
Integrating multicriteria analysis and geographic information systems: the ordered weighted averaging (OWA) approach

Jacek Malczewski

Department of Geography, University of Western Ontario,
London, Ont. N6A 5C2, Canada
E-mail: jmalczew@uwo.ca

Abstract: The ordered weighted averaging (OWA) is a family of multicriteria combination (aggregation) procedures. The generality of OWA is related to its capability to implement different combination operators by selecting appropriate order weights. By specifying suitable order weights it is possible to change the form of aggregation from the minimum-type combination through all intermediate types including the conventional weighted linear combination, to the maximum-type combination. The paper focuses on the OWA method and an approach for integrating geographic information system (GIS) and OWA. It also discusses an application of the GIS-OWA system to a real-world environmental management problem that involves developing watershed management strategies in the Cedar Creek watershed in Ontario, Canada.

Keywords: multicriteria analysis; ordered weighted averaging; geographic information systems; watershed management.

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Biographical notes: Jacek Malczewski is Associate Professor of Geography at the University of Western Ontario, London, Canada. He is a graduate of Polish Academy of Sciences (PhD) and Jagiellonian University, Poland (MSc). His research interests include multicriteria decision analysis and geographic information systems. He has authored a book on *GIS and Multicriteria Decision Analysis*.

1 Introduction

In the most general term, GIS-based multicriteria decision analysis involves the utilisation of geographical data, the decision maker's preferences and the combination (or aggregation) of the data and preferences according to specified decision rules. Over the last decade or so, a number of multicriteria evaluation methods (decision rules) have been implemented in the GIS environment including weighted linear combination (WLC) (Janssen and Rietveld, 1990; Jankowski, 1995; Eastman, 1997), ideal point methods (Carver, 1991; Pereira and Duckstein, 1993), concordance analysis (Carver, 1991; Jankowski and Richard, 1994), and analytic hierarchy process (Banai, 1993;

Jankowski, 1995). Among these procedures, the WLC (compensatory decision rules) and Boolean overlay operations (noncompensatory decision rules), such as intersection (AND) and union (OR), are considered the most straightforward and the most often employed. They have also traditionally dominated the use of GIS as decision support tools. Recent developments in multicriteria decision analysis suggest the two classes of decision rules can be considered as specific cases of a family of ordered weighted averaging (OWA).

OWA has been developed as a generalisation of multicriteria combination (Yager, 1988). Over the last decade or so there have been a number of attempts to integrate the OWA concept as a core of GIS-multicriteria decision analysis. The OWA concept has been extended to the GIS applications by Eastman (1997) as a part of decision support module in GIS-Idrisi. Subsequently, Jiang and Eastman (2000) demonstrate the utility of the GIS-OWA for land use/suitability problems. The implementation of the OWA concept in Idrisi resulted in several applications of OWA to environmental and urban planning problems (see Asproth et al., 1999; Mendes and Motizuki, 2001; Rasmussen et al., 2001; Araújo and Macedo, 2002). It also stimulated the implementation of the OWA procedures in the ArcView environment (Malczewski et al., 2003; Makropoulos et al., 2003). In addition, an effort has been made to implement GIS-OWA as a web-enabled system (Rinner and Malczewski, 2002).

The critical aspect of integrating the GIS and OWA capabilities is the way in which the order weights are obtained. For example, the Idrisi-OWA procedure does not provide a user (decision maker) with a method for obtaining the order weights (Eastman, 1997; Jiang and Eastman, 2000). The procedure assumes that the decision maker can ‘intuitively’ search and identify the order weights based on the degree of ANDness (or ORness) and trade-off between criteria (see also Asproth et al., 1999; Mendes and Motizuki, 2001; Rasmussen et al., 2001). To this end, it is important to note that for a given value of ANDness (or ORness) one can obtain a large number of different sets of order weights and associated trade-offs. Also, for a given degree of trade-off one can generate a number of different sets of order weights and associated degrees of ANDness (or ORness) (Yager, 1988; O’Hagan, 1990). Consequently, several authors proposed methods for generating the optimal order weights (Malczewski et al., 2003; Makropoulos et al., 2003; Rinner and Malczewski, 2002). The methods are based on the principles of maximum dispersion (entropy) or the maximum trade-off. These approaches are referred to as the parameterised-OWA methods.

