Addressing Accessibility Challenges of GIS-based Multiple-Criteria Decision Analysis for Integrated Land Management: Case study in the Humber region of Newfoundland and Labrador, Canada

by

© Randal Greene

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Abstract

Land management is an important and complex activity requiring decision makers to simultaneously consider diverse values. Strategic frameworks such as integrated land management (ILM) and ecosystem-based management (EBM) provide guiding principles, but do not dictate specific techniques for integrating multiple values when analysing land-management decisions. Multiple-criteria decision analysis (MCDA) is an established set of methods for supporting decisions by taking into account many perspectives. MCDA has historically been combined with geographic information systems (GIS) and can provide scenario analyses for ILM and EBM. However, the use of GIS-based MCDA by land-management decision makers is limited by accessibility challenges, where accessibility refers to the ease of understanding and use of available methods and tools. The goal of this research is to support land-management decision makers and analysts in simultaneously considering multiple values by improving the accessibility of GIS-based MCDA. The objectives are to (1) identify specific accessibility challenges for land managers in using GIS-based MCDA to support ILM and EBM, (2) design a generic approach to GIS-based MCDA that addresses some of the accessibility challenges identified, (3) implement the approach by developing GIS-based MCDA custom software, and (4) validate the approach through an applied land-management case study. The primary accessibility challenge identified is that GIS-based MCDA tools are most often focused on the evaluation phase of decision making, which assumes that the problem is already well understood and structured. The approach and GIS software developed in this thesis helps address this challenge by providing exploration tools integrated with evaluation tools and supplemented with geovisualisation capabilities. Case-study participant feedback revealed that exploration facilitates understanding and structuring of land-management decision problems in preparation for evaluation.

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The staff, faculty, and students of the Department of Geography also played important roles. Administrative support was always provided in an efficient and cheerful manner. Professors Arn Keeling, Alvin Simms, Alistair Bath, and Kelly Vodden generously provided both course-based instruction and specific feedback on various aspects of my thesis project. My fellow students, especially those in the Marine Geomatics Research Lab, were consistent sources of encouragement, feedback, and good humour. Finally, I would be remiss if I didn’t mention Bill and Jack, who always took the fall when called on.

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List of Abbreviations and Symbols

AHP – Analytic Hierarchy Process

AFC – Atlantic Forestry Centre

CBPPL – Corner Brook Pulp and Paper Limited

EBM – Ecosystem-Based Management

FAO – Food and Agriculture Organization

FMD – Forest Management District

GA – Genetic Algorithms

GIS – Geographic Information Systems

GISciences – Geographic Information Sciences

ILM – Integrated Land Management

MADM – Multiple-Attribute Decision Making

MCDA – Multiple-Criteria Decision Analysis

MCDAS – Multiple-Criteria Decision Analysis System

MCDM – Multiple-Criteria Decision Making

MCE – Multiple-Criteria Evaluation

MODM – Multiple-Objective Decision Making

MOLA – Multiple-Objective Land Allocation

NRCan – Natural Resources Canada

OWA – Ordered Weighted Averaging

PGIS – Participatory Geographic Information Systems

SA – Simulated Annealing

SDSS – Spatial Decision-Support System

SoftOR – Soft Operations Research

SOLAP – Spatial On-Line Analytical Processing

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution

UCD – User-Centred Design

UNEP – United Nations Environment Programme

WLC – Weighted Linear Combination

Chapter 1 Introduction

1.1 Context and problem

Land management is inherent in the policies and activities of many organisations and affects many other interest groups. Municipal and regional planning authorities, for instance, are concerned with land-use zoning and enforcement, real estate development, property management, water supply, and sewage handling, and all constituent residents and businesses have a vested interest. In forest management, there are a large number of perspectives that must be considered, representing interests from recreation like hiking, hunting, and snowmobiling, to industrial development such as large-scale agriculture and energy generation, to pure conservation (Dolter, pers. comm., 2009; Hammond, 2009). Land management is thus an important and complex activity that requires decision makers and analysts to simultaneously consider diverse values.

Integrated land management (ILM) is a strategic concept used that seeks to "systematically and practically assist in managing trade-offs and identifying win-win situations among environmental, economic and social conditions" in land-use planning and decisions (Bizikova, 2009). ILM appears primarily in policy and international-development contexts (Environment Canada and United Nations Commission on Sustainable Development, 2000; Russell, 2008), not in academic research. With regards to achieving ILM, ecosystem-based management (EBM) is a term that appears both in academic and practical contexts. It is a set of principles and guidelines that originally covered planning and management of only biotic phenomenon, but has expanded to take into account social, economic, and ecological factors in a planning process (Kappel, et al., 2006). EBM seeks to manage human activities with the view that human systems and natural systems co-evolve, and in particular focuses on how social and economic activities are embedded in and affect ecosystems (Layzer, 2008; Hammond, 2009).

Methods for analysing specific local and regional decisions to ensure they are consistent with strategic principles are required. Given that there are often high stakes and that simultaneously considering many perspectives and factors is cognitively complex, the methods need to be transparent and systematic. Whereas EBM has been identified as a relevant framework for analysing land management decisions (Luther et al., 2007; Hearn et al., 2008; Eddy, 2010), it requires specific tools and techniques for performing integrated analysis.

Multiple-criteria decision analysis (MCDA) is a suite of methodologies that can help decision makers and analysts combine multiple factors, and it typically results in a rating or ranking of alternatives (Belton and Stewart, 2002). MCDA combined with geographic information system (GIS) offers a set of methods that can provide transparent and systematic decision support for an integrated approach to land management (Joerin et al., 2001; Eastman, 2005). Fig. 1.1 shows one view of how ILM, EBM, GIS, and MCDA relate to each other. This project is situated in the area of overlap of these fields.

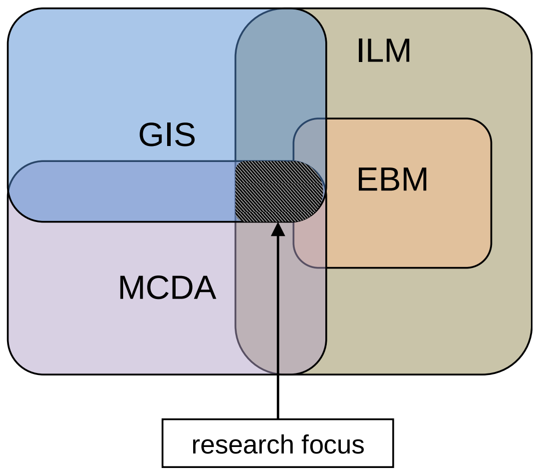

Fig. 1.1. Research focus shown with a hatch pattern at the intersection of geographic information systems (GIS), multiple-criteria decision analysis (MCDA), and integrated land management (ILM). Ecosystem-based management (EBM) is one set of principles for undertaking ILM.

MCDA methods have been combined with GIS in various ways over the last 20 years (Carver, 1991; Malczewski, 2006a) and applied to many different land management problems. However, accessibility of GIS-based MCDA, defined here as the ease of understanding and use of available methods and tools, is limited for land managers without sufficient experience in using GIS or MCDA tools and techniques. Some of the accessibility challenges of existing GIS-based MCDA approaches are due to the breadth and complexity of the diverse fields of information used in a given analysis, to the limited transparency and usability of tools and techniques available, and to the lack of support for and focus on first defining the problem through an exploration phase of decision analysis. Exploration involves problem understanding, refinement, and structuring, particularly specifying the decision objective(s) and the criteria for evaluating them.

1.2 Goal and objectives

The goal of this research is to support land-management decision makers and analysts in simultaneously considering multiple values by improving the accessibility of GIS-based MCDA. In helping to attain this goal, specific research objectives of this thesis include the following:

1. Identify specific accessibility challenges for land managers in using GIS-based MCDA to support ILM and EBM.
2. Design a generic approach to GIS-based MCDA that addresses some of the accessibility challenges identified.
3. Implement the approach by developing custom GIS-based MCDA software.
4. Validate the approach through an applied land-management case study.

1.3 Questions and hypothesis

The research problem and goal lead to a number of research questions:

- What are some of the accessibility challenges of GIS-based MCDA for land management?
- How can the process of selecting appropriate GIS-based MCDA methods for a particular land-management problem be guided?
- Which usability enhancements from other areas of GIS research might be incorporated in a customised software system to improve the accessibility of GIS-based MCDA?
- How can a generic approach that addresses accessibility challenges be validated?

The research hypothesis is that the proposed approach will improve the ability of land-management decision makers and analysts to simultaneously consider diverse values.

1.4 Methods

Fig. 1.2 summarises the research methodology by organising the methods and fields of research into groups and depicting them along the project timeline. The methods were employed in parallel and influenced each other through feedback loops.

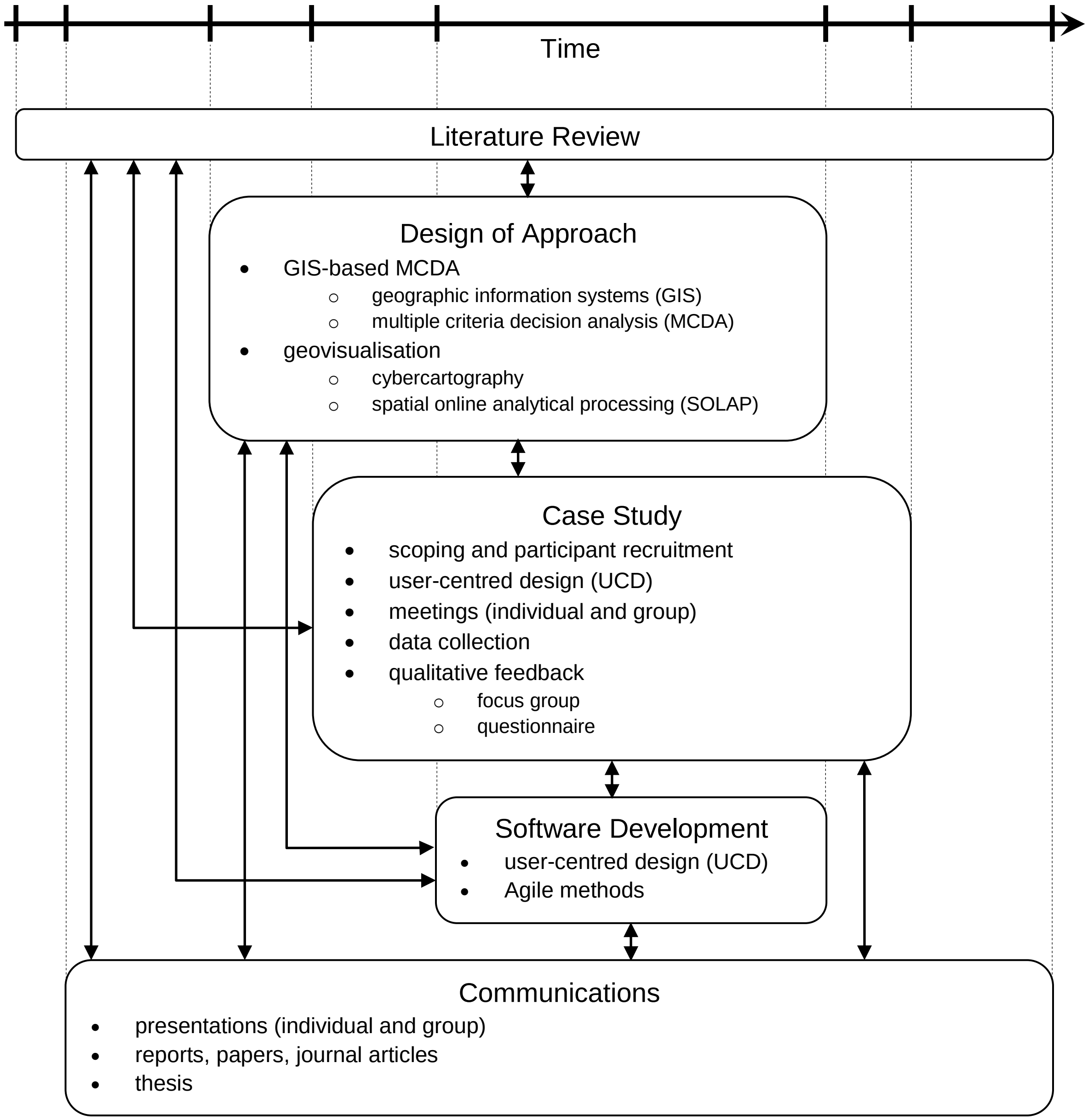

Fig. 1.2. Research methods, their relationships, and relative timelines.

The initial project concept was refined in a literature review that covered the state of the art of non-spatial MCDA methods and their adaptation in GIS-based MCDA, both generally and more specifically in relation to land management. Although less exhaustive, review of the literature from other research fields, such as geovisualisation and spatial on-line analytical processing (SOLAP), was included within the scope of addressing accessibility limitations in GIS-based MCDA.

