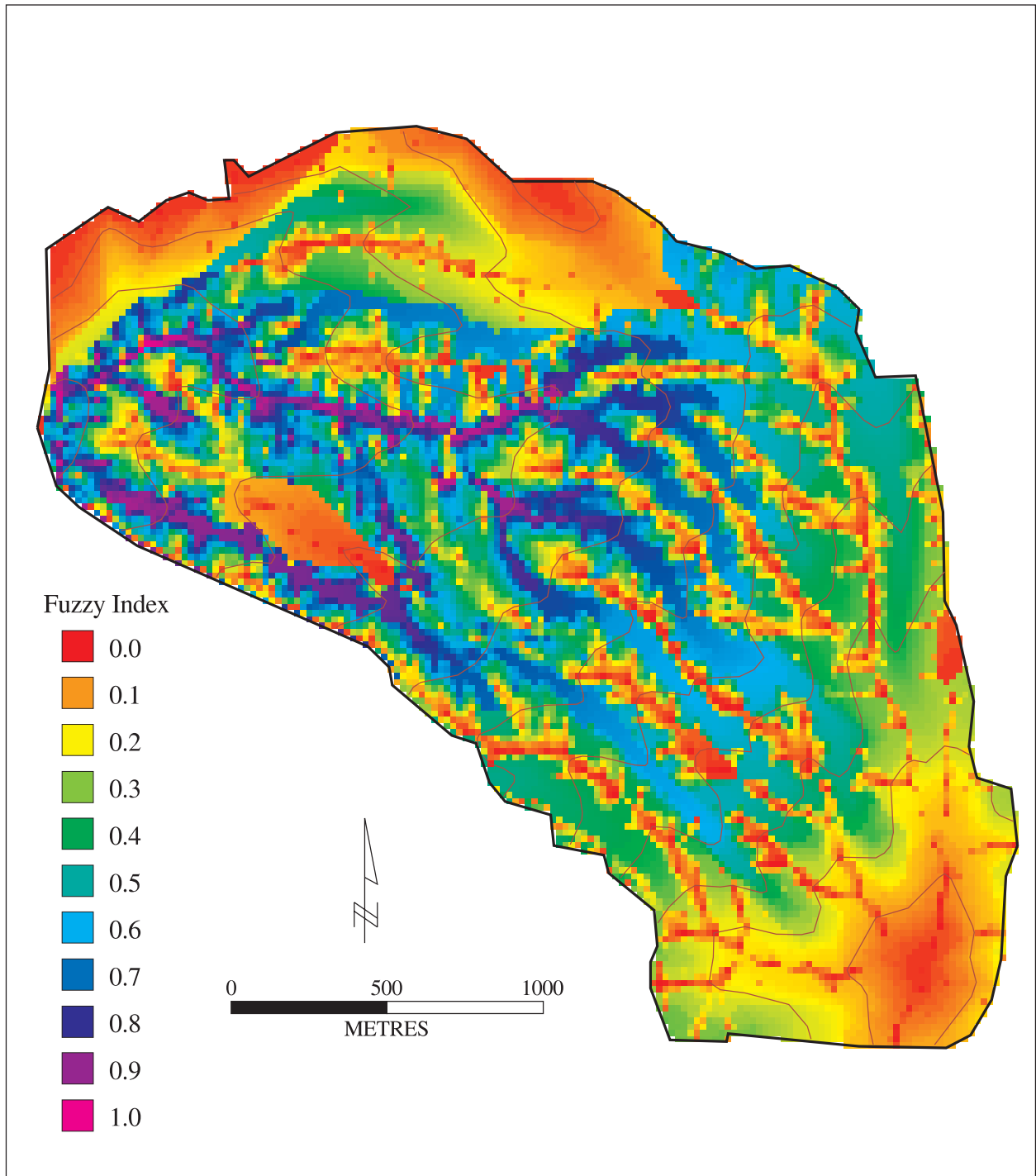


Figure 6b Rylstone 10m wetness index calculated using the CC filter. Small values indicate driest while larger values are wettest. Contour interval is 5m.