This paper focuses on an implementation of the parameterised-OWA in the GIS environment. Section 2 provides a formal definition of the parameterised-OWA concept. Section 3 describes an approach for integrating OWA and GIS (ArcView GIS 3.2). Section 4 discusses the application of the GIS-OWA system to a real-world environmental management problem that involves developing watershed management strategies in the Cedar Creek watershed in Ontario, Canada.

2 The parameterised-OWA approach

For a given set of n criterion (attribute) maps, OWA is defined as a map combination operator that associates with an i th location (object) a set of order weights $\mathbf{v} = v_1, v_2, \dots, v_n$ ($v_j \in [0,1], j = 1, 2, \dots, n$, and $\sum_{j=1}^n v_j = 1$) and a set of criterion weights $\mathbf{w} = w_1,$

w_2, \dots, w_n ($w_j \in [0,1]$, and $\sum_{j=1}^n w_j = 1$). Given the attribute values $a_{i1}, a_{i2}, \dots, a_{in}$ at the i th location:

$$\text{OWA}_i = \sum_{j=1}^n u_j z_{ij}, \quad u_j = \frac{v_j w_{j^{(*)}}}{\sum_{j=1}^n v_j w_{j^{(*)}}}, \quad (1)$$

where $z_{i1} \geq z_{i2} \geq \dots \geq z_{in}$ is the sequence obtained by reordering the attribute values $a_{i1}, a_{i2}, \dots, a_{in}$; and $w_{j^{(*)}}$ is the reordered j th criterion weight, w_j . The criterion weights are reordered according to $z_{i1} \geq z_{i2} \geq \dots \geq z_{in}$. It is important to note the difference between the two types of weights (the criterion weights and the order weights). The criterion weights are assigned to the evaluation criteria to indicate the trade-offs between criteria. All locations on the j th criterion map are assigned the same weight of w_j . The order weights are associated with the criterion values on the location-by-location (object-by-object) basis. They are assigned to the i th location's attribute value in decreasing order without considering from which criterion map the value comes.

The generality of OWA is related to its capability to implement a wide range of combination operators by selecting appropriate order weights (Yager, 1988). The family of OWA operators includes the most often used GIS-based map combination procedures: the weighted linear combination and Boolean overlay operations, such as intersection (AND) and union (OR) (Yager, 1988; Jiang and Eastman, 2000). The actual type of the OWA operator depends on the form of the order weights. Several methods for determining the weights have been suggested in the literature (for an overview see Grabisch et al., 1998). Here, we will focus on the maximum entropy approach (O'Hagan, 1990). This approach makes use of the measure of ORness and the measure of dispersion. The measure of ORness is defined as (Yager, 1988):

$$\text{ORness} = \alpha = \sum_{j=1}^n \frac{n-j}{n-1} v_j \quad (2)$$

The α value ranges from 0 to 1. It measures the degree to which an OWA operator is similar to the logical OR (or the MAX operator) in terms of its combination behaviour. The measure can be interpreted in the context of well-established behavioural theory of decision-making (March and Shapira, 1987; Bodily, 1985). According to the theory, an essential component of any decision-making process is the attitude of the decision maker (individual or organisation) towards risk. An individual with low risk-taking propensity will typically weigh negative outcomes more highly and, conversely, an individual with high risk-taking propensity is more likely to weigh positive outcomes more highly. Risk attitudes can be represented on a continuum from risk aversion to risk seeking (Bodily, 1985). Accordingly, ORness can be recognised as a measure of the degree of the decision-maker's optimism (Yager, 1988). The values of ORness in the range from 0.5 to 1 represent optimistic decision strategies, while the values less than 0.5 represent pessimism decision strategies. If $\text{ORness} = 0.5$, then a decision maker is indifferent towards risk or risk neutral. Thus, OWA can accommodate varying degrees of optimism (and pessimism) on the part of the decision maker (Yager, 1988; Jiang and Eastman, 2000).

Alternatively, OWA can be characterised by the measure of dispersion. Using the Shannon's measure of entropy, the normalised dispersion is defined as follows:

$$\omega = -\sum_{j=1}^n \frac{v_j \ln v_j}{\ln n} \quad (3)$$

The values of the measure range from 0.0 to 1.0. The greater the equality among the weights, the greater is the dispersion. The measure can be interpreted as the degree to which the OWA operators use the information contained in the n criterion maps. The more dispersed the order weights, the more information contained in the maps is being used in the process of combining the criterion maps.

