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A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge

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A B S T R A C T

This study reports the development of a new spatial multi-criteria decision analysis (SMCDA) software tool for selecting suitable sites for Managed Aquifer Recharge (MAR) systems. The new SMCDA software tool functions based on the combination of existing multi-criteria evaluation methods with modern decision analysis techniques. More specifically, non-compensatory screening, criteria standardization and weighting, and Analytical Hierarchy Process (AHP) have been combined with Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA). This SMCDA tool may be implemented with a wide range of decision maker's preferences. The tool's user-friendly interface helps guide the decision maker through the sequential steps for site selection, those steps namely being constraint mapping, criteria hierarchy, criteria standardization and weighting, and criteria overlay. The tool offers some predetermined default criteria and standard methods to increase the trade-off between ease-of-use and efficiency. Integrated into ArcGIS, the tool has the advantage of using GIS tools for spatial analysis, and herein data may be processed and displayed. The tool is non-site specific, adaptive, and comprehensive, and may be applied to any type of site-selection problem. For demonstrating the robustness of the new tool, a case study was planned and executed at Algarve Region, Portugal. The efficiency of the SMCDA tool in the decision making process for selecting suitable sites for MAR was also demonstrated. Specific aspects of the tool such as built-in default criteria, explicit decision steps, and flexibility in choosing different options were key features, which benefited the study. The new SMCDA tool can be augmented by groundwater flow and transport modeling so as to achieve a more comprehensive approach to the selection process for the best locations of the MAR infiltration basins, as well as the locations of recovery wells and areas of groundwater protection. The new spatial multicriteria analysis tool has already been implemented within the GIS based Gabardine decision support system as an innovative MAR planning tool.

1. Introduction

In the field of Water Resources Planning and Management, managed aquifer recharge (MAR) is becoming an important solution for mitigating water scarcity related problems in arid and semi-arid areas. MAR has been practiced throughout the world for the recovery of groundwater levels, improvement of groundwater quality, storage of surface water in the sub-surface, and as a barrier to salinity intrusion. Depending on the water source, water quality, geology, surface conditions, soils, and hydrogeology, a variety of methods have been developed to recharge groundwater (Bouwer, 2002). The spreading basin technique (infiltration) is widely practiced and is useful in areas with high land availability, highly permeable soil, and where the hydrogeology allows for infiltration to an unconfined aquifer (Ghayoumian et al., 2005). Other MAR techniques employing injection wells require less area but a better quality of source water due to the fact that the water is directly injected into the aquifer without taking advantage of natural attenuation processes within the vadose zone. The interdependency of the water quality,

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MAR location, and technology makes project planning multifaceted and complex.

Many factors need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). Apart from these hydrogeological considerations, other factors such as political and social factors are important in the decision-making process. National and international water policies, natural conservation regulations, environmental impact assessments, and socio-economic considerations make the site selection procedure complex. Complexity increases when MAR project managers are from different disciplinary backgrounds; this may often lead to disagreements concerning which criteria to give more weight in the decision-making process. These conflicts always need to be dealt before the MAR project is implemented. GIS and the traditional Decision Support Systems (DSS) alone do not effectively facilitate the implementation of MAR project parameters, which are equally based on complex decision criteria and spatial information (Jun, 2000). GIS based analysis methods are poor in dealing with uncertainty, risks, and potential conflicts; therefore, there is a large possibility of losing important information, which in turn may lead to a poor decision (Bailey et al., 2003). Multi-Criteria Decision Analysis (MCDA) integrated into GIS (SMCDA) provide adequate solution procedures to this problem because the analysis of potential MAR projects may be done more comprehensively and at a lower cost. Variable project sites, risks, MAR techniques, policies, and limits in geological as well as social, environmental, and political realms can easily be considered by the Spatial Multi-Criteria Decision Analysis (SMCDA) approach (Calijuri et al., 2004).