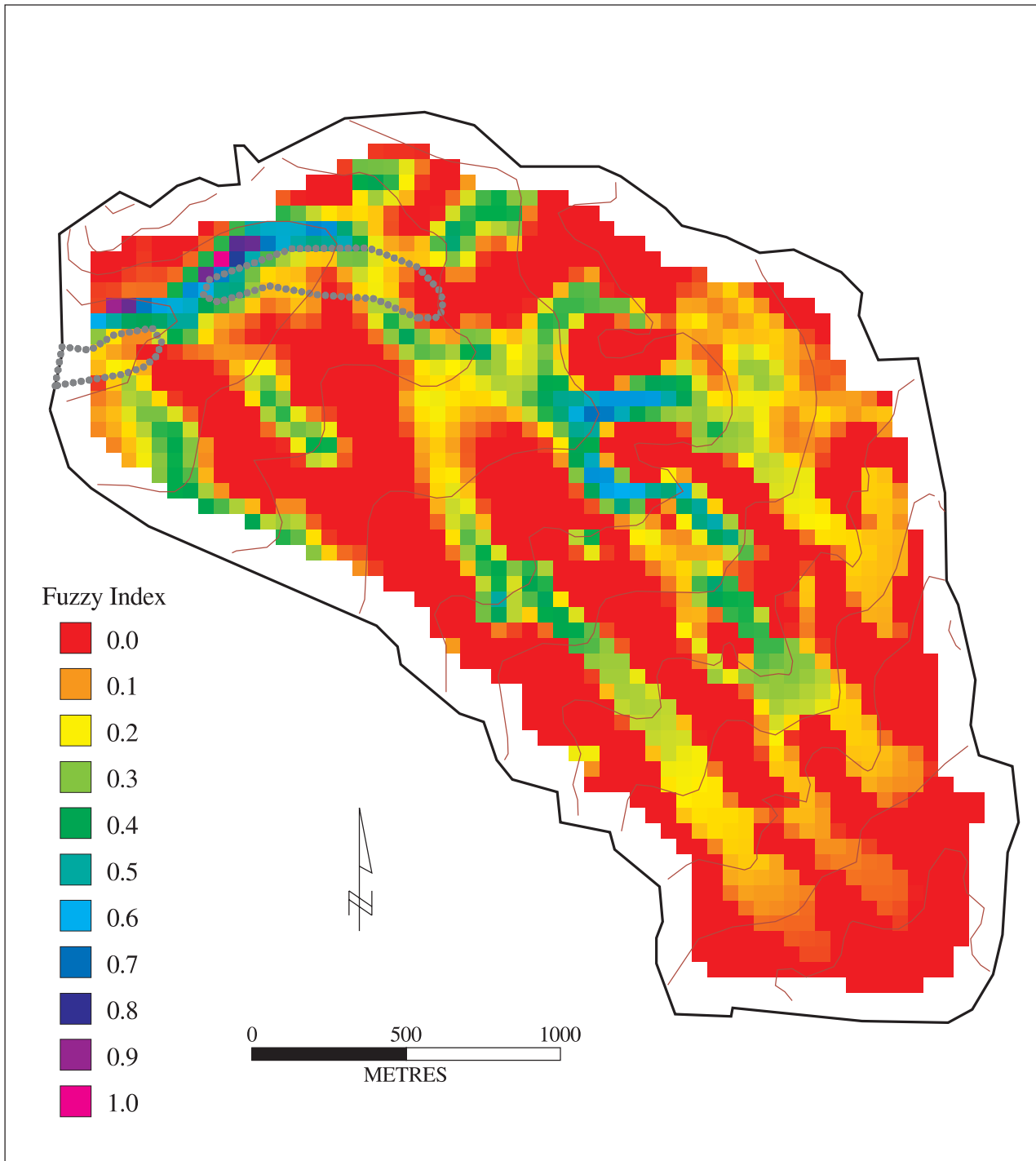


Figure 6c Rylstone 25m wetness index calculated using the LOW filter. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.