O'Hagan (1990) suggests that the approach for determining the order weights should be related to the degree of ORness and the measure of dispersion (entropy). Accordingly, the set of order weights is obtained by solving the following nonlinear mathematical programming problem:

$$\text{maximise } \omega, \quad (4)$$

$$\text{subject to: } \sum_{j=1}^n \frac{n-j}{n-1} v_j = \alpha, \quad \sum_{j=1}^n v_j = 1, \quad 0 \leq v_j \leq 1, \quad \text{for } j = 1, 2, \dots, n. \quad (5)$$

A solution to the problems (4)–(5) determines the maximum degree of dispersion (and trade-off) for a given degree of ORness (the α parameter).

3 The GIS-OWA module

Many researchers in information sciences recognise that the multicriteria decision analysis is at the core of decision support systems (DSS) (Keen, 1987; Angehrn, 1992). Indeed, the implicit or explicit assumption behind DSS concept is that the system offers support for multicriteria decision making (Angehrn, 1992; Javalgi and Jain, 1988; Dyer and Forman, 1991). In the context of GIS-based multicriteria analysis, DSS integrates the GIS capabilities and the multicriteria decision techniques (Malczewski, 1999). A number of strategies for coupling (integrating) GIS and spatial modelling (multicriteria modelling) have been suggested (Goodchild et al., 1992; Aselin, 2000). One can distinguish two major coupling strategies for linking GIS and multicriteria analysis: loose coupling and tight (or close) coupling (Jankowski, 1995; Malczewski, 1999). In the loose coupling approach, two systems (GIS and multicriteria modelling system) exchange files such that a system uses data from the other system as the input data. A tight coupling strategy is based on a single data or model manager and a common user interface. Thus, the two systems share not only the communication files but also common user-interface. There is no clear dividing line between the two strategies. Indeed, the distinction between the loose and tight approaches has recently become less relevant (Aselin, 2000). Many implementations of the link between GIS and spatial analysis models combine the two approaches. The GIS-OWA module is an example of a strategy which combines the loose and tight coupling approaches.

The GIS-OWA module has been designed as a core of GIS-multicriteria decision analysis (GIS-MCDA) support system in the ArcView GIS 3.2 software from the Environmental Systems Research Institute, Inc. (see Figures 1 and 2). ArcView and its extensions (such as spatial analysis) provide GIS capabilities of data input, store, management, manipulation and analysis, and output (see Ormsby and Alvi, 1999).

The GIS capabilities of ArcView are used for generating criterion maps and for identifying the set of feasible solutions (e.g. a set of all locations satisfying a given set of constraints). The criterion maps may represent qualitative (e.g. land use maps) and/or quantitative (e.g. proximity to wetlands). Once the criterion maps have been generated they can be processed by the GIS-OWA module. The module consists of three components: *standardise* (for criterion map standardisation), *weight* (for assigning criterion weights), and *aggregate* (for combining standardised weighted criterion maps using the OWA operators). These three components have been developed into dynamic link libraries (DLLs) by using Visual Basic and the DLLs have been linked into the macro language of ArcView. Several menus were created and grouped in three components (standardise, weight, aggregate) associated to the GUI controls (see Figure 2). This interface allowed the user to input data (preferences), run the multicriteria routines, and shows the results as maps display alternative decision strategies. The functions available in the three components are outlined below (for a detail discussion of the multicriteria analysis methods see Malczewski, 1999).