The central research method involved the design of an approach that considers several of the identified opportunities for improving GIS-based MCDA accessibility. A number of accessibility ideas come from the field of geovisualisation, which strives to actively engage users in a process of discovery using maps linked to graphs, tables, and other information displays (MacEachren and Kraak, 2001; Dykes et al., 2005; Dodge et al., 2008). For instance, information is initially presented at the summary level, and means are provided to quickly drill down for details in locations or categories of interest (Keim et al., 2005; Rivest et al., 2005).

A case study was used to test the approach and validate the research. It was based in the Humber region on the west coast of the Island of Newfoundland, where a number of researchers and practitioners are endeavouring to achieve ILM through EBM (Eddy, 2010). The region has an extensive history in harvesting and management of timber resources, primarily in relation to supplying fibre for a pulp and paper mill in the city of Corner Brook. The pulp and paper industry contributes approximately $135 million annually to the regional economy (CBCL Limited et al., 2010), but alternative uses and conservation now compete with it for land allocations (Fig. 1.3). For instance, wildlife management gained the attention of policy makers in the 1990s and 2000s based on concerns over the endangered (now threatened) Newfoundland marten (Forsey et al., 1995; Hearn, 2007). Tourism has grown into a year-round industry encompassing hunting, fishing, skiing, golfing, snowmobiling, hiking, and wildlife viewing, with a variety of classes of accommodations. In the past decade, the tourism and recreation sector has been exerting increasing influence in harvest planning and other land management processes (Chaisson, pers. comm., 2009; Kelly, pers. comm., 2009). Land management complexity is compounded by the fact that the highest priority forest values among many residents of the Island of Newfoundland are non-consumptive and non-recreational, such as protection and scenic beauty (Bath, 2006). There appears to be a consensus among land managers in the Humber region that it is desirable to have as many perspectives as possible represented when analysing land-management decisions (Doucet, pers. comm., 2009; Jennings, pers. comm., 2009; Wood, pers. comm., 2009).

Fig. 1.3. A selection of key land management values in the Humber region.

A number of other requirements for effective land-management decision support have been identified by interest groups in the region (Dolter, pers. comm., 2009; Doucet, pers. comm., 2009; Jennings, pers. comm., 2009). They include: (a) combining qualitative and quantitative decision criteria, (b) exploring alternatives and their consequences, (c) understanding the impact of favouring different perspectives, and (d) helping reach compromise or consensus. It is also evident from the strategic regional-planning initiative for Corner Brook and the Humber Valley currently underway that land management has gained widespread attention in the region (Downer, pers. comm., 2009; CBCL Limited et al., 2010).

Key case-study activities included participant recruitment, identification of potential criteria to represent participant perspectives, acquisition of relevant data, exploration to help structure the problem, and evaluation (Fig. 1.4). Case study participants consisted of experienced land-management decision makers and analysts in the Humber region. Qualitative feedback from participants was obtained in the course of individual and group meetings, in a focus group (appendix A), and with the use of a questionnaire (appendix B).

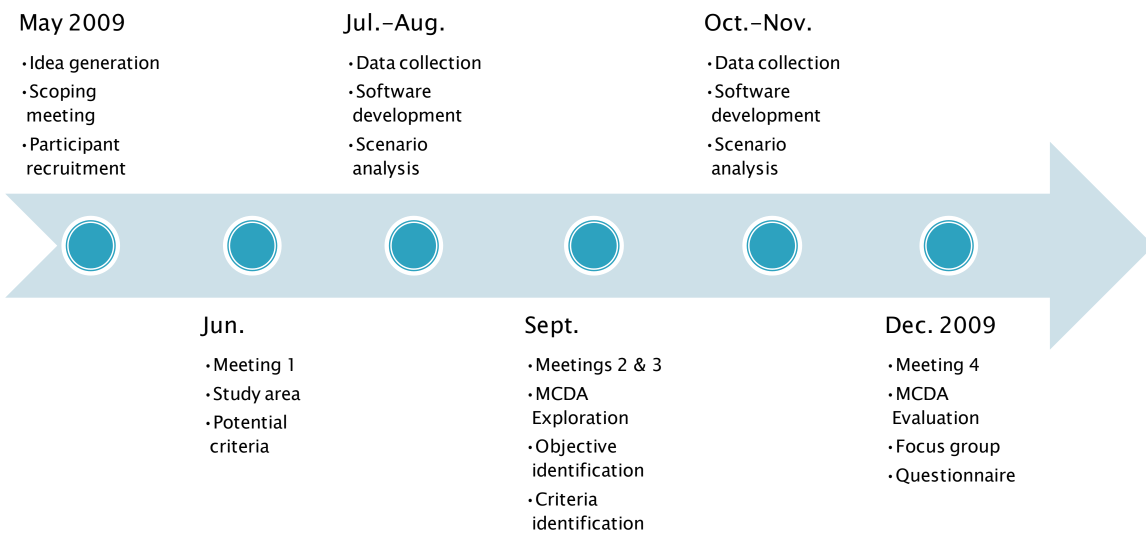

Fig. 1.4. Approximate timeline for the case study component of the research.

An important aspect of the research involved improving software tools, therefore a custom-developed software system was required to demonstrate the improvements incorporated in the designed approach. Referred to as the Multiple-Criteria Decision Analysis System (MCDAS), an Agile software engineering methodology (Beck et al., 2001; Hunt, 2006) was employed in its development to facilitate rapid programming and feedback cycles. User-centred design principles (Detweiler, 2007; International Organization for Standardization, 2010) provided a focus on usability and ensured user input and feedback were central to the process.

Communication of research ideas and progress to both academic and applied audiences facilitated feedback on and refinement of the approach and methods. The concept for the research was presented at the Humber River Basin Workshop (October 2008) and the Department of Geography (April 2009). Research results were presented at the ESRI Regional User Conference (November 2009), the Canadian Forest Service (December 2009), the Department of Geography (February 2010), the Humber River Basin Workshop (February 2010), GIS Day (March 2010), the Aldrich Interdisciplinary Conference (March 2010), and the Society for Conservation GIS Annual Conference (July 2010). Ethics approval for this project using these methods was obtained from Memorial University of Newfoundland's *Interdepartmental Committee on Ethics in Human Research* before the case study began. Case study participants were provided with a research overview, and formally provided their consent to participate.

1.5 Thesis organisation

This thesis uses a manuscript format wherein chapters 2 and 3 are papers that have been submitted to peer-reviewed journals. Chapter 2 is a literature review of GIS-based MCDA based on an article submitted to the journal *Geography Compass*. It first introduces the reader to the non-spatial foundations of MCDA and then discusses the integration of MCDA methods with GIS. It aims to make GIS-based MCDA more accessible to decision makers and analysts by categorising and introducing available methods and providing guidelines for selecting methods to apply to land-management problems. It also identifies research opportunities for improving the accessibility of GIS-based MCDA. Chapter 3 presents an approach to GIS-based MCDA that addresses a number of accessibility challenges, the MCDAS software that demonstrates the approach, and the results of the land management case study used for testing and validation. It is based on an article that has been published in the journal *Forest Ecology and Management*. Chapter 3 helps address some of the challenges identified in chapter 2, particularly the research gap in GIS-based MCDA that is concerned with a lack of explicit recognition and support for an exploration phase to help understand and structure a problem. It also demonstrates enhanced accessibility by integrating several concepts from the field of geovisualisation. Chapter 4 summarises how the research questions have been addressed, discusses how the hypothesis has been validated, expands on the significance of the work, and presents opportunities for further application and research. Further information on the design of MCDAS is presented in appendix C (preliminary design of a multiple-criteria exploration technique called coincidence analysis), and functionality details are provided in appendix D (MCDAS high-level architecture) and appendix E (MCDAS user documentation).

1.6 Co-authorship statement

After I had expressed interest in working in GIS and forestry, the concept for the project came from thesis co-supervisor Joan Luther and her colleagues at the Canadian Forest Service, and was further developed in discussions with thesis co-supervisor Rodolphe Devillers of Memorial University of Newfoundland and me. The first formal communication of the general ideas was in a funding proposal completed by the thesis co-supervisors. More specific ideas were generated by myself during preliminary literature review, and formalised in my thesis proposal and ethics proposal which were reviewed iteratively by the thesis co-supervisors. I organised and executed the practical aspects of the research, including preliminary discussions with interested parties, design of the decision analysis approach and its development as custom software, recruitment of case-study participants, logistics and chairing for case-study meetings, and communication of the results in various forums. I also coordinated the data analysis, which took the form of group decision analysis as directed by the input, perspectives, and priorities of the case study participants. Joan Luther and thesis committee member Brian Eddy also attended the case study meetings and assisted by participating in the discussions, taking notes, and providing feedback after the meetings. Design review, software feedback, and other guidance for the case study and data analysis aspects of the research were provided by all three thesis committee members. Regarding the two journal articles that form the core (chapters 2 and 3) of this thesis, the general outlines were developed and refined in meetings of the thesis committee and me. I wrote the entire first draft of both papers, and then the thesis committee provided feedback and suggested ways to improve them. Hence, I was the primary author of both journal articles, and Rodolphe Devillers, Joan Luther, and Brian Eddy were co-authors. I am the author of this document that integrates the articles and research in a single manuscript.

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Chapter 2 A review of GIS-based multiple-criteria decision analysis (MCDA)

Abstract

Important and complex spatial decisions, such as allocating land to development or conservation-oriented goals, require information and tools to aid in understanding the inherent tradeoffs. They also require mechanisms for incorporating and documenting the value judgements of the interest groups and decision makers. Multiple-criteria decision analysis (MCDA) is a family of techniques that aid decision makers in formally structuring multi-faceted decisions and evaluating the alternatives. It has been used for about two decades with geographic information systems (GIS) to analyse spatial problems. However, the variety and complexity of MCDA methods, with their varying terminologies, means that this rich set of tools is not easily accessible to the untrained. This paper provides background for GIS users, analysts and researchers to quickly get up to speed on MCDA, supporting the ultimate goal of making it more accessible to decision makers. A number of factors for describing MCDA problems and selecting methods are outlined then simplified into a decision tree, which organises an introduction of key methods. Approaches range from mathematical programming and heuristic algorithms for simultaneously optimising multiple goals, to more common single-objective techniques based on weighted addition of criteria values, attainment of criteria thresholds, or outranking of alternatives. There is substantial research that demonstrates ways to couple GIS with multi-criteria methods, and to adapt MCDA for use in spatially continuous problems. Increasing the accessibility of GIS-based MCDA provides new opportunities for researchers and practitioners, including web-based participation and advanced visualisation of decision processes.

2.1 Introduction

People often make spatial decisions, in both personal and professional matters: what route to take on a daily commute, where to locate a new branch office, or which forest stands to harvest. Selecting an alternative usually requires trading off different considerations. Route selection, for instance, may be a trade-off among distance, driving time, road quality and scenery. Different people facing the same problem may apply different values and reach different conclusions. In addition to being a product of values, decisions are also affected by the decision makers' motivations and expectations (Ajzen and Fishbein, 2008). As decisions increase in complexity and importance, so does the need to formalise the underlying decision-making processes using available information, and to document the value judgements and rationale behind the decisions.

Multiple-criteria decision analysis (MCDA) can be defined as "a collection of formal approaches which seek to take explicit account of [key factors] in helping individuals or groups explore decisions that matter" (Belton and Stewart, 2002, p. 2). For approximately 20 years, MCDA methods have been used for spatial problems by coupling them with geographic information systems (GIS) (Carver, 1991; Malczewski, 2006a). The goal of this paper is to make the GIS-based MCDA field more accessible to a wider audience. This includes the GISciences community of researchers, analysts, and users, and ultimately experts and decision makers in many fields. The GIS literature is filled with tools, scenarios, and cases involving spatial decision support (Dragićević, 2008; Thomas and Humenik-Sappington, 2009; Nyerges and Jankowski, 2010), so there is a major challenge for newcomers in even identifying GIS-based MCDA research and tools. It requires an understanding of the concepts of non-spatial MCDA, hence a related goal is to make sense of the sheer variety of MCDA methods and the many ways they can be integrated with GIS.

Section 2.2 introduces MCDA, and section 2.3 lists a number of factors used to categorise decision scenarios and select formal methods. These selection factors are used to build a methods decision tree in section 2.4, which organises brief descriptions of key MCDA methods. We then discuss the spatial extension of MCDA in section 2.5, particularly spatially continuous problems that are ideally suited to modelling with GIS. Research trends in the field of GIS-based MCDA are also reviewed. Section 2.6 is geared toward the practitioner, covering available software and coupling strategies for integrating MCDA with GIS. The Conclusion identifies opportunities related to making the field more accessible.

2.2 MCDA background

MCDA aids decision makers in analysing potential actions or alternatives based on multiple incommensurable factors/criteria, using decision rules to aggregate those criteria to rate or rank the alternatives (Malczewski, 1999a; Figueira et al., 2005; Eastman, 2009). Although the decision criteria normally cannot all be maximised in selecting an alternative or action, MCDA researchers and practitioners do not view it simply as a quantitative optimisation problem that identifies the best potential “solutions.” Instead, the focus is on eliciting and making transparent the values and subjectivity that are applied to the more objective measurements, and understanding their implications (Belton and Stewart, 2002; Roy, 2005). The field is often referred to as multiple-criteria decision making (MCDM), but decision “analysis” or “aiding” (MCDA) better reflects the more subtle and broader-ranging intentions.