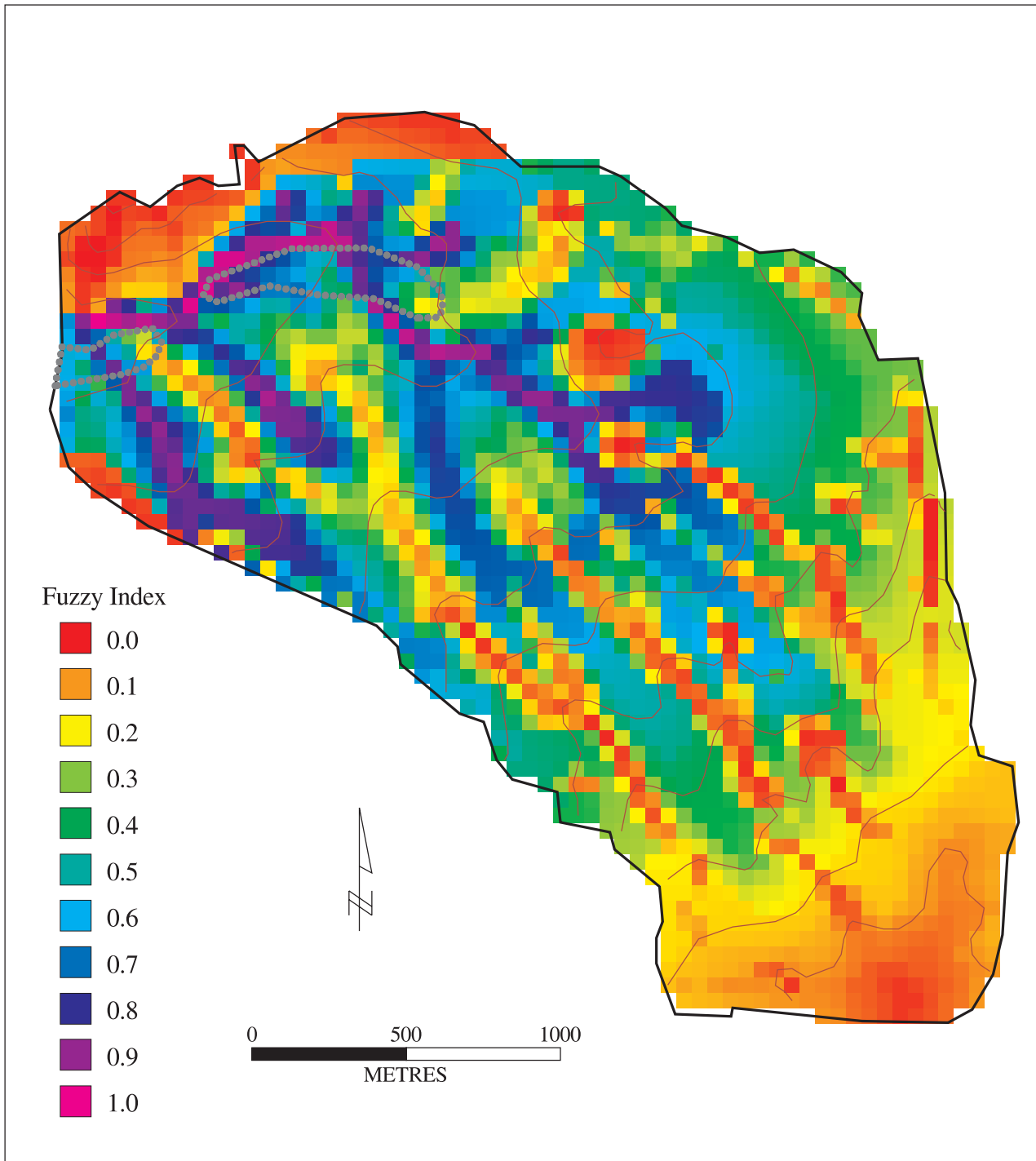