Figure 1 The structure of the GIS-OWA module

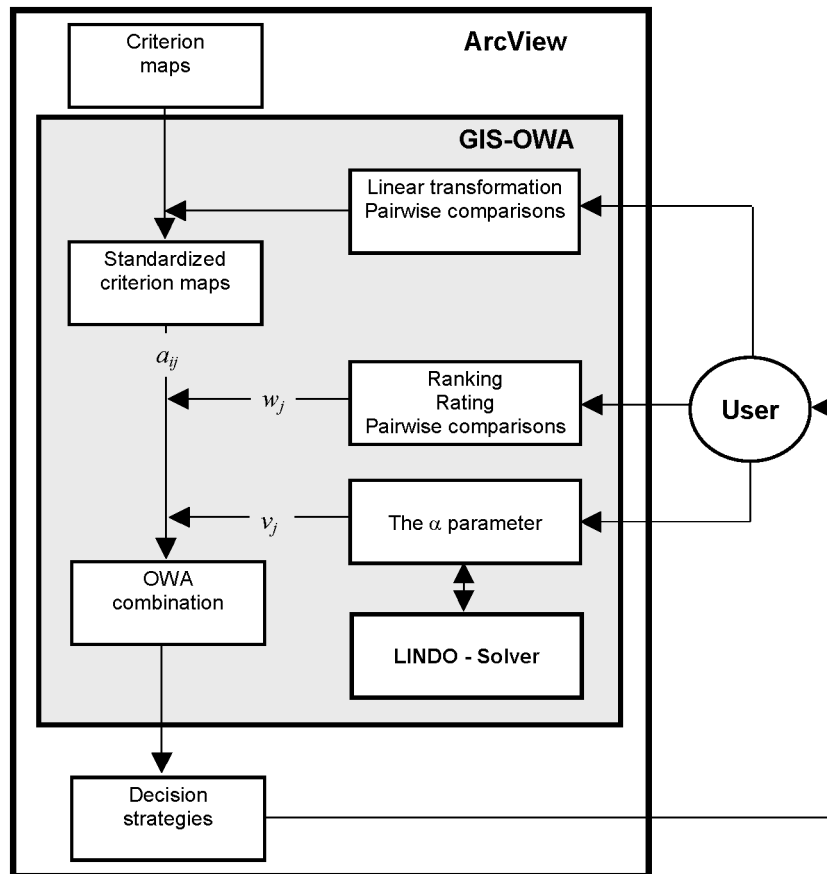
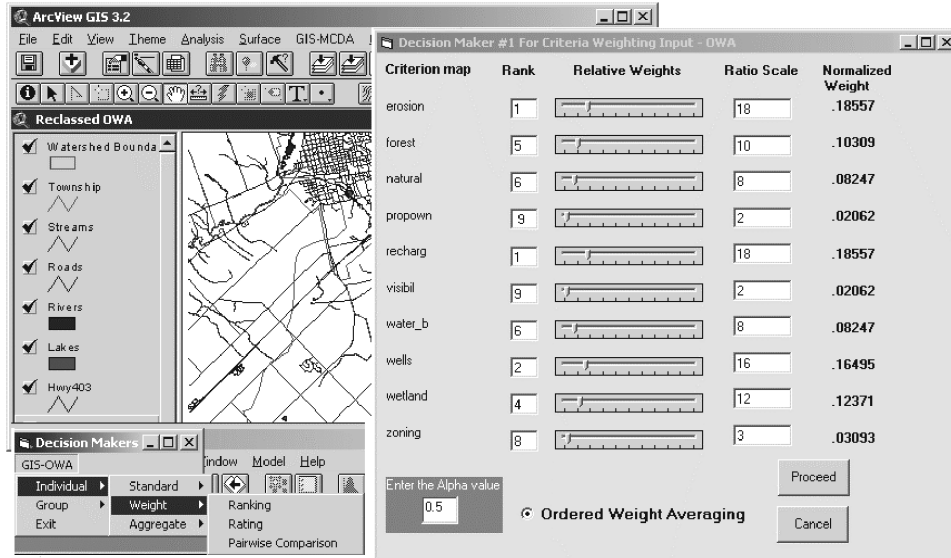


Figure 2 The GIS-OWA interface in the GIS-MCDM support in ArcView GIS 3.2

The GIS-OWA approach requires that the criterion maps be represented in the form of standardised criterion maps. The criterion maps can contain data measured on the qualitative and/or quantitative scales. Accordingly the standardised component of GIS-OWA provides the *linear transformation* and *pairwise comparison* routines for standardising quantitative and qualitative criterion maps, respectively. The linear transformation is used to convert the row data to standardised scores ranging from 0.0 to 1.0 (Malczewski, 1999). The pairwise comparison method is based on the analytic hierarchy process (AHP) (Saaty, 1980). The GIS-OWA pairwise comparison routine takes as an input the pairwise comparisons and produces the standardised criterion map as an output.

The weight component of GIS-OWA includes three methods for assigning the weights to the criterion maps: the *ranking*, *rating* and *pairwise comparison* methods (for an overview see Malczewski, 1999). Irrespective of the method, the resulting criterion weights must be ratio scaled and the weights should represent the rate at which the decision-maker is willing to trade-off one criterion for another. Given the criterion weights, w_j , the GIS-OWA combines the weights and criterion maps. The resulting standardised weighted criterion maps are the input data to the OWA combination procedure.

