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Evaluation of potential irrigation expansion using a spatial fuzzy multi-criteria decision framework

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ABSTRACT

This paper presents a spatial framework which can be used to perform multi-criteria assessments for different purposes. We tested the framework on a case study of evaluating potential expansion for irrigated pasture in the Limestone Coast of South Australia. The core of the framework is the fuzzy linguistic ordered weighted averaging (FLOWA) model which integrates and implements fuzzy quantifiers, Ordered Weighted Averaging (OWA) and Analytical Hierarchy Process (AHP) in the ArcGIS environment. Fifteen criteria were chosen, including groundwater, topography, landscape and soil attributes which significantly affect irrigated landuse. Criterion weights were determined at both objective and attribute levels using the AHP, and several scenarios were derived using the OWA operator for selected values of fuzzy quantifiers. The resultant evaluation map from the weighted linear combination (WLC) approach was then compared with regional present landuse map. Most currently irrigated areas are contained within the area predicted to be suitable for irrigated agriculture. Relatively large additional areas are also predicted to be suitable, suggesting potential expansion, or that factors including total regional water availability and enterprise-specific economics are at play. The framework provides a useful tool with flexibility and efficiency. It enhances the existing AHP and OWA methods in the spatial context, and incorporates the uncertainty mechanism for guiding the multi-criteria decision making. It is particularly valuable given its capability to generate and visualise a wide range of multi-criteria decision scenarios, which can facilitate a better understanding of the spatial patterns of alternative landuse suitability potentials for future regional-scale landuse planning and water resource management.

1. Background

It is well-known that irrigated land is far more productive than rain-fed land. But there is a shortage of irrigable land (and suitable water) in many regions of the world. Agriculture experts expect a continuing growth in irrigated land to meet future food needs (FAO, 2002). If expansion of irrigated areas is to occur then it should be guided by decision support tools that integrate various factors required for an economically productive and environmentally responsible development. Here we present a spatial framework to carry out multi-criteria assessment for this problem and evaluate it in the setting of a current irrigation area in Australia.

Multi-criteria decision making (MCDM) is a useful approach to serve this purpose due to its ability to combine quantitative and qualitative criteria for selection of the proper alternative. Geographic information systems (GIS) are best suited for handling a wide range of criteria data from various sources for a time-efficient and cost-effective analysis. A number of spatial-based multi-criteria evaluation methods have been implemented in a GIS environment (Carver, 1991; Jankowski, 1995; Malczewski, 1999; Chen et al., 2007, 2010; Boroushaki and Malczewski, 2008) for various studies over the last decades. These have covered many areas including water resource management (Tkach and Simonovic, 1997; Wang et al., 2011), landuse and catchment planning (Dai et al., 2001; Chen et al., 2008, 2011; Yu et al., 2011a; Zerger et al., 2011) and land suitability assessment (Pereira and Duckstein, 1993; Bojorquez-Tapia et al., 2001; Joerin et al., 2001; Malczewski, 2004, 2006a; Chen et al., 2009; Yu et al., 2011b). In general, a GIS-based MCDM involves a set of geographically defined basic units (e.g. polygons in vectors, or cells in rasters), and a set of evaluation criteria represented as map layers. The problem is to combine the criterion maps according to the attribute values and decision maker's preferences (based on criteria weights) using a set of decision rules (based on order weights) so as to rank each unit with an overall score (Malczewski, 2006a).

The Analytical Hierarchy Procedure (AHP) is a method (Saaty, 1977, 1980; Saaty and Vargas, 1991) for ranking multi-criteria weights. It calculates the needed weighting factors with the help of a preference matrix where all identified relevant criteria are compared against

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each other with reproducible preference factors. The Ordered Weighted Averaging (OWA) is a procedure to determine order weights of the weighted criteria for multi-criteria aggregation procedures (Yager, 1988, 1996; Rinner and Malczewski, 2002; Malczewski et al., 2003; Makropoulos and Butler, 2005). The nature of OWA depends on its capability to implement different combination of operators by specifying an appropriate set of order weights. Both AHP and OWA have been employed individually or jointly into GIS-based spatial models in the past (Jankowski and Richard, 1994; Jiang and Eastman, 2000; Marinoni, 2004; Boroushaki and Malczewski, 2008). The fusion of AHP and OWA can provide a more powerful MCDM tool for structuring and solving spatial decision problems. However, one of the major drawbacks of the AHP is its inability to address the uncertainty and imprecision of the decision maker's perceptions (Deng, 1999). Yager (1996) also pointed out that the conventional OWA operators have limited applications in situations involving a large set of evaluation criteria. Under a complex spatial decision situation, the decision maker might find it difficult or impossible to provide the precise numerical information on the OWA parameters (Malczewski, 2006a). Yager and Kelman (1999) suggested that the capabilities of the AHP as a comprehensive tool for decision making can be improved by integration of the fuzzy linguistic OWA operators. This calls for an extension of the conventional OWA which should be developed in the context of fuzzy logic theory.