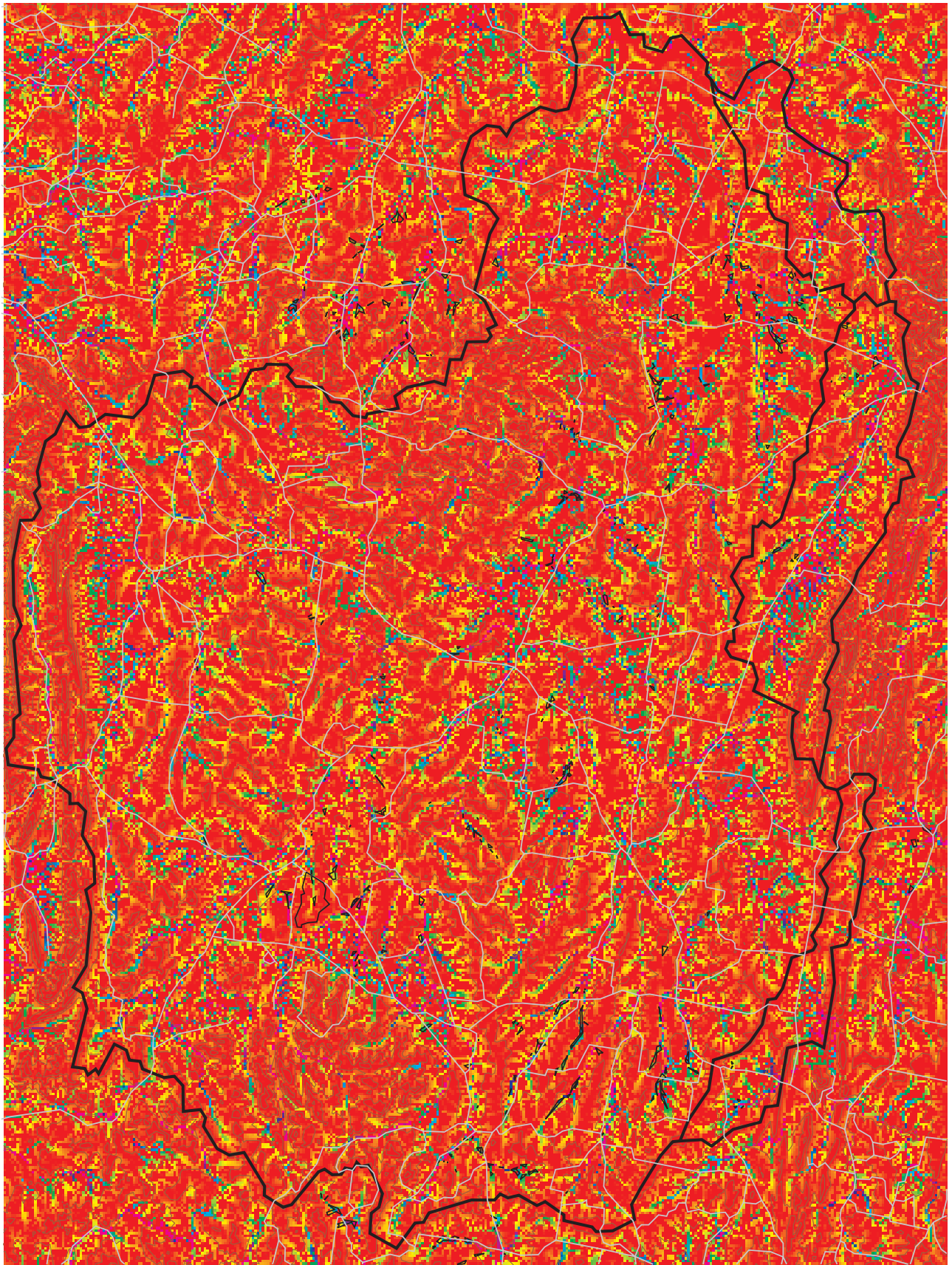