MCDA grew out of and in reaction to single-criterion optimisation techniques, most notably linear programming. These were developed during World War II and honed in the early days of the business management field of Operations Research, in both contexts without considering secondary consequences that require multiple criteria (Zeleny, 1982). Simple and somewhat crude approaches to reconciling multiple criteria require alternatives to meet one, some or all criteria based on cut-off values. These approaches are named non-compensatory methods, in that increases in the value of one criterion cannot be offset by decreases in the value of another (Hwang and Yoon, 1981).

Among advocates of more sophisticated compensatory approaches that facilitate criteria tradeoffs, two prominent schools of MCDA (American and European, summarised in Table 2.1) evolved simultaneously but somewhat separately during the 1960s and 1970s. Both schools shared the concepts of decision alternatives and criteria, but differed in their philosophy and approach to aggregating criteria. The early American school of MCDA followed the Operations Research tradition. One set of its methods used a value or utility function based on multi-attribute utility theory (Keeney and Raiffa, 1976), multiplying weights by normalised criteria values (for instance converted to a continuous 0-1 scale) and summing these to derive a score or rating for each alternative. Another set of methods within the American school centred on the idea of specifying desirable or satisfactory outcomes and using mathematical programming to come as close as possible to these in criteria outcome space (multi-dimensional space where each dimension represents the possible values of one criterion) (Dykstra, 1984). The word "programming" is used in the sense of the program of action that is recommended as a result of the analysis. The European school moved away from the Operations Research idea of obtaining an optimum, and developed outranking relations to help decision makers compare alternatives in a pair-wise manner to rank their preferences for the alternatives in various ways (Roy 1968a cited in Roy and Vanderpooten, 1996; Vincke, 1992). A key assertion in this approach is that decision makers do not have precise preconceptions of the relative importance of the criteria, and that decision aiding should help them develop this insight. A somewhat less prominent school of MCDA, also based on the value-function approach to aggregation, is the Analytic Hierarchy Process (AHP) developed by Saaty (1980). AHP uses pair-wise comparison of criteria to derive relative weights.

Table 2.1. Early schools of MCDA

	American School	**European (French) School**
Assumptions	Precise knowledge and judgements, optimal decisions	Imprecision in evaluating criteria, optimal decisions not achievable
Goal	Rating and selection of alternatives	Ranking of alternatives
Aggregation Approaches	Value/utility function, multi-criteria and multi-objective optimisation	Outranking
Key Institutions	Decision Sciences Institute – http://www.decisionsciences.org/ Institute for Operations Research and the Management Sciences – http://www.informs.org	LAMSADE – http://www.lamsade.dauphine.fr/ EURO Working Group – Multicriteria Decision Aiding – http://www.inescc.pt/~ewgmcda/

As MCDA has grown, the clear divisions among the schools have diminished. For instance, subtleties introduced by the European school, such as recognition of subjectivity and imperfect knowledge (Roy and Vanderpooten, 1996), are now widely recognised and are reflected in the accepted definitions of MCDA. The various techniques are considered tools in the analyst's toolkit to be applied as appropriate to different problems or phases of the same problem. Consequently, the primary research challenges moved from development of methods, to such issues as frameworks for method integration (Belton and Stewart, 2002) and application in distributed collaborative environments (Carver, 1999; Malczewski, 1999a), and resulted in a growth in MCDA's range of application beyond its original focus in logistics and business. For instance, MCDA now has a strong history in environmental and resource applications such as forest management (Mendoza and Martins, 2006; Diaz-Balteiro and Romero, 2008).

Perhaps MCDA's greatest strength is its ability to simultaneously consider both quantitative and qualitative criteria, as long as the latter can be represented using an ordinal or continuous scale. One result is that MCDA is an alternative to decision analysis based solely on economic (monetary) valuation. There is substantial literature on economic valuation of non-monetary phenomenon, such as ecosystem goods and services (van Kooten and Bulte, 2000; Turner et al., 2008). A practical challenge of such approaches is avoiding dismissal by decision makers of these often very large and theoretical valuations when pitted against hard economic criteria like jobs and exports. MCDA approaches can help overcome economic biases (Herath and Prato, 2006) by either using a non-monetary common denominator (a continuous scale like 0-1) or avoiding altogether the need to convert criteria from their original values.

2.3 Method selection factors

One approach to succinctly categorising virtually all MCDA scenarios is their association with various problem types, or *problématiques*. These include choice (making a single selection or recommendation), ranking (establishing a preference order for some or all of the alternatives), sorting (separating alternatives in classes or groups), description (learning about the problem), design (developing new alternatives for possibly addressing the problem), and portfolio (selecting a subset of alternatives) (Roy, 1996; Belton and Stewart, 2002).

Other factors that describe decision problems or affect the choice and implementation of MCDA methods include:

- Number of decision makers: MCDA techniques designed for individuals can be applied for group decisions where consensus can be achieved through education or negotiation (Malczewski, 2006a). Otherwise, the methods must be extended using approaches such as aggregated weighting (Malczewski, 1999b) or voting (Hwang and Lin, 1987). Group approaches open up a variety of issues, often studied in Collaborative GIS research (Rinner, 2001; Balram and Dragićević, 2006; Joerin et al., 2009).
- Decision phase: The phase or phases of the decision process to be supported. There are many ways to organise and describe decision phases (Turban and Aronson, 2001; Anderson et al., 2003; Bouyssou et al., 2006), with a critical distinction for MCDA between the problem exploration/structuring phase and the evaluation/recommendation phase.
- Number of objectives: With a single objective (such as recommending the site for a new fire station), the decision maker(s) can focus on relevant criteria or factors with measurable attributes, and thus corresponding techniques are often called multiple-criteria evaluation (MCE) or multiple-attribute decision making (MADM) (Jankowski, 1995; Malczewski, 1999a). With multiple-objective decision making (MODM), it is necessary to establish whether the objectives are in synergy or conflict (for instance allocating urban land either to housing or green space) and to group the criteria by objective (Eastman et al., 1995; Malczewski, 2004).
- Number of alternatives: Scenarios with a limited number of clear alternatives (like analysing three pre-selected locations for a new fire station) are discrete problems that usually culminate in a single selection (Chakhar and Mousseau, 2007). A large or infinite number of alternatives (like identifying all possible sites for the new fire station) signifies a continuous problem usually characterised as screening, search, or suitability rating (Malczewski, 1999a; Eastman, 2009).
- Existence of constraints: Limitations on solutions, either in the form of alternatives/areas to be excluded from consideration or conditions that the recommended solution must meet. Common constraints in spatially continuous problems are that recommended areas must be a

minimum contiguous size (Eastman, 2009) or provide corridors of connectivity (Chakhar and Mousseau, 2008).

- Risk tolerance: The decision makers' level of risk tolerance (Eastman, 2009) and desire to quantify the risk inherent in a choice (Chen et al., 2001; Eastman, 2005). For instance, when screening alternatives, a risk-tolerant decision maker might be willing to accept alternatives that meet just a few criteria or even one criterion. A risk-averse decision maker, on the other hand, may accept only alternatives that meet all criteria.
- Uncertainty: Whether the criteria and weighting should be modelled with certainty (i.e., deterministically) or uncertainty (i.e., probabilistically or fuzzily) (Malczewski, 1999a; Jiang and Eastman, 2000; Shepard, 2005). Uncertainty may be any of the types identified in the resource management literature (Wynne, 1992; Mitchell, 2002), but is often the indeterminate type. The choice to model uncertainty or not may simply be based on modelling preference. For instance, in a land-classification problem, the transition from woodland to wetland could be modelled with crisp boundaries (either one or the other) or fuzzy boundaries (with one or more classification levels where the land is partially wooded and partially wet).
- Measurement scales and units: Whether it is possible to convert heterogeneous criteria based on various measurement scales (such as currency and qualitative survey results) to a common scale, and whether decision makers are comfortable with representing criteria numerically (Joerin et al., 2001; Chakhar and Mousseau, 2008).
- Experience: The training and experience of the analyst and decision makers (Belton and Stewart, 2002). Given the large number of methods and their vastly different assumptions (see discussion of the early schools of MCDA in the Introduction), this is a very practical consideration that results in technique biases.
- Computational resource capacity: Another practical consideration is available software (Malczewski, 1999a; Weistroffer et al., 2005) and hardware, and these can have budget implications.
- Direction of problem solving: Typically, problems are worked forward in support of a new decision. However, existing decisions can be worked backward to elucidate the value

judgements that would be needed to support them, in a process called preference disaggregation (Jacquet-Lagrèze and Siskos, 2001; Siskos, 2005).

2.4 MCDA methods

Given the diversity of MCDA methods, selection of an appropriate method or combination of methods depends on the context. The decision tree of Fig. 2.1 is, therefore, not intended to be comprehensive or definitive, but provides one approach to simplifying the selection process. The clearest separation of methods is based on whether or not there are multiple objectives (Jankowski, 1995; Malczeswki, 1999a). If the decision maker or analyst determines that the multiple objectives are either complementary or can be prioritised, then multi-attribute decision making (MADM) methods can be applied repeatedly in a two-level or stepwise fashion (Malczewski, 1999a; Eastman, 2009). If the multiple objectives are in conflict, multi-objective decision making (MODM) methods are required. The choice is based on the number of alternatives, between mathematical programming for locating an optimal solution, and heuristic methods for locating a satisfactory solution close to the optimum. Unfortunately, there is no easy definition of what constitutes a “large” number of alternatives as it depends on the computational capacity of the software or algorithm being used.

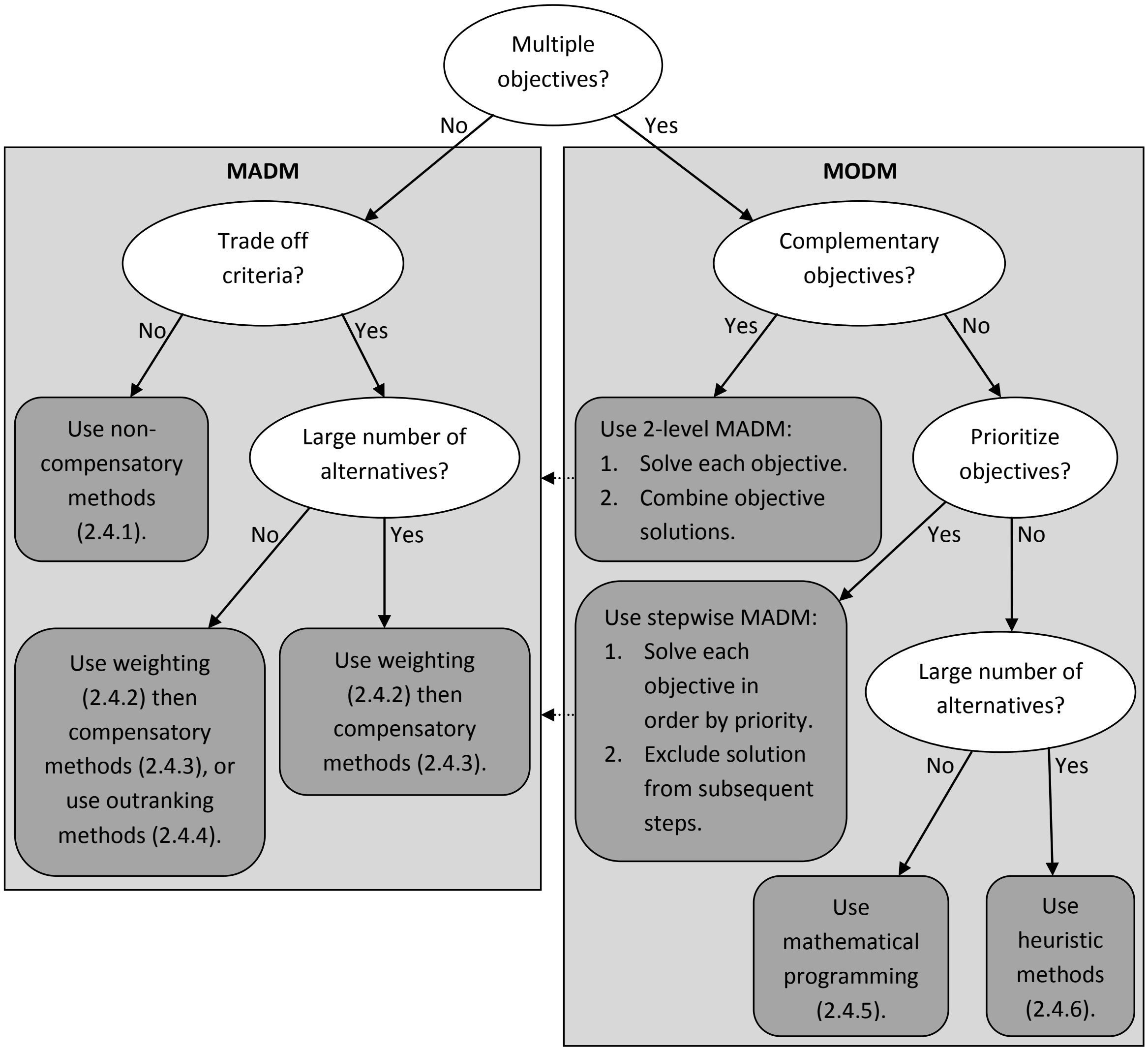

Fig. 2.1. MCDA methods decision tree. Shaded action nodes (dark grey) indicate the numbered subsection of the paper that describes the set of methods.