The OWA combination procedure requires the user to specify the MAXness (ORness) parameter, α (see Section 2). The parameter is the input data to the Solver – LINDO system (commercial software from LINDO Systems Inc., (1994)). The loose coupling approach was applied to link the Solver with ArcView/GIS-OWA. LINDO solves the mathematical programming problem (4)–(5) and it provides the OWA combination routine with a set of optimal order weights corresponding to the specified value of α . The user can communicate with LINDO via GUI by entering the value of the parameter α . The output (a vector of order weights) from LINDO is imported to the GIS-OWA as an ASCII file.

Given the order weights, v_j , the set of criterion weights, w_j , and the standardised criterion maps, a_{ij} , GIS-OWA combines these inputs into an overall value assigned to each location on the output map according to the OWA algorithm (1) (see Figure 1). The output map represents a decision strategy associated with a particular value of α . The procedure is interactive as depicted by the feedback loops in Figure 1. There are three feedback loops connecting the decision strategies to the criterion standardisation, weighting, and the α parameter component. The connection between the decision strategy and the α parameter is of critical importance for the functionality of GIS-OWA. By changing the parameter the user can develop a wide range of alternative decision strategies ranging from a pessimistic strategy (for $\alpha=0$) to an optimistic strategy (for $\alpha=1$).

4 Developing management strategies for rehabilitation and enhancement projects

The GIS-OWA system has been used for developing environmental management strategy in the Cedar Creek watershed, Ontario, Canada (Malczewski et al., 2003; UTRCA, 1998). The overall goal of the management strategy is to evaluate and prioritise areas in the Cedar Creek watershed for rehabilitation and enhancement projects. The woodstock environmental advisory committee (WEAC) and the Upper Thames River conservation authority (UTRCA, 1998) initiated the process for developing the management strategy. At the same time, the Cedar Creek watershed technical subcommittee was established to supervise the process (the subcommittee is referred to as the decision maker). It identified four main objectives of the watershed management: to increase the amount of natural vegetation cover, to improve the overall quality and biodiversity of natural areas, to protect groundwater, and to improve the health of watercourses (UTRCA, 1998). These objectives are operationalised in terms of a set of evaluation criteria (or attributes) of the potential project sites in the watershed. The criteria reflect opinions and concerns raised by the community at open houses, community days and public meetings. The set of criteria includes:

- protection of groundwater recharge areas
- distance to city well heads
- erosion-prone area protection
- wetland protection
- forest interior protection
- proximity to surface water
- proximity to natural areas
- land use protection
- protection of property ownership
- visibility (the criterion maps were provided by the UTRCA, Ontario Ministry of Natural Resources and Oxford County).

Each criterion map displays land suitability measured on the ordinal scale; that is, parcels of land were assigned value of *high*, *medium*, or *low suitability* depending of land attributes. The maps are the input data to the GIS-OWA-based decision-making procedure. Given the criterion maps the problem is to combine the maps so that one can identify the ‘best’ sites for rehabilitation and enhancement projects. The combination procedure follows the conventional scheme for GIS-based multicriteria decision analysis (Jankowski, 1995; Eastman, 1997; Malczewski, 1999). It involves three main steps: standardising criterion map, identifying the criterion weights, and combining the weights and the standardised criterion maps by means of the OWA operators (these steps correspond to the three main components of the GIS-OWA module, see Section 3).

4.1 *Standardising the criterion maps*

Since the criterion maps contain qualitative data, they are standardised using the pairwise comparison method (Saaty, 1980). In this study the pairwise comparisons were done by the technical subcommittee. The standardised criterion maps were automatically generated once the pairwise comparison matrix was entered in the GIS-OWA module. An example of the pairwise comparisons matrix and resulting standardised values for the groundwater recharge criterion map is given in Table 1. Accordingly, the ordinal values (high, medium, and low) on the criterion map were replaced by the standardised scores of 0.556, 0.333, and 0.111, respectively. The remaining criterion maps were standardised in a similar way.