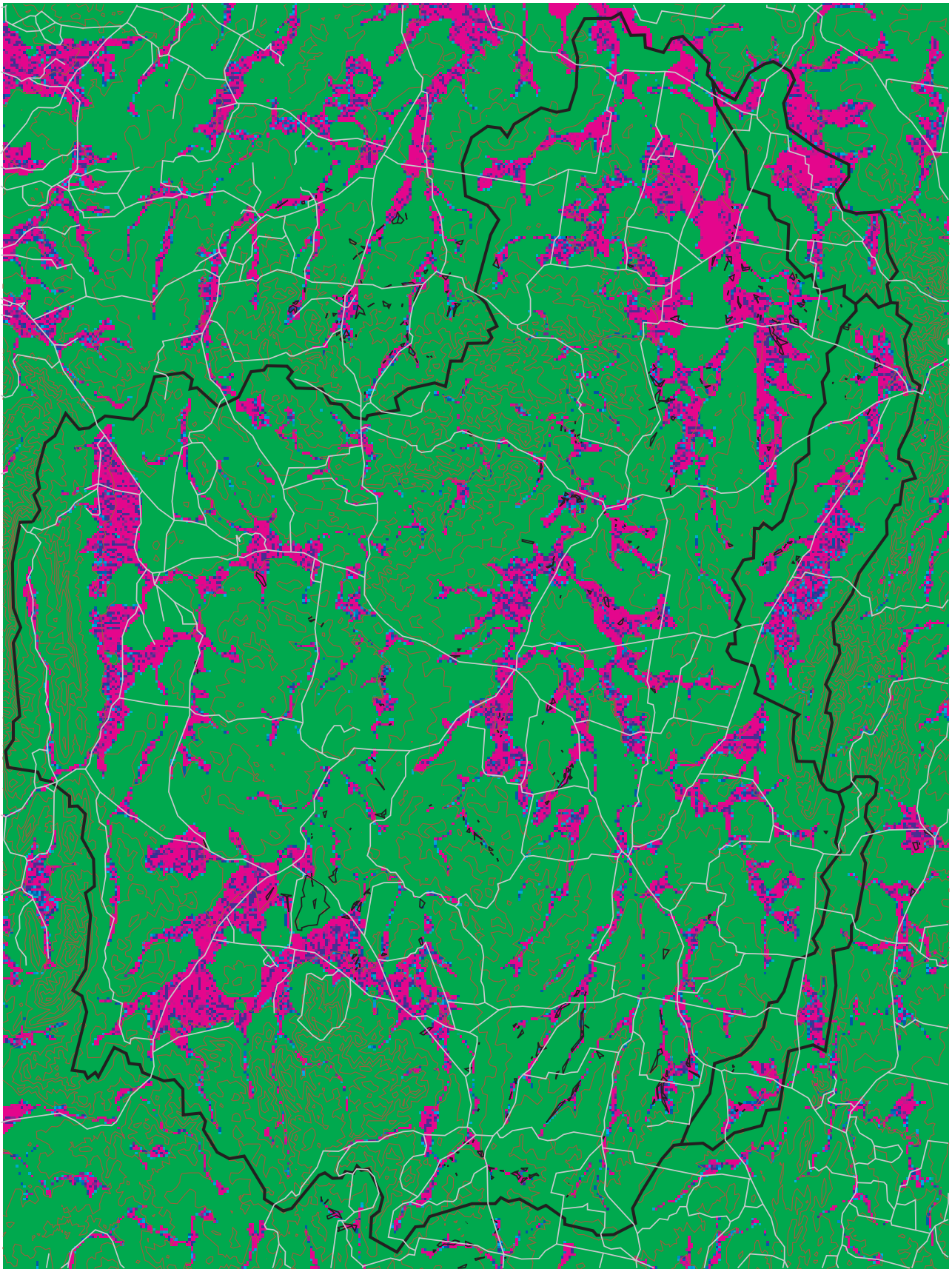