The MADM side of the tree is divided based on the question of trading off criteria. Non-compensatory approaches are easier to understand and apply, but they require including or excluding alternatives based on hard cut-offs. Compensatory approaches are more realistic and subtle in their modelling, as they allow criteria outcomes to be traded off against each other on a continuous scale, so that a loss in one criterion can be compensated for by a gain in another. Note that MODM methods are generally compensatory by nature, and therefore always support criteria tradeoffs. Like MODM, selection of compensatory MADM methods is also differentiated based on the number of alternatives.

It is important to realise that the methods are not mutually exclusive, due to the complexities and multiple phases of decision analysis. For instance, non-compensatory techniques could be used for preliminary screening of alternatives, followed by a compensatory method to support final selection. Multiple techniques can also be applied in parallel as part of a strategy to validate the robustness of the recommendations (Carver, 1991; Roy, 2005). A more common approach to sensitivity analysis is to run multiple iterations using the same method, each time making slight adjustments in the inputs (such as the selection and weighting of criteria) to assess the sensitivity of the resulting outputs (Malczewski, 1999b; Store and Kangas, 2001; Feick and Hall, 2004).

2.4.1 Non-Compensatory aggregation methods

Often used for screening as well as selection, non-compensatory methods include:

- Conjunctive: Accept alternatives if they meet a cut-off value on every criterion. Implementations involving spatial problems often use binary overlay (McHarg, 1969; Jankowski, 1995), where the objects or cells in each layer are set to 1 if they pass the cut-off for that criterion and 0 otherwise. The layers are combined using an intersection operation (logical AND) to identify "solution areas" that meet criteria, as shown in Fig.2.2. Conjunctive methods are risk averse because all criteria must be fully met (Eastman, 2009).
- Disjunctive: Accept alternatives that meet a cut-off value on at least one criterion (Hwang and Yoon, 1981). It can also be implemented for spatial problems using binary overlay, where the map criteria layers are combined using a union (logical OR) operation. It is a risk-taking method, because only one criterion must be met (Eastman, 2009).

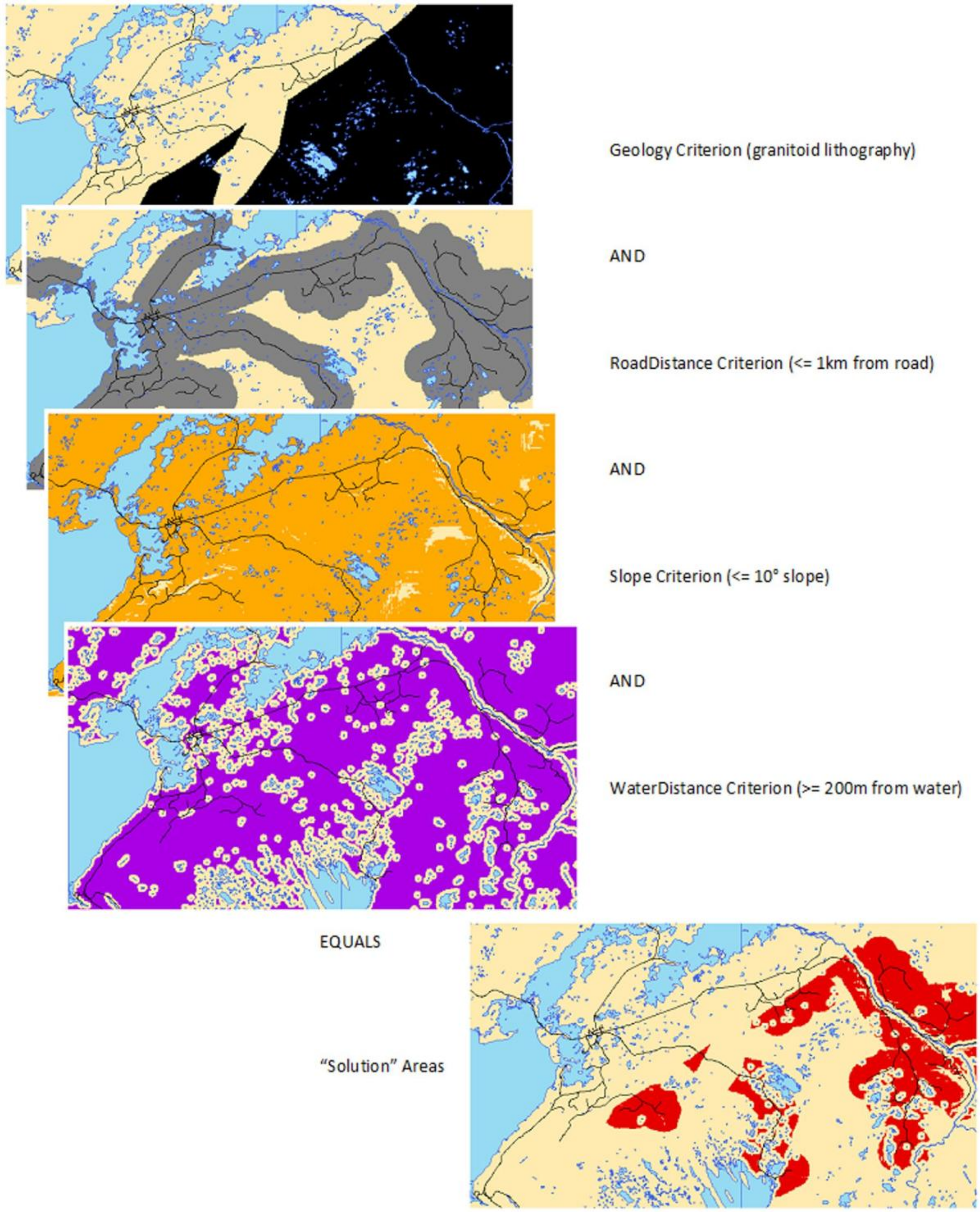

Fig. 2.2. Conjunctive example. Binary overlay for mineral exploration site identification, showing areas that meet the selected cut-off on all criteria.

- Lexicographic: Rank/order the criteria, then eliminate alternatives hierarchically by comparing them on the highest ranked criterion, followed by the second highest ranked, etc. (Carver, 1991; Jankowski, 1995).
- Elimination by Aspects: Use a lexicographic approach, but also enforce a conjunctive cut-off for each criterion (Malczewski, 1999a).
- Dominance: Look for dominant alternatives that score at least as high as every other alternative on every criterion (Jankowski, 1995).

2.4.2 Weighting methods

The following methods are used to derive relative criteria weights/importance before applying a compensatory aggregation method (Malczewski, 1999a; Belton and Stewart, 2002; Nyerges and Jankowski, 2010):

- Ranking: Ranks/orders the criteria, then converts the ranks to weights using:
    - Rank sum—each rank value divided by the sum of all rank values.
    - Rank reciprocal—1 divided by each rank value.
    - Rank exponent—a rank sum with the numerator and denominator raised to a power between 0 and 1, thereby reducing the resulting weight differences.
- Rating: Rates the criteria using a common scale (such as any value between 0 and 1) or point allocation (for instance allocating 100 points among all criteria).
- Trade-off Analysis: Directly assesses tradeoffs between pairs of criteria to determine the cut-off values at which they are considered equally important.
- Analytic Hierarchy Process (AHP): Compares criteria pair-wise on a ratio scale and subsequently computes overall relative weights based on aggregate calculations of all pair-wise ratios (Schmoldt et al., 2001; Saaty, 2005; Eastman, 2009). AHP is more than a criteria weighting method, as it also provides an additive, hierarchical aggregation of criteria. Fig. 2.3 shows AHP weighting of three of the criteria from the mineral exploration example.

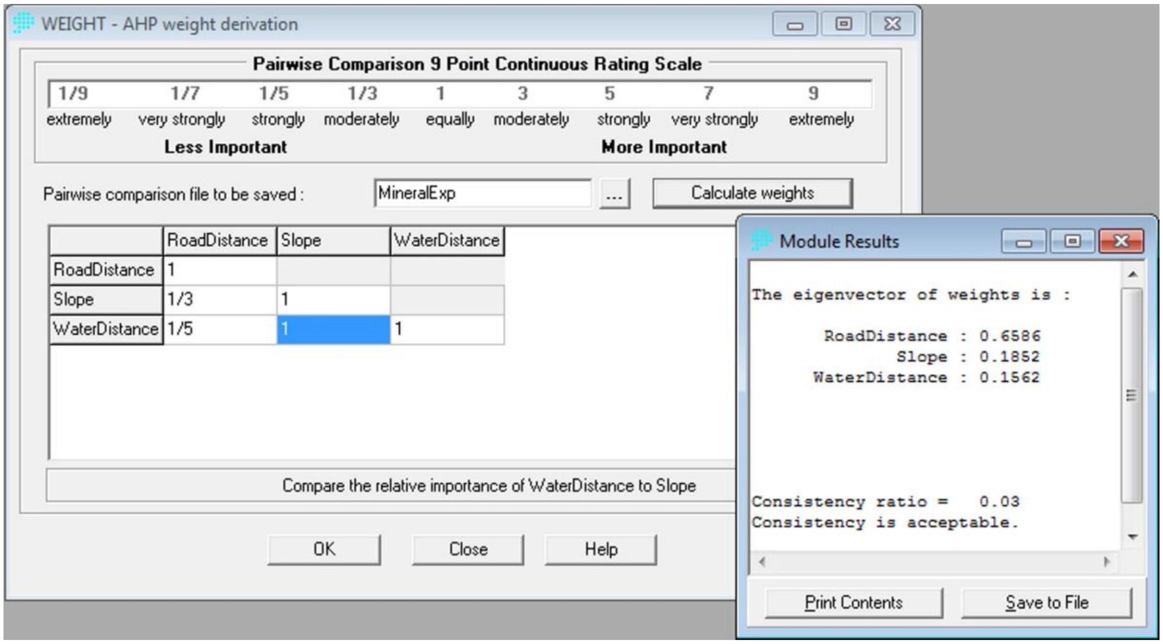

Fig. 2.3. Weight derivation using AHP in IDRISI GIS (http://www.clarklabs.org/). First, the criteria are compared pair-wise. For instance, WaterDistance is considered to be strongly less important than Road Distance (1/5). Then the eigenvector of the pair-wise comparisons is used to determine the overall criteria weights. The consistency ratio ensures, in this example, that the comparisons Slope/RoadDistance (1/3) and WaterDistance/RoadDistance (1/5) are sufficiently consistent with the comparison WaterDistance/Slope (1/1).

2.4.3 Compensatory aggregation methods

Compensatory decision rules not requiring pair-wise comparison of alternatives are of two types:

- Additive methods that normalise criterion scores to enable comparison of performance on a common scale:
  - Weighted Linear Combination (WLC): Also known as simple additive weighting, this approach multiplies normalised criteria scores by relative criteria weights for each alternative (Carver, 1991; Geldermann and Rentz, 2007; Sugumaran and Bakker, 2007; Nyerges and Jankowski, 2010). WLC can sum all weighted criteria values in a single step, or proceed hierarchically so that each group of related criteria (such as wildlife, tourism and agriculture in a rural land-management problem) is first aggregated before being combined with other groups. In Fig. 2.4, the earlier mineral exploration example is analysed using single-step WLC, showing criteria normalisation and weighting, and the

resulting map of aggregated suitability scores. Because it supports full trade-off or compensation among criteria values, WLC is mid-way on the risk tolerance continuum between conjunctive and disjunctive approaches and is thus considered a risk-neutral technique (Eastman, 2009).