Fuzzy logic has gained importance due to its flexibility in handling imprecise subjective data. Yin et al. (1999) employed fuzzy relation analysis for multi-criteria water resource management in a river basin of US. Raju and Kumar (2005) applied the concepts of fuzzy logic and MCDM to a case study for selecting the best performing irrigation subsystem. Fuzzy logic has emerged as an effective methodology in the field of MCDM with numerous works reported on its integration to MCDM in a spatial context (Banai, 1993; Jiang and Eastman, 2000; Makropoulos et al., 2003; Makropoulos and Butler, 2005; Malczewski and Rinner, 2005). Malczewski (2006a) incorporated the concept of fuzzy (linguistic) quantifier into a GIS-based land suitability analysis via the OWA. By applying or changing a quantifier, the quantifier-guided OWA can generate a wide range of decision strategies or scenarios. The two most widely used conventional decision rules in GIS, the weighted linear combination (WLC) methods and the Boolean overlay operations such as intersection (AND) and union (OR), can be considered as specific cases of an OWA family. These have paved the way to the development of the AHP-OWA operators using fuzzy linguistic quantifiers, and its implementation as a user built extension within the ArcGIS environment, that is, the fuzzy linguistic ordered weighted averaging (FLOWA) model (Boroushaki and Malczewski, 2008) adapted in this study.

The Limestone Coast region has some of the most productive land in South Australia (SA). The irrigation industry, with about 80,000 ha under irrigation and more than 2300 farms, is the largest user of groundwater which is the dominant water resource in this region. According to Paydar et al. (2009), there has been a marked increase in irrigation activity in the region over the last few years. The majority of this irrigation has been established for dairy enterprises, with improved pastures being the main irrigated crop. Based on the regional water balance reported in Paydar et al. (2009), irrigation expansion in the future is likely to rely on a continuing or increased availability of groundwater of suitable quality, in localities of favourable climate and soils. A spatial analysis considering factors which have impacts on the suitability of irrigated lands in the region would assist in future planning of such expansions. In the 1980's and 1990's, with the substantially growing demand for regional land assessment to meet the needs of landuse planning in natural resource management, a program was established by the SA government to prepare a common set of baseline soil landscape data for the agricultural districts of SA (DWLBC, 2007a, 2007b). Soil landscapes were defined as areas of land with similar topographic features, within which there is a limited and/or definable range of soil types. Each of these soil landscapes represents a unit which has a different set of characteristics and therefore variable potential for different landuses or crop types. Soil landscape units were classified with respect to a range of attributes which affect agricultural and horticultural landuse (PIRSA, 2000). By matching the values of these attributes with the requirements of specific crops, the potential of a particular soil landscape unit to sustain a landuse were assessed (SA Government, 2000). This has been a tried and tested way of assessing limitations of land for primary production from paddock level to regional planning scale. However, the results are only useful to identify the factor which is the primary limitation in each mapping unit because the overall classification of potential evaluation for a land was derived essentially based on the most limiting attribute/factor principle. In particular, one of the major limitations of these applications was caused by using a conventional spatial multi-criteria evaluation method which is impractical to weight individual attributes and to evaluate resultant uncertainties.

This study is built on the data basis of the previous soil landscape mapping and applying a novel GIS-based MCDM methodology for the assessment of irrigation expansion. The objective is to develop a spatial framework adapting the FLOWA approach as a key model which integrates fuzzy quantifiers, AHP and OWA into the ArcGIS, to evaluate potential for future expansion of irrigated pasture in the Limestone Coast region of SA.

2. Study area

The area under study is in South East corner of SA and extends from the SA–Victoria border in the east, to the coast in the south and west, covering 21,000 km^2 (Fig. 1). Mount Gambier is the main regional centre and city in the region. The climate of the region is typified by cool wet winters and mild to hot, dry summers. Rainfall increase within the region moving from north to south with annual average rainfall ranges from more than 450 mm to about 800 mm. Evaporation is extremely high during the summer months with the long term mean potential evaporation rate ranging from 1330 mm/year in the north to around 1000 mm/year in the south.

The landscape includes low stony ranges, undulating rises, sand dunes, flat plains and depressions, many of which are swampy, and some saline. There are two main geological components: the older Pinnaroo Block of the north-eastern section and the younger South East Coastal Plain. The SE Coastal Plain consists of a series of old coastal dune ranges and intervening corridor plains with naturally poor drainage that are old lagoonal environments. The old or stranded coastal dune ranges reflect a south-westerly retreating coastline. Overlying coastal sand spreads have affected much of this region, particularly in the north. Land affected by shallow saline groundwater occurs mostly along the coast and in the north-west (Hall et al., 2009). These variations have significant impacts on landuse through their effects on drainage, soil salinity and frost occurrences. Most of the soils in the region are a combination of sand and calcium carbonate, with small areas of loam and clay. Dominant soils include shallow stony sandy loam, deep sand, sand over clay, sandy loam over clay and shallow black clay loam, with cracking clay, red gradational loam, with saline soil and peat (SA Government, 2000). Many soils are underlain at shallow depth by hard to semi-hard calcrete, calcarenite or limestone, and many soils either have sandy topsoils or are sandy throughout. Rich volcanic ash soils occur in the very south (Hall et al., 2009). These variations have implications for landuse because of effects on, for example, inherent fertility and plant available water holding capacity.