Table 1 The pairwise comparison matrix and the standardised values for the groundwater recharge criterion map

<i>Categories</i>	<i>High</i>	<i>Medium</i>	<i>Low</i>	<i>Standardised value</i>
High	1.000	1.667	5.000	0.556
Medium	0.600	1.000	3.000	0.333
Low	0.200	0.333	1.000	0.111
Sum				1.000

4.2 *Assessing the criteria weights*

The criterion weights have been derived using the pairwise comparison method. This approach required the technical subcommittee to provide its best judgment regarding the trade-offs it was willing to make among the evaluation criteria. After debate and careful analysis of the set of evaluation criteria, the subcommittee made all the pairwise comparisons for the set of the ten criteria. The criterion weights are automatically calculated once the pairwise comparison matrix is entered in the GIS-OWA module. In addition, the module computes the consistency ratio (CR) associated with the pairwise comparison matrix (see Saaty, 1980). After a few iterations and adjustments of the values in the pairwise comparison matrix, the subcommittee was able to achieve a satisfactory level of consistency; that is, CR was less than 0.1. Once a satisfactory level of CR is achieved the GIS-OWA module calculates the criterion weights based on the pairwise comparison matrix. Table 2 shows the resulting criterion weights.

Table 2 The criterion weights

Criterion weights	Evaluation criteria									
	Ground-water recharge	City well heads	Erosion	Wetlands	Forest interior	Proximity to water	Proximity to natural areas	Land use	Property ownership	Visibility
	0.180	0.180	0.180	0.120	0.100	0.080	0.080	0.030	0.025	0.025

4.3 The OWA combination

The aim of the OWA combination procedure is to identify and prioritise areas in the Cedar Creek watershed for rehabilitation and enhancement projects. The analysis is focused on developing various decision strategies in the context of the decision maker's degree of optimism. This can be achieved by varying the ORness or α parameter using the GIS-OWA module (see Section 2). The α parameter guides the user (the technical subcommittee) along the continuum ranging from the pessimistic to optimistic decision strategies. Given the values of α the optimal order weights are automatically determined by GIS-OWA. Theoretically, one can obtain an infinite number of alternative decision strategies by continuously varying the parameter α . Table 3 shows a selection of the α values and associated optimal order weights (the weights identified by solving the program (4)–(5)).

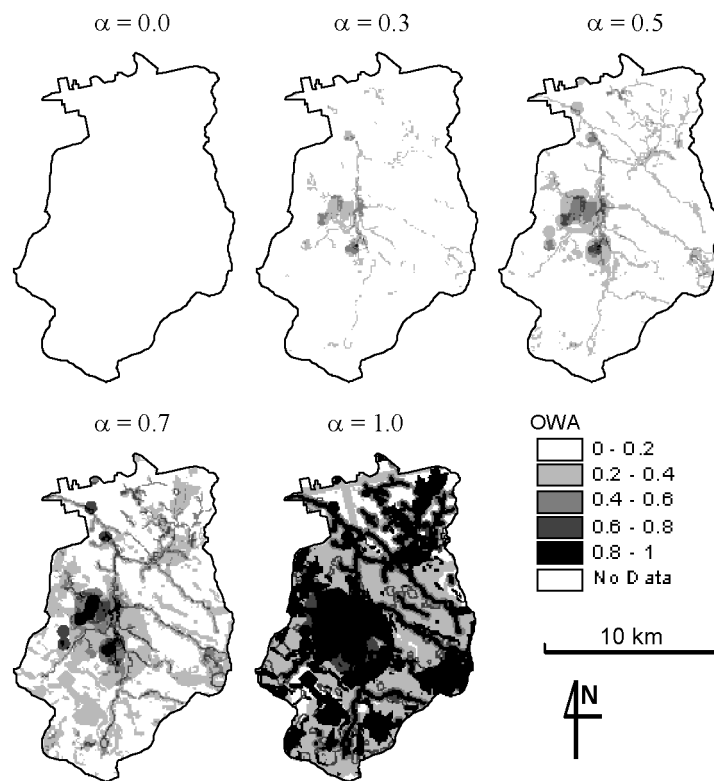
Table 3 The order weights for selected values of the parameter α