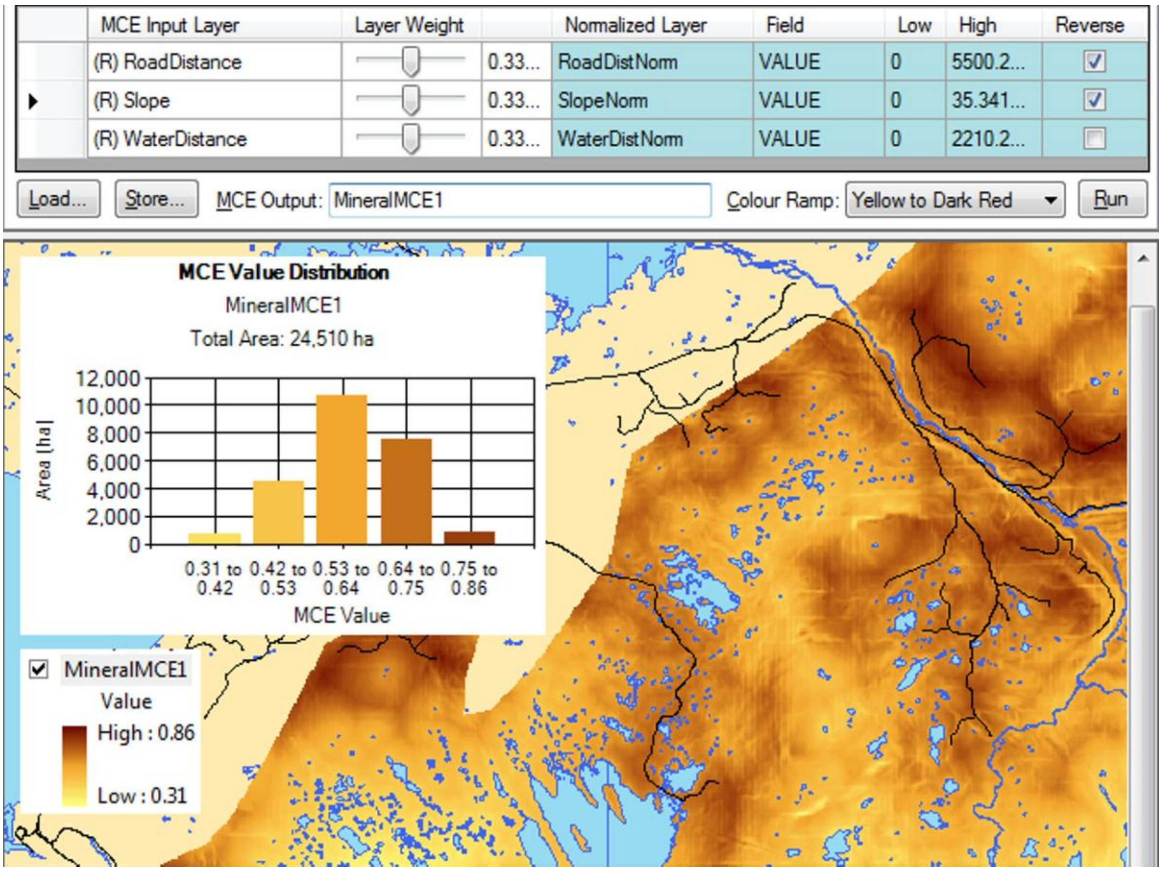

Fig. 2.4. WLC example. Mineral exploration site identification based on the inputs from Fig. 2, leaving the Geology criterion as a hard constraint, but using continuous values for the RoadDistance, Slope and WaterDistance criteria. Continuous values are normalised to a 0-1 scale, with optional scale reversal for criteria where less is better. Then they are weighted (in this case equally) and summed to produce the continuous output shown. Darker areas are more suitable, with the highest rated area scoring 0.86 (of a possible maximum of 1).

- Fuzzy Additive Weighting: Adapts WLC using non-crisp criteria and weight values derived from fuzzy linguistic quantifiers such as “high,” “medium,” and “low” (Malczewski, 1999a). Fuzzy methods are often applied in combination with other techniques, including AHP and OWA (Gorsevski et al., 2006; Gemitzi et al., 2007; Boroushaki and Malczewski, 2008).

    - Ordered Weighted Averaging (OWA): Extends WLC using criteria-order weights to control the levels of criteria trade-off, allowing decision makers to place themselves along a continuous spectrum of risk tolerance (Rinner and Malczewski, 2002; Bell et al., 2007; Eastman, 2009).
- Non-Additive methods that use the original criteria scores:
    - Ideal Point: Identifies a point in criteria outcome space (multi-dimensional space consisting of all possible combinations of criteria values) by specifying the preferred value of each criterion (Malczewski, 2004; Nyerges and Jankowski, 2010). This ideal point may not be close to a feasible alternative, but there are a number of methods for selecting one, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Chen et al., 2001; Liu et al., 2006).
    - Non-dominated Set: Identifies the set of alternatives that score at least as high as every other alternative on at least one criterion, also called the efficient set or Pareto set (Malczewski, 1999a; Lotov et al., 2004).
    - Reasonable Goals Method: Extends the non-dominated set to help visually select from the alternatives using a series of two-dimensional graphs of criteria outcome space (Jankowski et al., 1999).

2.4.4 Outranking aggregation methods

Outranking methods undertake pair-wise comparison of a discrete set of alternatives to rank them based on concordance (the set of criteria for which one alternative dominates another) and discordance (the opposite set) (Belton and Stewart, 2002). The outranking philosophy recognises that decision makers are subject to ambiguous and evolving value judgements, even during the MCDA process. Well-known methods of this type include:

- ELECTRE: A family of outranking methods (ELECTRE I, II, III, IV and TRI) that have evolved along with the European school of MCDA (Joerin et al., 2001; Bouyssou et al., 2006). ELECTRE can handle various problem types (choice, ranking, sorting) and approaches to decision modelling. It introduced thresholds for declaring indifference or preference between two alternatives on a particular criterion, and support for criteria that cannot be weighted (Belton and Stewart, 2002).

- PROMETHEE: An outranking method that supports various criterion preference functions such as U-shaped, linear and flat (no threshold) (Brans and Mareschal, 2005; Marinoni, 2006; Geldermann and Rentz, 2007).

2.4.5 Mathematical programming methods

The following methods attempt to find the optimal way to satisfy goals by solving systems of equations:

- Linear/Integer Programming: Mathematically optimises by maximising or minimising a single criterion value using constraints, commonly employed in Operations Research and Management Science (Wisniewski, 2002; Anderson et al., 2003). An example is to minimise the driving time to visit a specific set of customers, subject to speed limit constraints. To apply this approach, multi-objective problems are converted to a single-objective using value functions (in the case of deterministic models) or utility functions (in the case of probabilistic models) (Malczewski, 1999a).
- Goal/Compromise Programming: Finds the alternative that minimises overall deviation or distance from user-specified ideal points or aspiration/reservation levels simultaneously for multiple objectives (Anderson et al., 2003; Baja et al., 2007; Ghosh, 2008).
- Interactive Programming (Reference Point): Uses successively refined aspiration/reservation levels for each objective to select a feasible alternative (Malczewski, 1999a; Zeng et al., 2007; Janssen et al., 2008).

2.4.6 Heuristic methods

Due to computational limitations, mathematical optimisation is not possible when there are a large number of alternatives (such as developing an investment portfolio from the thousands of available stocks and other instruments). This issue also manifests itself in spatially continuous problems modelled using raster layers, where every possible outcome of every raster cell is an alternative. The following methods can be used to allocate cells among conflicting objectives, with the aim of a close to optimal “solution”:

- Multiple-objective land allocation (MOLA): Allocates each cell to the objective with the closest ideal point. Objectives can optionally be weighted unequally, so that a cell may be allocated to an objective with a higher weight even when there is an objective with a closer ideal point (Eastman et al., 1995; Eastman, 2009).
- Genetic algorithms (GA): Allocates cells based on a trial-and-error process that introduces small changes (evolutionary mutations) and tests for solution improvement (Malczewski, 2004; Aerts et al., 2005; Bone and Dragićević, 2009).
- Simulated annealing (SA): Allocates cells based on an iterative random process that tests for overall improvement at each step (Possingham et al., 2000; Duh and Brown, 2007; http://www.uq.edu.au/marxan/).

GA, SA, and other techniques such as cellular automata (CA) (Malczewski, 2004; White et al., 2004; Myint and Wang, 2006) are collectively referred to as geocomputation when used in spatial problems. They can be applied to related aspects of spatial decision support, such as time series used to predict the future outcome of proposed alternatives resulting from MCDA.

2.5 GIS-based MCDA

The basic intention underlying *spatialised* applications of MCDA is to augment the traditional question of “what” with the additional question of “where” (Malczewski, 1999a). GIS-based MCDA also facilitates calculation and analysis of spatial criteria such as distance, travel time, and slope. Virtually all MCDA methods can be applied to spatial problems, as shown by the examples and the many GIS-oriented references in the methods just elaborated. As discussed earlier, many MCDA methods can only be applied to a small number of alternatives due to computational limitations (in the case of mathematical optimisation) or practical considerations (in the case of pair-wise comparisons). This limits the choice of methods in spatially continuous problems, which attempt to rate or allocate swaths of land (i.e., where every cell or parcel of land is potentially part of the recommended solution). One approach to opening up additional methods for these problems is to convert them to a smaller number of discrete alternatives. For instance, strategic regional planning exercises (e.g., http://www.geog.leeds.ac.uk/papers/99-8/, http://www.cbhvregionalplan.ca/) can employ representative scenarios showing a few possible land configurations for debate and discussion. A risk of this approach, though, is potentially biasing subsequent analyses by excluding good alternative configurations (Belton and Stewart, 2002). Another option for spatially continuous study areas is classification into homogeneous zones based on criteria values or categories (van Herwijnen and Rietveld, 1999; Joerin et al., 2001; Chakhar and Mousseau, 2008). This limits the number of alternatives to the combination of possible outcomes for the zones, although often with a loss of spatial resolution.

An important element of accessibility for any field is a vibrant research community. Use of MCDA with and in GIS has been an active and growing topic of research since the early 1990s (Malczewski, 2006a, b). These literature reviews also reveal use of many different combinations of methods and approaches. Leading application areas include environment/ecology, transportation, urban/regional planning, waste management, hydrology/water resources, agriculture and forestry. The reader is encouraged to refer to Malczewski (2006a; http://publish.uwo.ca/~jmalczew/gis-mcda.htm) for case studies in their areas of interest.

Despite the breadth of methods and applications, GIS-based MCDA can still be categorised as a niche field. A field-specific research group and related journal (http://publish.uwo.ca/~jmalczew/gimda/) did not survive. Non-GIS publications such as *Journal of Multi-Criteria Decision Analysis*, *Operations Research*, *Decision Sciences* and *Management Science* are important sources of information, but rarely publish GIS-oriented material. GIS-based MCDA publishing typically occurs in the general GISciences literature or in application-oriented journals. These trends were confirmed with a search of the Scopus citation database using the query (“GIS” AND ("multiple criteria decision" OR "multi-criteria decision" OR "multicriteria decision" OR "MCD*" OR "multiple criteria evaluation" OR "multi-criteria evaluation" OR "multicriteria evaluation" OR "MCE")) resulted in 279 articles, broken down by year in Fig. 2.5. Other combinations of search terms could yield additional relevant articles, but these results are representative of the steady progression of the publications in the field.

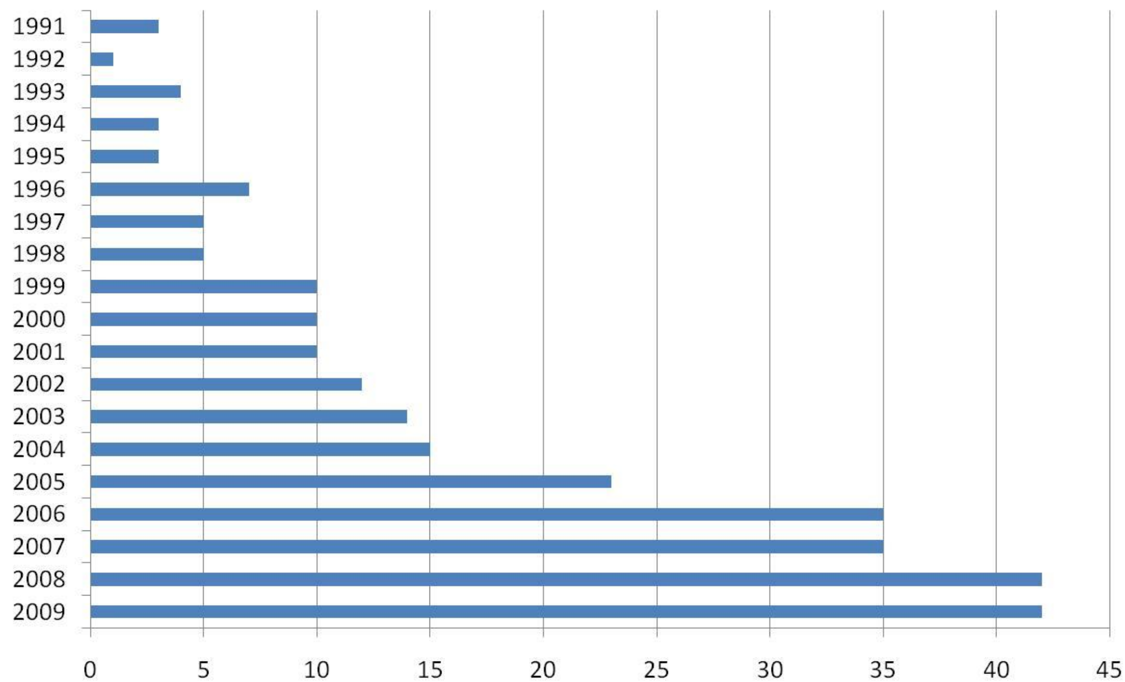

Fig. 2.5. GIS-based MCDA article count by year (from http://www.scopus.com).

