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Assessing the spatial extent of dryland salinity through fuzzy modeling

David Malins *, Graciela Metternicht

Department of Spatial Sciences, Curtin University of Technology, GPO Box U 1987, Perth, WA 6845, Western Australia

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Abstract

This paper presents applied research on fuzzy logic modeling to predict the distribution of secondary dryland salinity. An existing approach to predicting the distribution of salinity, fuzzy landscape analysis GIS (FLAG), developed by Roberts et al. (1997) is implemented. An attempt is made to optimize the predictive power of FLAG through the inclusion of geological and vegetation data. As FLAG models salinity distribution within the framework of fuzzy logic, results from this investigation are compared with the outputs of a predictive model of salinity based on probability theory.

The attempt to optimize FLAG was not as successful as expected. Of the FLAG based predictions, the model derived from fuzzy discharge indices (CC) produced the most accurate result. Of the modified FLAG models, FLAG_VEG (that incorporates vegetation data) produced the best result. The prediction of areas at risk of salinity derived from the probabilistic model presented similar accuracy when validated against ground truth data used to validate the results of this research. The comparison of CC and FLAG_VEG with the probability-based prediction model of salinity indicated that the differences between them were not significant at a 95% confidence level, with the fuzzy logic based models outperforming the probabilistic model in steeper terrain.

Keywords: Salinity; Spatial modelling; Fuzzy sets; Fuzzy logic; GIS; Landscape analysis; Australia

1. Introduction

Secondary dryland salinity, defined as the build up of salt in the soil usually as a result of a rising water table caused by human-induced changes in land use, is one of the greatest environmental threats facing Australia (Cooperative Research Centre for Plant Based Management of Dryland Salinity, 2002). Within the south-west agricultural region of Western Australia, 1.8 million ha of land have already been affected, mainly due to the replacement of deep-rooted native vegetation with shallow-rooted agricultural crops (Nulsen and McConnell, 2002). The National Land and Water Resources Audit (2000) found approximately 5.7 million ha of Australia are at risk or affected by dryland

* Corresponding author.
E-mail addresses: david.malins@student.curtin.edu.au (D. Malins), g.metternicht@curtin.edu.au (G. Metternicht).

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salinity, with an expected increase to over 17 million ha in 50 years.

As remedial action requires reliable information to help set priorities and choose the most appropriate course of action (Metternicht and Zinck, 2003), this paper compares the outputs of a model for predicting secondary dryland salinity based on fuzzy logic, against one that is based on Boolean logic and probability theory. This comparison was conducted to assist in drawing conclusions on the applicability of fuzzy modeling for salinity mapping and prediction, and highlight differences between probability-based and fuzzy logic-based modeling.

As the research builds on the work of Roberts et al. (1997) who developed fuzzy landscape analysis GIS (FLAG), the first aim was to perform fuzzy landscape analysis using the fuzzy modelling methodology presented in FLAG. An extension of FLAG recommended by Roberts et al. (1997) involving the use of a vegetation layer was implemented along with the use of geological data, as recommended by Laffan (1996a).

The second aim of the research is to statistically compare the fuzzy modelling of salinity as performed by FLAG with an existing 'crisp' (probability based) method for modelling salinity. The probability-based model used for the comparison is described in Evans and Caccetta (2000). Having performed the comparison, areas of agreement and disagreement between the results were analysed to determine possible causes of disagreement. The aim of the last step was to gain insight into possible means of extending and improving fuzzy landscape analysis of salinity. The hypothesis is that the use of fuzzy landscape analysis to model salinity will produce both accurate and realistic results, with minimum data requirements (e.g. a digital elevation model).

2. Background

2.1. Factors affecting dryland salinity

Jolly et al. (2002) state that under natural conditions, catchment discharge approximates recharge entering the groundwater system in a dynamic hydrological equilibrium. Due to land use changes, vegetation discharge is no longer in operation in large areas of Australia, resulting in increased recharge. This means that discharge must also gradually increase until the catchment reaches a new dynamic equilibrium, with discharge occurring where the aquifer cannot transmit the additional recharge, i.e. the aquifer capacity is exceeded. The spatial distribution of discharge can be extremely complex and is triggered by a range of factors, including: (i) the aquifer becoming more constricted due to thinning or narrowing (e.g. basement highs); (ii) a groundwater gradient decrease due to changes in topography (e.g. break of slope); (iii) the permeability of the aquifer decreasing (e.g. dykes, faults, thinning of sediments) (Jolly et al., 2002).

Barrett-Lennard and Nulsen (1989) concluded that topography alone is not sufficient to predict the location of saline areas, a finding supported by Clarke et al. (1998a), who also found that regolith depth and the location of cleared areas do not fully explain the location of saline areas. Both works agreed on the importance of geology in influencing the location of saline areas.

Geological barriers such as dykes, faults bedrock highs and perched aquifers intersected by topographic change have been shown to be important features when considering groundwater flow and show a spatial association with salt affected land (Engel et al., 1987; Lewis, 1991; Clarke et al., 1998a; Salama et al., 1993). Likewise, clay saprolite formed above dolerite dykes is generally less permeable than the surrounding regolith (the weathered product of granite and granitic gneiss), acting as linear hydraulic barrier to lateral groundwater flow resulting in the discharge of saline water into the surface soils (Engel et al., 1987).

Faults and fractures modify groundwater flow as they can act as carriers or barriers (or both) of groundwater (Clarke et al., 1998b). Clarke et al. (1998a) showed that the relationship between faults and salinised land is causal, not just spatial, with higher hydraulic conductivity inside the fault zone as the mechanism underlying this relationship. Faults in the Western Australian Wheatbelt have a zone of influence between 2 and 4 km either side of the centre line of the fault, with the risk of salinity increasing upslope from these structures (George, 1998).

2.2. Fuzzy sets and fuzzy modelling

Two main types of logic can be used in spatial data processing: Boolean and fuzzy logic (Fisher, 1996).