Figure 6d Rylstone 25m wetness index calculated using the CC filter. Small values indicate driest while larger values are wettest. Grey boundaries show pre 1995 salinity mapping. Contour interval is 5m.



0 5000 10000
METRES

Figure 7a. Little River 25m wetness index calculated using the LOW filter. The key is the same as other figures, red is driest and magenta is wettest. Fine black boundaries show pre 1995 salinity mapping and also the Yahoo catchment in the lower left quadrant. Contour interval is 40m.



0 5000 10000
METRES

Figure 7b. Little River 25m wetness index calculated using the CC filter. The key is the same as other figures, red is driest and magenta is wettest. Fine black boundaries show pre 1995 salinity mapping and also the Yahoo catchment in the lower left quadrant. Contour interval is 40m.

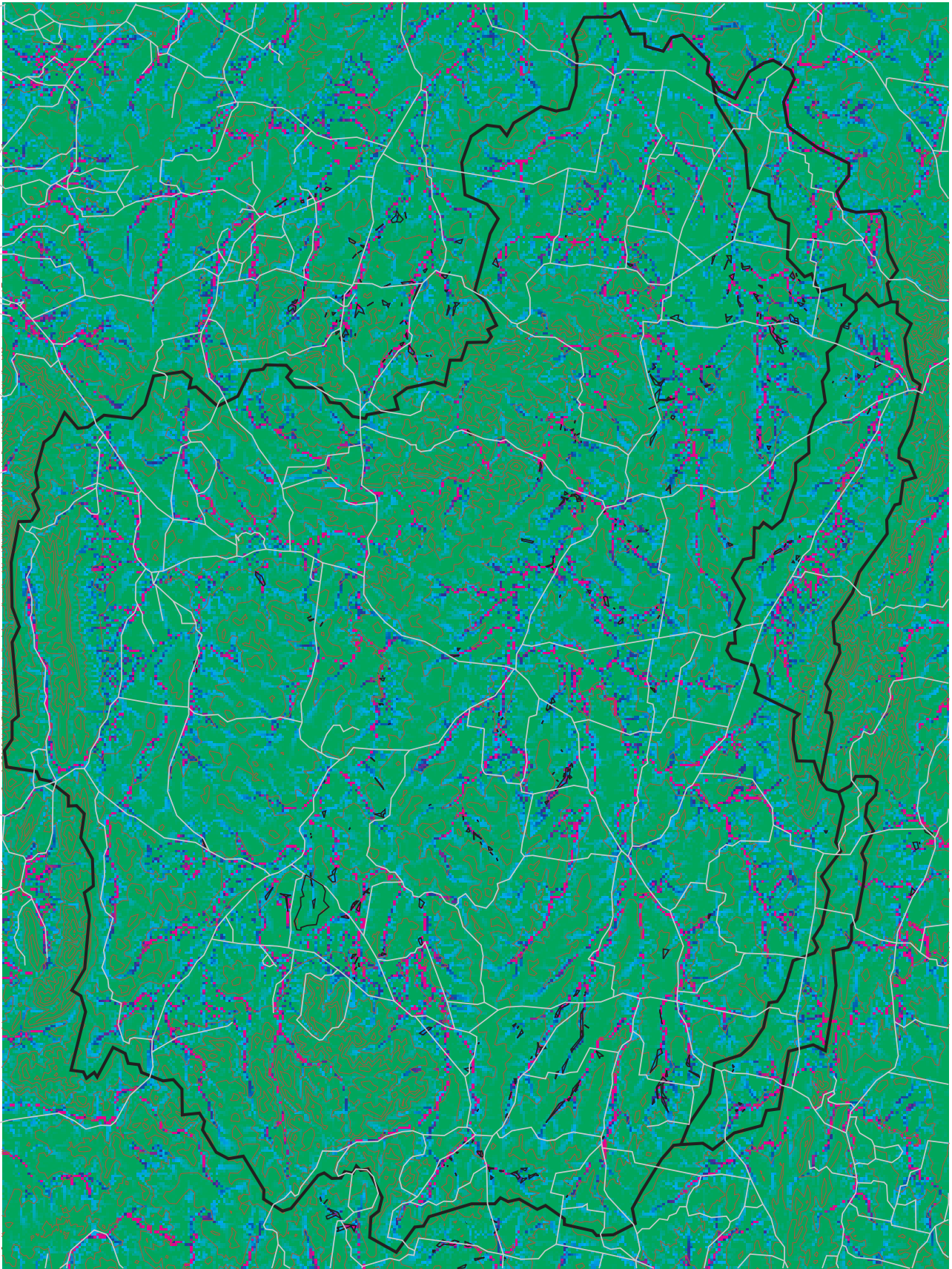


Figure 7c. Little River 25m wetness index calculated using the LOW filter (same data as Fig. 7a) plotted using the ArcInfo default linear stretch for which there is no key. This stretch highlights higher wetness values (magenta & blue). Map details, except the key, are the same as for Fig 7a.

4. DISCUSSION

If detailed reliable (recent) field data can be obtained to support them, process models should provide detailed and more accurate quantitative answers than FLAG. For the purposes of rapid assessment and visualisation FLAG has some advantages including simplicity, speed and the use of continuous classification which helps reduce uncertainty.