Fig. 2.6 lists the journals containing three or more of the 279 articles. They are overwhelmingly in the GIS, Environmental and Planning fields, with the leader being the *International Journal of Geographical Information Science*. One of the few noteworthy academic conferences for the field is the Urban and Regional Information Systems Association (http://www.urisa.org/) annual conference. Again, researchers have to look to general GISciences, general decision research, application-specific fields, or industry events for dissemination. No academic institution is a clear leader in GIS-based MCDA, although a selection of leading researchers is provided in Table 2.2. This list was generated by the author during literature review based on the researchers' apparent prominence, their stated research interests, and their publications in the field.

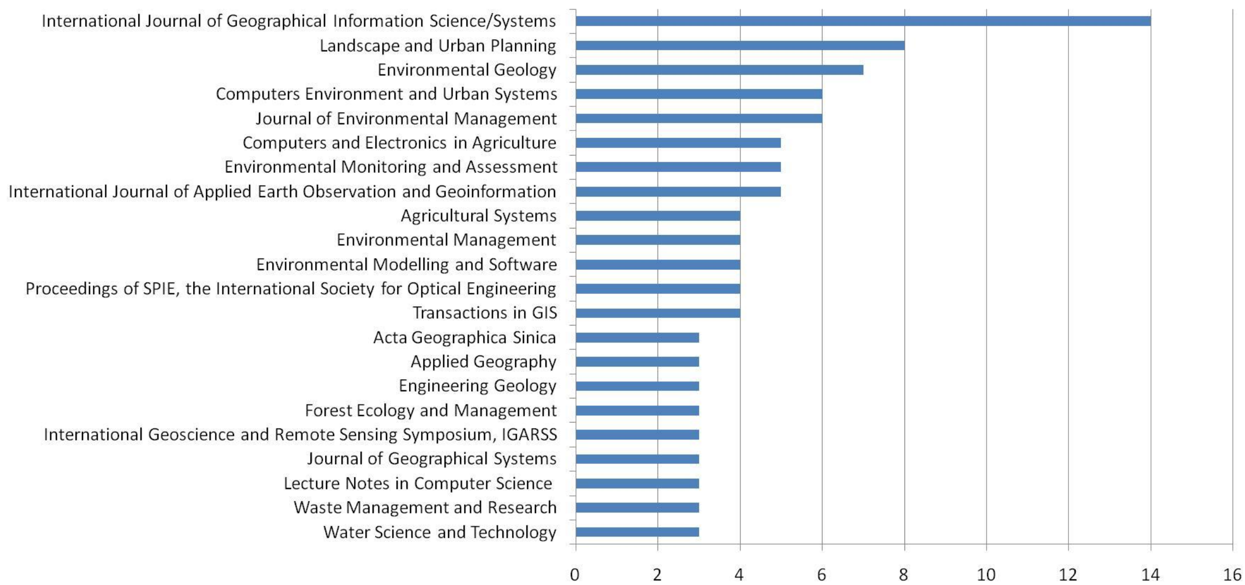

Fig. 2.6. GIS-based MCDA article count by journal (from http://www.scopus.com).

Table 2.2. Selected GIS-based MCDA researchers.

Researcher	**Institution**	**Link**
Steve Carver	University of Leeds	http://www.geog.leeds.ac.uk/people/s.carver/
Salem Chakhar	Université Paris-Dauphine	http://www.lamsade.dauphine.fr/~chakhar/
Suzana Dragićević	Simon Fraser University	http://www.sfu.ca/dragicevic
Ronald Eastman	Clark University	http://www.clarku.edu/academiccatalog/facultybio.cfm?id=61
Piotr Jankowski	San Diego State University	http://geography.sdsu.edu/People/Faculty/jankowski.html
Florent Joerin	Université Laval	http://www.adt.chaire.ulaval.ca/1_chaire/presentation_titulaire.php
Jacek Malczewski	University of Western Ontario	http://geography.uwo.ca/faculty/malczewskij
Oswald Marinoni	Commonwealth Scientific and Industrial Research Organisation	http://www.csiro.au/people/Oswald.Marinoni.html
Timothy Nyerges	University of Washington	http://faculty.washington.edu/nyerges
Claus Rinner	Ryerson University	http://www.ryerson.ca/~crinner

2.6 GIS-based MCDA Software

An important factor in the accessibility of research and methods is the availability of tools that implement them. GIS-based MCDA software can be categorised based on the level of integration of MCDA capabilities within GIS. Jankowski (1995; 2006) defines three levels of GIS-MCDA coupling: full (a single software package provided by the vendor), tight (a common user interface and data management, achieved through package customisation) and loose (based on data exchange between packages). Most MADM techniques can be implemented in most GIS packages without custom programming (Malczewski, 1999a). For instance, ESRI's ArcGIS suite of products (http://www.esri.com) provides the building blocks needed to implement WLC, including weighting overlay and map algebra. There are numerous free and commercial ArcGIS add-ons implementing other GIS-based MADM techniques (Marinoni, 2004; Boroushaki and Malczewski, 2008; http://arcscripts.esri.com). Only two packages, IDRISI and CommonGIS, provide full integration of MCDA (Nyerges and Jankowski, 2010).

IDRISI (http://www.clarklabs.org) is a commercial GIS that includes decision-support modules based on WLC, AHP, OWA and MOLA, among others, plus a wizard to assist in selection of appropriate decision techniques (Eastman, 2009). Fig. 2.7 shows a spatially continuous example of IDRISI's WLC capabilities (Rinner, 2003a). CommonGIS (http://www.commongis.com), originally called "Descartes", is a Java-based program that runs in a web browser or as a desktop application, and provides a number of multi-criteria decision capabilities including Ideal Point, WLC, OWA and Pareto Sets. Fig. 2.8 shows a discrete WLC example from Jankowski et al. (2001), depicting interactivity and map-graph linking.

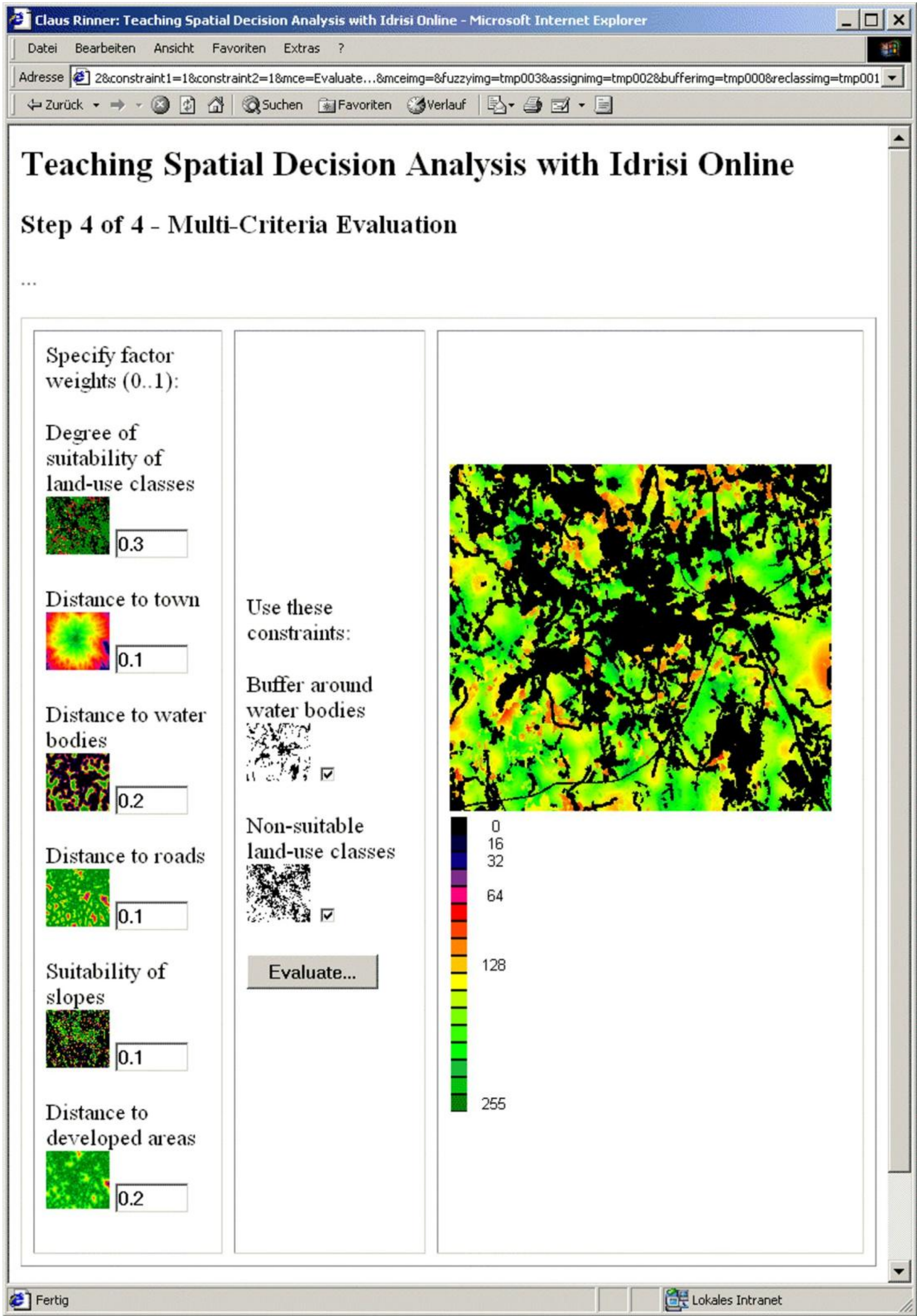

Fig. 2.7. IDRISI MCE example (from Rinner, 2003a). Users specify criteria weights and optionally select constraints, then evaluate all locations within the study area using a 0-255 rating scale. It employs a custom web-based interface to the non-Web IDRISI package.

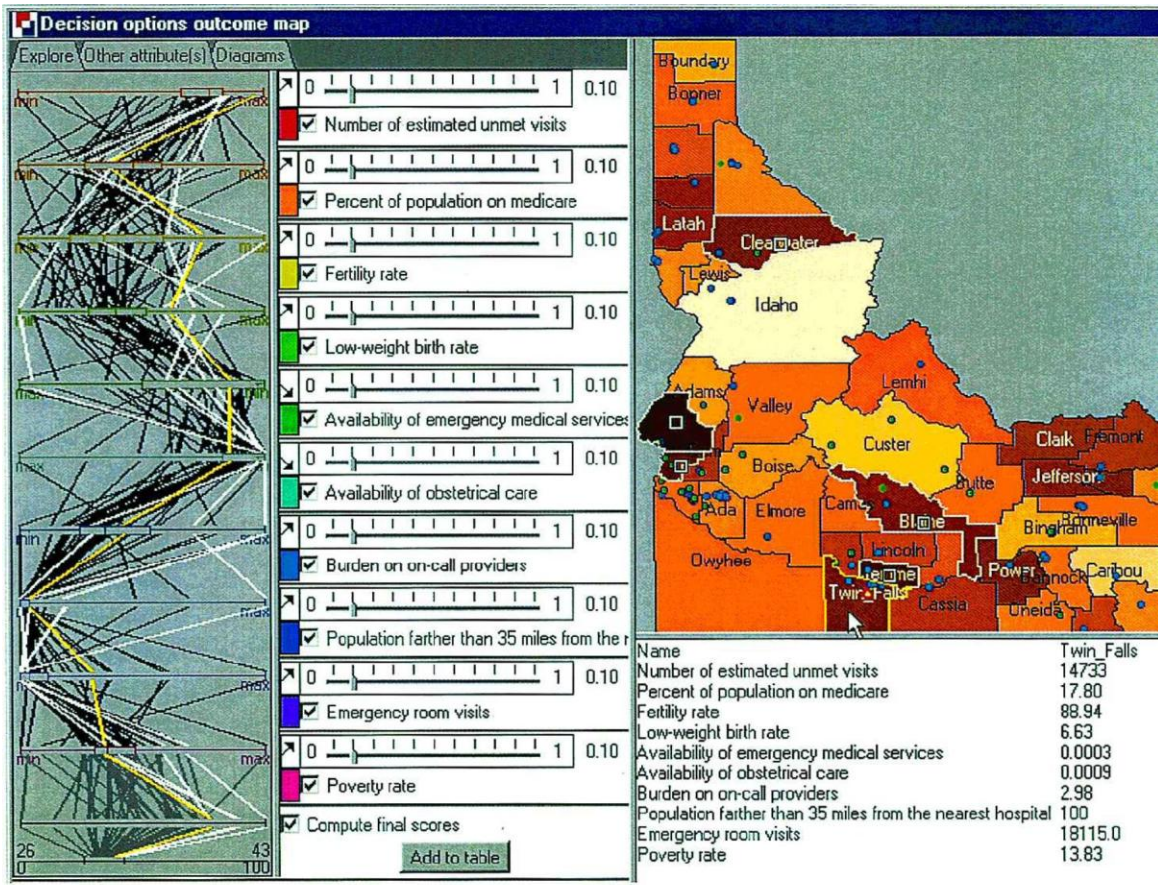

Fig. 2.8. CommonGIS MCE example (from Jankowski et al., 2001), showing counties of Idaho measured on ten healthcare criteria. Interactivity includes the ability to visually select counties in the map, and to set criteria weights using sliders. Links can be seen (1) between the selected county and the textual information in the bottom right, (2) between the highlighted counties in the map and the parallel coordinates graph to the left, and (3) among the criteria weights, the overall county score at the bottom of the graph and the county shading in the map.