MCDA is helpful in identifying priorities for a given MAR project (Gomes and Lins, 2002). The integration of MCDA techniques with GIS has considerably advanced the traditional map overlay approaches for site suitability analysis (e.g. Malczewski, 1996; Eastman, 1997). MCDA procedures utilize geographical data, consider the user's preferences, manipulate data, and set preferences according to specified decision rules (Malczewski, 2004). The advantage of integrating GIS with MCDA has been elaborated by many authors (e.g. Malczewski, 1996; Jun, 2000; Gomes and Lins, 2002; Sharifi and Retsios, 2004). According to Malczewski (2004), the two critical considerations for SMCDA are: (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation, and analysis; and (ii) the MCDA capabilities for combining the geographical data and the manager's preference into unidimensional values of alternative decisions. A number of methodologies have already been developed for SMCDA in different fields of science and engineering to select the best alternatives from a set of competing options (e.g. Sharifi et al., 2006; Zucca et al., 2007).

The overlay MCDA plays an important role in many GIS applications. Boolean logic and Weighted Linear Combination (WLC) are the most popular decision rules in GIS (e.g. Eastman, 1997; Malczewski and Rinner, 2005) and both can be generalized within the scope of Ordered Weighted Averaging (OWA) (e.g. Malczewski and Rinner, 2005; Malczewski, 2006). In OWA, a number of decision strategy maps can be generated by changing the ordered weights. Several OWA applications have been implemented already (e.g. Rinner and Malczewski, 2002; Calijuri et al., 2004; Malczewski et al., 2003; Malczewski, 2006). The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is another well-known procedure. This procedure is important for spatial decision problems with a large number of criteria (Eastman et al., 1993). AHP can be used to combine the priorities for all levels of a "criteria tree," including the level representing criteria. In this case, a relatively small number of criteria can be evaluated (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2008). The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. Boroushaki and Malczewski (2008) implemented AHP-OWA operators using fuzzy linguistic quantifiers in the GIS environment, which has been proven to be effective.

An intensive review of the respective literature has indicated that the modern and updated analysis techniques as GIS and MCDA have not been well investigated and compiled in the field of MAR site selection (see the following section for details). In this respect, a structured, non-site specific and flexible decision analysis tool has been developed. In this study, a methodology has been settled up to support the identification of suitable sites by combining modern spatial multi-criteria analysis techniques with decision analysis methods. As consequence, a new tool has been developed to offer the following:

- A comprehensive framework consisting of AHP, WLC, and OWA analysis techniques for spatial multi criteria analysis for MAR site selection.
- A wide range of flexibility and preferences for criteria selection, standardization, and weighting.
- An interactive user interface, which offers the standard techniques and leads the user systematically to complete the site selection process.

This paper includes a review on MAR site selection techniques and may be read at any time as needed for reference purposes (section 2). Section 3 is a description of SMCDA for site suitability analysis and also information on how AHP, suitability mapping, and weighting are involved in the analysis. A brief description on possible sensitivity analysis is done the presentation of a *GIS Based Site Suitability Analysis Tool in* Section 4. This section together with Section 3 provides distinctive information to MAR site selection. The two sections together are considered to embody the core objective of this paper, which is to explain the development and functionality of a new SMCDA tool for MAR site selection. Section 5 presents the concepts described in Sections 3 and 4 as applied in the field. The case study presented in Section 5 refers to a MAR site selection. It has been developed on the Querenca-Silves aquifer system in Portugal. Section 6 provides a summary of conclusions and recommendations in the scope of future applications and further developments.

2. The state-of-the-art: MAR site selection techniques

Only very few studies exist which focus on site selection procedures for Managed Aquifer Recharge (MAR). Respectively, the following three sections differentiate data types (section 2.1), present data processing via GIS (section 2.2), and give reference to the steps involved in site suitability analysis methods (section 2.3) for example, screening of sites, criteria hierarchy and standardization, criteria weighting, overlay, and sensitivity analysis. The three parts of this chapter are intended to serve as a reference for the basic methods which have been integrated into the SMCDA tool for site suitability analysis of MAR.

2.1. Data types

For MAR site selection, different types of data are required. Considerations for data type selection derive from data availability and the objective of the analysis as dependent on each data type. Geological maps, geomorphologic maps, lineament maps (e.g. Saraf and Choudhury, 1998; Jothiprakash et al., 2003; Reddy and Pratap, 2006), slope, infiltration rate (e.g. Ghayoumian et al., 2005; Werz