While the evaluation of the results from the field assessment was very positive, further investigations by DLWC are needed to evaluate the usefulness of the FLAG outputs. In general, the LOW wetness index at both resolutions gave results that were in broad agreement with site inspections and were easier to interpret than the CC wetness index.

A major impetus behind the development of FLAG was the ability to process large areas easily. Processing a larger area than required, then clipping the relative wetness index to the area of interest, was shown to have a significant generalising effect. This occurs because the UPNESS index grows larger and dominates the LOW index. Whether this is in any way a real simulation of regional groundwater effects requires the local knowledge and judgement of DLWC staff.

Although not visited, the Rylstone site (Figs 6a-d) shows some significant sources of errors using the 25m DEM. The first is that, apart from the generalisation of contour detail, the main watercourse was significantly realigned close to the outlet of the catchment. This is most probably due to positional errors in the 1:25,000 source data. The second is that the pre 1995 mapped salinity outbreak aligns best with this relocated gully and suggests that the salinity map was based on the 1:25,000 map series. Use of this training set for predicting salinity with the higher resolution analysis would produce significant errors and illustrates the implications of using poor quality DEMs or training set data.

The predictive component of FLAG was unsuccessfully applied to the Little River catchment because of a poor correlation between the wetness index and the available training set. Reliable predictive capability in FLAG is affected by a number of factors that must be considered, including:

- i. Grid resolution: a trade-off between the ability to resolve topographic shapes at the resolution of salinisation processes while minimising computer processing needs and complexity.
- ii. Quality of the ground truthing information available that will vary with:
 - o The methods available for training set mapping and ability of the interpreter
 - o Age of air photos used in ground truth relative to stage of salinisation
 - o Stage of salinisation relative to potential salinisation
 - o Time of the year and type of season
 - o The condition of indicators, such as vegetation species, indicative of discharge or salinity, which is likely to be changed, *e.g.* being ploughed out.

FLAG predicts a fuzzy relative wetness index that can be thought of as the spatial distribution of the potential discharge. The training set is a means to divide it into discrete classes – discharge or recharge. However, the training set is most likely to be mapped on the basis of current, *i.e.* visible, outbreaks of discharge, or salinity, and not necessarily the potential for them. If the aim is to predict potential discharge and salinity (*i.e.* risk) then we need to know accurately what the potential areas of discharge and salinity for the training area are. This is a role for process models.

With the exception of a case study of the Boorowa catchment, using the same pre 1995 training set as the Little River analysis, the POWER statistic gave a reliable means to select an optimum alpha threshold value for the production of binary maps. Pre-1995 salinity was plotted on the 25m analysis maps (grey dotted boundaries, Figs. 4 to 7). These mapped saline areas are much smaller than the areas of modelled high relative wetness index. The area of salinity has more than doubled from this pre-1995 mapping in to the June 1999 salinity map and gives a significantly better visual correlation. Salinity has expanded towards the perimeter of the catchment and into geologies previously thought to contain only freshwater discharge zones. The field inspection indicated that even this revised map may under-estimate the incipiently saline land. Following this argument the next revision would be even closer to the FLAG high wetness values. Thus FLAG appears to be giving a reasonable estimate of potential salinisation for very little cost.

The POWER statistic used in the model was chosen because it predicts areas of discharge or salinity that are about the right size in about the right place. That is, the predicted and actual areas may not exactly overlay but the areas over-predicted and those under-predicted are about equal. This was found to be the best compromise to achieve a good indication of the area at risk and tends to make the prediction more robust against known sources of error like data registration and errors in interpretation or digitising which produce displacements.

Once α has been determined it should be usable for prediction of discharge/salinity in surrounding areas as long as the landscape characteristics remain similar to the training area. Once the landscape characteristics change significantly, the procedure has to be re-iterated with a new ground truth training set. Promising methods for automatically assessing the landscape, *e.g.* wavelet analysis, are increasingly available, and may enable automatic calculation of appropriate smoothing window sizes.

5. CONCLUSIONS

1. At both resolutions FLAG provided information that was perceived to be useful to DLWC staff as an additional visualisation tool in their extension 'toolkit'. The indices used did not require any process modelling, surrogate parameters or collection of extra data.