IDRISI is the only GIS package to have full coupling of a MODM method, the MOLA heuristic described in section 4.6. Mathematical optimisation is typically integrated by loose coupling of GIS with packages or libraries such as those provided by Lindo (Malczewski, 1999a; http://www.lindo.com/), or using custom programs to tightly couple the algorithms (Ghosh, 2008). An important question is the order of integration (van Herwijnen and Rietveld, 1999; Malczewski, 2006a), as it can introduce biases related to the steps performed by each tool. Fully integrated GIS-based MODM is required to flexibly address this issue. Progress toward this goal has been made in the realms of nature conservation and land-use planning, as several organisations have developed packaged add-ons tightly coupled with ArcGIS (http://www.natureserve.org/prodServices/vista/overview.jsp; http://gg.usm.edu/pat/overview.htm; http://www.placeways.com). Customisation and integration generally also hide technical complexity, and therefore, work toward the goal of accessibility. It is important, however, that the underlying methods and assumptions are well documented, to avoid creating a black box that is not trusted.

2.7 Conclusions

This paper has provided an overview of the background and methods of MCDA, and its spatial extension using GIS. Although research output, tools, and applications in GIS-based MCDA continue to expand, the field has not achieved widespread acceptance. One reason is that it is often considered to be just an element of spatial decision support. Another reason is the breadth and complexity of available methods, particularly when viewed from the perspective of someone with little or no background in formal decision analysis. This introduction to the field is but one step toward making GIS-based MCDA more accessible. The need for cursory treatment of the methods selected for presentation here, and the exclusion of many other techniques and important issues, speaks to the richness that awaits those who choose to delve further into this field. In addition to continued refinement of the underlying methods and improved integration of MCDA with GIS software, there are many other opportunities for increasing accessibility. We conclude by highlighting two of them: web-based delivery and improved visualisation.

The Internet is an obvious deployment platform for collaborative GIS-based MCDA and decision support, and this approach is not new (Carver, 1999; Rinner, 2003b; Mason and Dragićević, 2006; http://www.collaborativegis.com/; http://141.117.104.183/argoomap/test/). Web-based applications have certainly helped the momentum of Participatory GIS (PGIS), a newer sub-discipline that emerged from the GIS and society debates (Pickles, 1995) as a broad research umbrella regarding socio-political aspects of interest group engagement using GIS (Jankowski and Nyerges, 2001a; Craig et al., 2002; Haklay and Tobón, 2003; Weiner and Harris, 2008). Researchers are beginning to explicitly combine MCDA and PGIS (Simão et al., 2009; Boroushaki and Malczewski, 2010) and it is possible that GIS-based MCDA will be increasingly positioned as a component of PGIS. Regardless, an important element of PGIS that GIS-based MCDA practitioners could embrace in order to ensure broad acceptance is incorporating traditional and local knowledge (Sheppard and Meitner, 2005; McIntyre et al., 2008; Rantanen and Kahila, 2009). Doing this effectively requires approaches that support the exploration/structuring phase of decision processes, not just the evaluation/recommendation phase, to avoid a biased pre-selection of criteria and alternatives (Ramsey, 2009). Beyond the PGIS realm, GIS-based MCDA can look to Web 2.0 (Haklay et al., 2008; http://oreilly.com/web2/archive/what-is-web-20.html) for developments like crowdsourcing (Hudson-Smith et al., 2009; Poore, 2010), whereby members of the public could suggest novel alternatives in a decision problem.

GIS and map-based applications have always provided visual appeal. However, the visual element of the platform is far from stagnant, being driven by the increasing expectations of web users and those performing advanced interactive analysis. GIS-based MCDA could add to its limited visualisation research (such as Jankowski et al., 2001; Rinner, 2007; Lidouh et al., 2009), by considering how to incorporate visualisation advances from a number of other fields. These include a reinvented Cartography (Slocum et al., 2009; http://cartography2.org/), which vies with Geovisualisation (Dykes et al., 2005; Dodge et al., 2008; Salter et al., 2009; http://www.geovista.psu.edu/) for leadership in interactive electronic mapping. Also noteworthy are Cybercartography, which incorporates both visual and non-visual senses (Taylor, 2005; Taylor and Caquard, 2006), and Geovisual Analytics, an extension of Exploratory Data Analysis (Andrienko et al., 2007). Increased accessibility to GIS-based MCDA requires more than making tools and information about their algorithms available; the experience must be rich and engaging.

2.8 References

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Chapter 3 An approach to GIS-based multiple-criteria decision analysis that integrates exploration and evaluation phases: Case study in a forest-dominated landscape

Abstract

The increasing importance and complexity of land and natural resource management are creating a need for ecosystem-based management (EBM). Multiple-criteria decision analysis (MCDA) combined with geographic information systems (GIS) can integrate factors related to the triple bottom line of ecological, economic, and social perspectives required by EBM. However, GIS-based MCDA is limited in this role because it rarely integrates or encourages an exploration phase in preparation for structured evaluation and inexperienced users may find MCDA methods and GIS software difficult to use. This paper presents a novel approach for supporting an exploration phase to help structure a problem and integrating the exploration and evaluation phases in an easy-to-use software system. The approach, based on coincidence analysis of binary-valued inputs during exploration and weighted summation of continuous-valued inputs during evaluation, was validated through a land-management case study in a forest-dominated landscape with a variety of interest groups. Case-study participants used the approach to rate areas within a timber harvest plan based on their potential for conflict with conservation values. The case-study decision analysis determined that between 1.3% and 6.6% of the harvest plan area had a relative conservation rating of 0.30 or higher on a scale of 0-1. The system was made available to the forest industry and other interested parties to support harvest plan adjustments, demonstrating how such tools can be used to improve and integrate our knowledge of forest ecology and management. Assessment of participant feedback revealed that an exploration phase is effective in helping understand a problem and prepare for multiple-criteria evaluation (MCE). It also uncovered some user complexity in the software tool, due in part to the flexible design of the software for use in other problems and locations.

3.1 Introduction

Land-management decisions are becoming increasingly important. Growing populations and consumerism are putting pressure on natural resources and biodiversity (Food and Agriculture Organization and United Nations Environment Programme, 1999; Dearden and Mitchell, 2005; Knight, 2009). Moreover, public awareness of land-management and sustainability issues is growing in many sectors, including forestry, and is placing greater expectations on managers to balance competing values (Rammel et al., 2007; Pollard et al., 2008). Consequently, the responsibilities involved in land management are becoming more complex. For example, conflicting objectives, such as allocating land based on economic development or conservation interests, often have to be taken into consideration and there are diverse criteria available to gauge such objectives (Herath and Prato, 2006; Brownsey and Rayner, 2009).

As land management increases in importance and complexity, and because the public requires more transparency in decision processes, there is a greater need to formalise and rationalise decisions with available scientific information. This requires approaches for integrating very heterogeneous data, making them available to the various interest groups to allow them to make more informed decisions. Accordingly, there is a recent trend toward redefining ecosystem-based management (EBM) of land resources. EBM now integrates ecological, social, and economic objectives (Layzer, 2008), often referred to as a triple bottom line (Bennett et al., 2006). It recognises human dimensions as key functional components of the ecosystem, and is being applied across natural resource sectors including wildlife (Sage et al., 2003), water resources (Gregersen et al., 2007), and forestry (Luther et al., 2007; Hearn et al., 2008; Hammond, 2009).

Multiple-criteria decision analysis (MCDA) is a set of methods that offers structured and systematic decision support for EBM of land and natural resources (Mendoza and Martins, 2006; Prato and Herath, 2007; Diaz-Balteiro and Romero, 2008). MCDA supports decision makers in simultaneously considering multiple factors and their value judgements about the relative importance of those factors (Belton and Stewart, 2002; Roy, 2005). In forestry, for example, MCDA has been often applied to harvest scheduling decisions based on criteria such as stand age, height class, species composition, proximity to production facilities, and accessibility, as well as on constraints such as protected areas, riparian zones, and landscape fragmentation limits. Geographic information systems (GIS) have been combined with MCDA in various ways, from helping to calculate spatial criteria such as distance and slope, to providing a basis for sophisticated spatial decision-support systems (SDSSs) (Malczewski, 1999a; Nyerges and Jankowski, 2010). If GIS-based MCDA models include relevant criteria, they can be used to support land and resource management practices that follow EBM principles.

A number of limitations associated with GIS-based MCDA are preventing it from being used more widely in support of EBM (see chapter 2). First, it is often assumed that decision problems are well understood and can be formally structured. Non-spatial MCDA researchers have highlighted the importance of undertaking an exploration phase to help structure the problem in preparation for a more formal evaluation phase (Belton and Stewart, 2002; Bouyssou et al., 2006). Moreover, participatory GIS research has identified that decision processes are often biased by having predetermined alternatives and criteria (Ramsey, 2009). However, the GIS-based MCDA literature does not cover research in methods and tools to integrate preliminary exploration and problem structuring in a decision-making process. A second limitation is the complexity of these methods for untrained users. Participatory and collaborative GIS have, for instance, raised this challenge (Jankowski and Nyerges, 2001; Balram and Dragićević, 2006). The next generation of tools would benefit from easy-to-use interactive interfaces so that GIS analysts are not always needed to formulate basic queries, produce charts, and generate maps on behalf of the users (McHugh et al., 2009). MCDA methods must also be easy to use and understand, yet many available methods are perceived by decision makers as being a black box (Belton and Stewart, 2002; Kangas and Kangas, 2005; Løken, 2007).

The objectives of this paper are to present a generic approach to GIS-based MCDA that:

(a) Supports an exploration phase of land-management decision making with tools that facilitate exploratory analysis and visualisation and help structure the problem for evaluation.

(b) Integrates the exploration and evaluation phases of the decision-making process in a transparent and interactive system that allows users without advanced GIS or MCDA training to carry out the analyses.

A land-management case study on the west coast of the island portion of the province of Newfoundland and Labrador, Canada, a region historically dominated by forest harvesting and management, was used to test the approach. In more recent years, decision-making processes about land use in the region have included a number of other interest groups such as the tourism and wildlife conservation sectors (CBCL Limited et al., 2010). This has resulted in more complex land-management decisions, and a need for SDSS has been identified (Kucera et al., 2010). The case study also demonstrates the approach's applicability to the broader goal of assisting land and natural resource managers to integrate diverse values as required by EBM.

Section 2 provides background on MCDA and its GIS-based application to spatially continuous land-management problems. Section 3 elaborates the approach, which combines a user-centred design (UCD) methodology, a process supporting two phases of analysis, and the development of an integrated software system. Section 4 describes the land-management case study that was used to test and validate the approach through participant feedback. Section 5 discusses how the feedback from case-study participants validates the research objectives, some limitations of the work along with opportunities for further research, and how the approach supports the broader goals of EBM in forested landscapes.

3.2 Background

MCDA is a set of methods used in support of decision-making processes. Fig. 3.1 presents a simplified combination of several decision-making process models (Turban and Aronson, 2001; Anderson et al., 2003; Bouyssou et al., 2006). If an identified problem is to be evaluated systematically, it must be structured to suit the evaluation method being used. This structuring is the key outcome of an exploration phase. To apply MCDA methods, structuring must include selection of decision objectives and the criteria by which they will be evaluated. In MCDA, the evaluation phase involves aggregating criteria values for each alternative, typically by applying criteria weights, to determine a rating or ranking of alternatives. The iterative nature of decision analysis is represented in Fig. 3.1 by the arrow in each direction between the exploration and evaluation phases. The recommendation(s) from the evaluation phase are subsequently carried forward for final selection and implementation. A feedback loop recognizes the importance of critical post-implementation analysis, a step that, confusingly for the purposes of this research, is often called “evaluation” in non-MCDA decision processes.

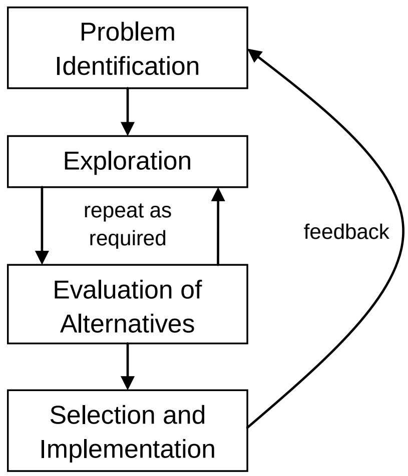

Fig. 3.1. A simplified decision-making process. This project concentrates on the exploration and evaluation phases, which can be repeated as required.

MCDA offers a wide range of methods that can apply to different types of problems. It is now widely recognised that, regardless of the methods employed, MCDA is about aiding and documenting the decision process, not making the decision (Belton and Stewart, 2002; Roy, 2005). While MCDA can support both “discrete” problems (selecting from a few alternatives) and “continuous” problems (rating a large or infinite number of alternatives), GIS is particularly well suited to evaluating spatially continuous MCDA problems such as rating the suitability of all parcels or cells within a larger study area (Malczewski, 1999a). Many spatial criteria such as land cover, forest inventory, and wildlife range encompass large continuous areas. GIS can combine these using overlay techniques to derive multiple-criteria ratings or scores.