α	0.0	0.1	0.3	0.5	0.7	0.9	1.0
<i>Order weights</i>							
v_1	0.000	0.001	0.027	0.100	0.234	0.525	1.000
v_2	0.000	0.001	0.035	0.100	0.184	0.250	0.000
v_3	0.000	0.003	0.044	0.100	0.145	0.119	0.000
v_4	0.000	0.006	0.056	0.100	0.114	0.056	0.000
v_5	0.000	0.013	0.071	0.100	0.090	0.027	0.000
v_6	0.000	0.027	0.090	0.100	0.071	0.013	0.000
v_7	0.000	0.056	0.114	0.100	0.056	0.006	0.000
v_8	0.000	0.119	0.145	0.100	0.044	0.003	0.000
v_9	0.000	0.250	0.184	0.100	0.035	0.001	0.000
v_{10}	1.000	0.525	0.234	0.100	0.027	0.001	0.000
<i>Dispersion</i>	0.000	0.571	0.911	1.000	0.911	0.571	0.000

Figure 3 shows five decision strategies. Each strategy is associated with a given value of α and the measure of dispersion (or trade-off) between evaluation criteria. The strategy associated with $\alpha=0$ is referred to as the pessimistic strategy. Interpreting the strategy from probabilistic perspective it is a situation in which a probability of 1 is assigned to the worst case scenario (the lowest value is assigned to each location). Also, this strategy is characterised by a dispersion of 0. This implies no trade-off between evaluation

criteria. The map representing this strategy indicates that each location within the watershed has been assigned a value of 0 (there is at least one criterion value of 0 at each location). This means that under the extreme pessimistic strategy no action should be taken. Increasing the value of α from 0.0 to 0.5 corresponds to the increasing the degree of optimism as well as the increasing trade-off between evaluation criteria. This implies that gradually higher and higher probabilities (ordered weights) are assigned to the higher-ranking criterion values at a given location at the expense of assigning smaller probabilities to the lower-ranking criterion values for that location. As a result, the size of the areas that could be recommended for rehabilitation and enhancement gets gradually larger (Figure 3).

Figure 3 Alternative decision strategies for the Cedar Creek watershed management



The strategy for $\alpha = 0.5$ represents a decision maker characterised by neutral attitudes. It is also a strategy resulting in a full trade-off between criteria. Assigning an order weight of 0.1 to each criterion value at a given location implies a situation in which an equal probability is associated with all possible outcomes at that location.

Increasing the value of α from 0.5 to 1.0 represents increasing degree of optimism and decreasing level of the trade-off among criteria. The strategy for $\alpha = 1.0$ represents an extremely optimistic strategy. This strategy assigns a probability (order weight) of 1.0 to the highest value at each location in the watershed. In other words, the decision maker is characterised by optimistic attitudes represented by the best possible outcome (that is, the highest possible value is selected at each location). Under this strategy, most

of the watershed area should be considered for rehabilitation and enhancement (see Figure 3). However, an implementation of the extremely optimistic strategy would be beyond the limited resources available for rehabilitation and enhancement projects. Consequently, the strategy selected for implementation was associated with the parameter $\alpha = 0.7$. It is a moderately optimistic strategy. This strategy is also characterised by a moderate trade-off between criteria. It recommends that the rehabilitation and enhancement projects should be undertaken at locations of the existing natural areas. The areas of highest priorities are situated near Cedar Creek Swamp and around woodlots and wetlands. Also, sections along watercourses are identified as high or medium priority.

5 Conclusions

This paper focused on an implementation of the parameterised-OWA approach as a platform for integrating multicriteria decision analysis and GIS. The approach has been implemented as a core of GIS-MCDA support system in the ArcView environment. The system has a range of multicriteria evaluation capabilities including criterion standardisation, criterion weighting and the OWA procedures. The paper also presented an application of GIS-OWA to a real-world environmental management problem that involved developing management strategies in the Cedar Creek watershed in Ontario, Canada. It has been shown that the OWA concept is an extension and generalisation of the conventional GIS operations such as the weighted linear combination and the Boolean overlay analysis. This was achieved by incorporating the α parameter into the GIS-OWA procedure.

The fact that the OWA weights are obtained by specifying a single parameter α is one of the major advantages of the proposed approaches. This property of the parameterised-OWA provides an effective way for incorporating the decision maker's attitudes towards risk into the GIS-based multicriteria evaluation procedures. The decision maker has the flexibility of modifying the parameter to reflect his/her degree of optimism via the α parameter. The parameterised-OWA approach provides a mechanism for guiding the decision maker through the multicriteria combination procedures. It allows decision makers (individuals or organisations) to explore different decision strategies (solutions) based on their attitudes towards risk.

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