2. The local lowness (LOW) index produced the most appropriate results in terms of the expert opinion provided by Allan Nicholson. The concavity (CC) index was less reliable given the inflexibility imposed by a fixed 3x3 processing window and proved to be too detailed for an effective visualisation tool.

3. Results at both resolutions generally compare well, with instances where one resolution appears to match field observations better than the other.

4. Salinity prediction had to be abandoned due to the lack of an adequate training set. The training set available for salinity was developed by DLWC (pre 1995) and used by Bradd *et al.* (1997). At the time of writing, a June 1999 version was available as a printed map. It exhibits more, and larger, areas of salinity that match more closely with the FLAG wetness index. A test of the predictive component of FLAG is dependent on the future availability of a digital version. To test it properly a map of potential salinity is required, if only for a small but representative training area.

5. FLAG is a simple model with low overheads, providing good predictions and well defined sources of error. Using continuous classification and fuzzy logic helps reduce uncertainty since information is retained throughout the modelling process and classified only at the end. FLAG can be used as the first step in a process to establish salinity risk in areas where indices can be adequately defined using DEMs.

ACKNOWLEDGEMENTS

DLWC provided data through Greg Summerell, from the DLWC, Wagga Wagga Research Centre, who I also thank for his contributions while training to use the model and his assistance in the field checking and writing up stages. Allan Nicholson provided the opportunity to do this consultancy and was very helpful with his broad local knowledge and comments both in the field and on the text. Peter Richardson, John Gallant, Mirko Stauffacher and John Knight, CSIRO Land and Water, helped with many useful discussions and reviewing.

REFERENCES

- Bradd, J.M., Milne-Home, W.A. and Gates, G. (1997) Overview of factors Leading to Dryland Salinity and its Potential Hazard in NSW Australia. *Hydrogeology Journal*, (5)1:51-67, 1997.
- Dawes, W.R. and Hatton, T.J. (1993). TOPOG_IRM: 1. Model Description, CSIRO, Div. Water Resources, Tech. Memo. 93/5.
- Dowling, T.I., Roberts, D.W. and Walker, J. (1997) Predicting Salinity Risk without the Use of a Process Model. Murray-Darling 1997 Workshop, Groundwater in the Balance, Toowoomba, QLD, 26-28th Aug 1997
- ESRI (1995). ARC/INFO User's Guide, version 7.0, Environmental Systems Research Institute Inc. California.
- Furby, S.L., Wallace, J.F., Caccetta, P. and Wheaton, G.A. (1995) Detecting and Monitoring Salt-affected Land. CSIRO Mathematical and information Sciences and Agriculture Western Australia. Report to LWRRDC.
- Hutchinson, M.F. (1989). A new method for gridding elevation and streamline data with automatic removal of pits. *J. Hydrol.* 106:211-232.
- Laffan, S.W. (1996) Rapid Appraisal of Groundwater discharge using fuzzy logic and topography. Proc. 3rd Intl Conf./Wshop on integrating GIS and Env. Modelling, Jan 21-25, 1996, Santa Fe
- Roberts, D.W., Dowling, T.I. and Walker, J. (1997) FLAG: A Fuzzy Landscape Analysis GIS Method for Dryland Salinity Assessment. CSIRO, Land and Water Tech. Report 8/97, Canberra, Jul 1997.
- Salama,R.B., Farrington, P., Bartle, G.A. and Watson, G.D. (1993) Distribution of recharge and discharge areas in a first order catchment in the wheatbelt of Western Australia. *J. Hydrol.* 143:259-277.
- Searle, R. and Baillie, J. (1998) Prediction of Landscape Salinity Hazard Using a Geographic Information System. Dept of Natural Resources Queensland On-line, <http://www.dnr.qld.gov.au/resourcenet/land/lris/era/projects/sham/>
- Speight, J.G. (1990) Landform in *Australian soil and land survey Field Handbook*, (McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S.) 2nd Ed, Inkata Press, Melbourne.
- Zevenbergen, L.W. and Thorne, C.R. (1987) Quantitative analysis of land surface topography, *Earth Surface Processes and Landforms*, 12, 47-56.