Whereas exploration could facilitate learning about where potential criteria interact in a spatial context, the GIS-based MCDA literature has not yet explicitly targeted this phase of the process. One potential advantage of encouraging an exploration phase in a decision-making process is avoiding the tendency to fully structure a problem before all interest group input has been considered (Ramsey, 2009). Use of GIS-based MCDA is affected by a number of challenges of “usability”, defined as “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (International Organization for Standardization, 1998). For example, MCDA methods require varying degrees of comfort with mathematics and decision notation, which often puts the burden of a learning curve on decision makers. Usability challenges in GIS-based MCDA may also relate to the complexity of the GIS software employed. Identified challenges include reducing cognitive complexity for decision makers (Jankowski and Nyerges, 2001), introducing UCD principles, particularly for the human–computer interface (Haklay and Tobón, 2003), and integrating data and technology into decision-making processes (Balram and Dragićević, 2006).

Recent advances in the field of geovisualisation offer potential for addressing MCDA usability issues and for presenting the complexities and richness of information that characterise spatial decisions. Geovisualisation builds upon the more general field of information visualisation described by Dodge et al. (2008, p. 4) as “a cognitive process of learning through the active engagement with graphical signs that make up the display... it differs from passive observation of a static scene, in that its purpose is also to discover unknowns, rather than to see what is already known.” Flexible interaction is driven not only by the capabilities of the technology, but by the demands of evermore sophisticated information users (Dykes et al., 2005). An important construct from this field is the visual exploration paradigm: start with an overview, then zoom in on or filter areas or items of interest, and drill down for full details as required (Keim et al., 2005; Plaisant, 2005).

Geovisualisation extends beyond the conventional mapping capabilities of GIS, and has been featured in some GIS-based MCDA studies (Jankowski et al., 2001; Rinner and Taranu, 2006). In geovisualisation, maps and graphics can become active instruments in the end-users’ thinking process (MacEachren and Kraak, 2001). For example, providing dynamic links among maps, tables, and statistical charts can help users discover new relationships in the data (Bédard et al., 2006). The capability to present information in summarised interfaces such as dashboards

(Devillers et al., 2007), then drill down for additional details can be applied to a variety of user interface elements, including map legends, statistical charts, and data tables (Rivest et al., 2005). Usability is significantly enhanced by synchronisation of views (Baldonado et al., 2000), such as recalculating linked charts based on changes in visible map extents (Slocum et al., 2001). Developing guiding principles for implementing these techniques is a focus of the field of cybercartography, which seeks to dynamically synthesise spatial and non-spatial information in integrated and easy-to-use analytical packages (Taylor, 2005; Eddy and Taylor, 2005). While no perfect solution exists to present large volumes of complex data intelligibly to a non-expert audience, these advances in balancing richness of information with ease of understanding can offer effective ways of supporting the exploration and evaluation phases of land-management decision analysis.

3.3 Approach

Three elements define the overall approach. First, a UCD is critical to the objective of providing transparent and effective MCDA tools. Second, the exploration and evaluation phases are integrated in a decision analysis process. Finally, a multiple-criteria decision analysis system (MCDAS) demonstrates the approach in a transparent and interactive software system.

3.3.1 User-centred design

UCD is a philosophy that pays extensive attention to the end user's experience in human–computer interaction (Detweiler, 2007; International Organization for Standardization, 2010). It is now a common methodology in software design, whereby users' needs and computer interaction are placed at the centre of the design process (Macaulay et al., 2009). UCD is helpful for considering the usability of user interfaces as well as issues such as the level of trust in the algorithms and data processing that underlie analysis tools. Researchers in participatory GIS have emphasised the need for more UCD in GIS applications (Haklay and Tobón, 2003). In the proposed approach, UCD is applied both to the design and development of the supporting software and to the process of exploring and structuring the decision problem (selecting the decision objectives, criteria, and weights). The latter appears to be a novel application of the UCD paradigm.

3.3.2 Two phases of analysis

The exploration and evaluation phases of GIS-based MCDA are central to the proposed approach. A key requirement for supporting exploration phase activities is to allow decision makers to explore where multiple land values, represented in separate GIS layers, interact spatially. There are many GIS overlay methods available to support this type of analysis. Because this project aims at integrating exploratory analysis and in keeping with the UCD philosophy of usability and transparency, it employs a simple exploration method based on binary overlay techniques (Bonham-Carter, 1994) where pixels record the presence or absence of a phenomenon. The exploration tool is called "Coincidence Analysis" to reflect the fact that input data can, depending on the situation, represent either conflict or synergy. Several GIS-based processing steps are involved in coincidence analysis (Fig. 3.2). A critical first step is the conversion of textual, continuous, or interval input values contained in vector polygons or raster layers to binary values, where a value of 1 is assigned if the input value meets the cut-off and a value of 0 if the cut-off is not met. An optional step allows for grouping layers, whereby two or more input layers are combined to create a grouped binary layer, with a value of 1 at locations where either of the group inputs have a value of 1. The final step sets the coincidence output value, also known as the layer count, at each location (i.e., at each raster cell in the study area) by counting and identifying the input layers that have a binary value of 1 for that location. Because Coincidence Analysis is based on an additive binary technique, it is a simple way to introduce non-GIS experts to MCDA using spatial overlay.

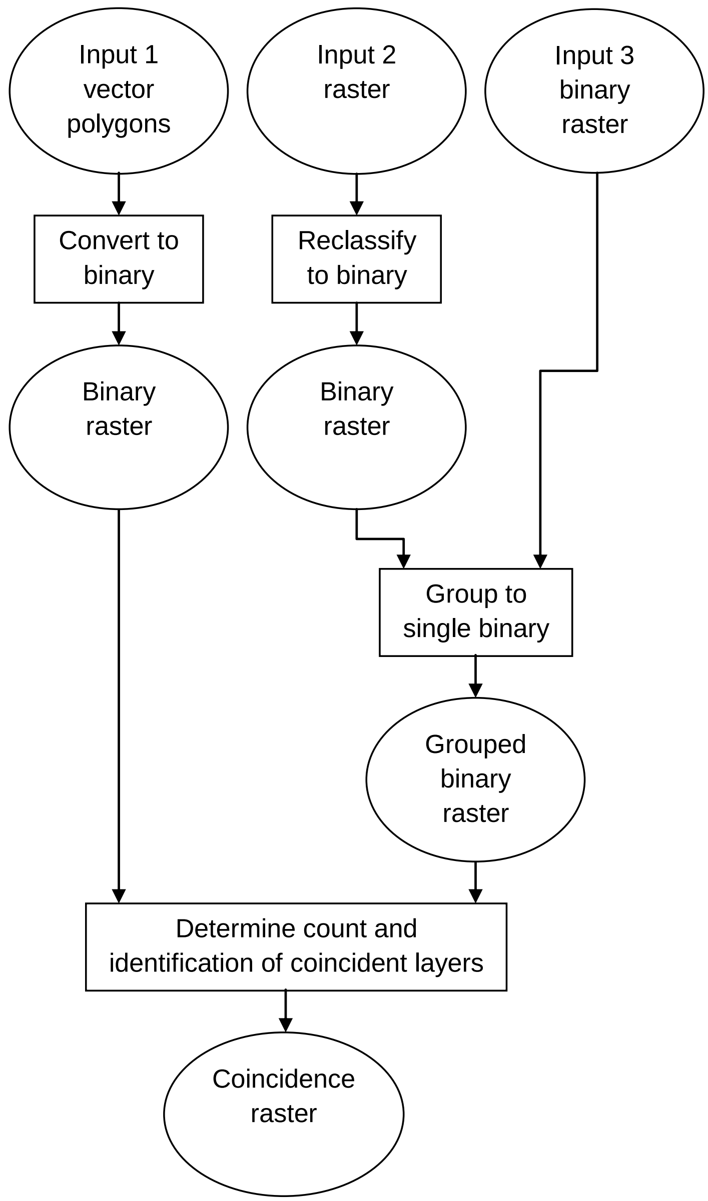

Fig. 3.2. Coincidence analysis geoprocessing.

The evaluation phase rates/ranks alternatives using the selected criteria and weights. Because of its transparency and simplicity, a weighted overlay method is used for multiple-criteria evaluation (MCE) (Belton and Stewart, 2002; Løken, 2007). As in the exploration phase, several GIS-based processing steps are used in MCE (Fig. 3.3). However, in the evaluation phase, the continuous or ordinal criteria values associated with vector polygons or raster layers (which can include raw measurements, probability values, or fuzzy quantifiers) are first normalised to a common scale (in this implementation, a value between 0 and 1).The range of variation is retained between a minimum and maximum value, which are set by the user, based on the range of values present in the data or from known theoretical minima and maxima. Normalised values for each criterion input layer at each location are then multiplied by their respective weights and summed across all criteria to provide an overall MCE rating or suitability score for that location. The weighted overlay formula is

$$V_I = \Sigma_J W_J V_{IJ}$$

where V_I is the overall value or rating of the Ith alternative or location (I = 1 to M alternatives/locations), W_J is the weight of the Jth criterion (J = 1 to N criteria), and V_{IJ} is the normalised value of the Jth criterion for the Ith alternative/location (Malczewski, 1999a; Nyerges and Jankowski, 2010). Weighting establishes the relative importance of the criteria, and in this approach, all weights sum to 1. This means the highest possible MCE rating for a location is 1.0, which would result from the presence of all criteria at their maximum value at that location.

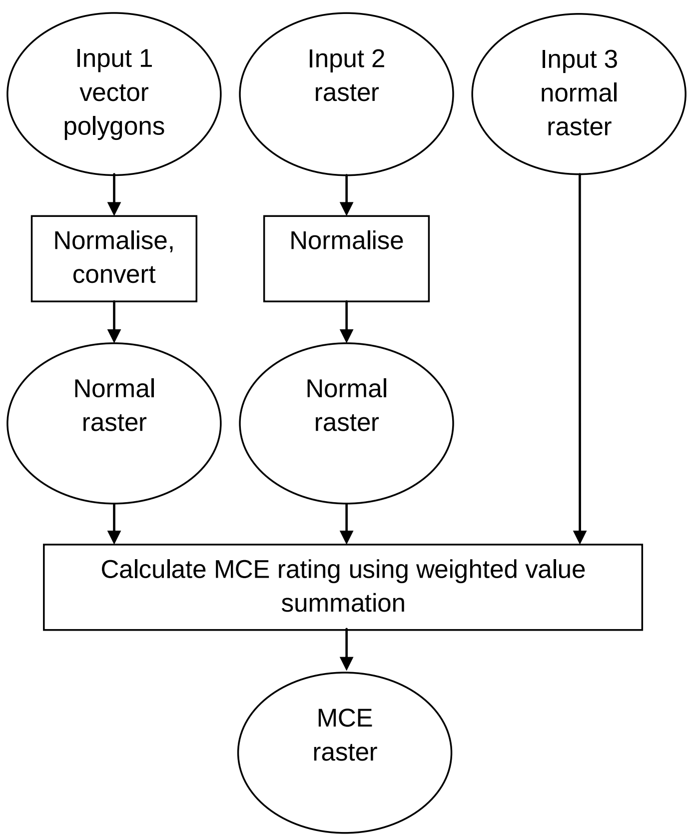

Fig. 3.3. Multiple-criteria evaluation (MCE) geoprocessing.

3.3.3 Integrated system (MCDAS)

Integration of the exploration and evaluation phases of MCDA in a single system is guided by a set of high-level user requirements (Table 3.1). The exploration phase activities help users build coincidence analysis scenarios. For instance, browsing and visualising the distribution of potential criteria data values using histograms can help users decide on the cut-off values for converting data to binary (as required by coincidence analysis). The evaluation phase incorporates a simple weighted overlay MCE using the criteria chosen as a result of the exploration phase. Effectively analysing the outputs from both phases of analysis benefits from interactive geovisualisation techniques, introduced in section 2, based on map colours, charts, drill-down, and dynamic synchronisation among interface elements (Baldonado et al., 2000; Slocum et al., 2001; Rivest et al., 2005). In addition to facilitating data sharing throughout the MCDA process, the integration of the two phases of analysis within a single system supports the cyclical, iterative nature of land-management planning (Simão et al., 2009).

Table 3.1. High-level conceptual requirements of MCDAS based on user activities.

GIS-based MCDA user activity	Decision phase
Browsing potential criteria layers using maps and their underlying attribute tables	Exploration
Understanding the distribution of potential criteria data values using histograms	Exploration
Understanding potential criteria by consulting metadata and referenced documentation	Exploration
Building coincidence analysis scenarios to explore potential criteria layer interactions and help structure the decision problem	Exploration
Building MCE scenarios to rate locations using selected criteria	Evaluation
Interactively analysing scenario outputs using coordinated map and chart views and drilldown	Both
Repeating the process as required, reusing criteria and incorporating outputs of previous analyses	Both

MCDAS is a custom software application which fully integrates GIS and MCDA. Its development follows Agile principles, a family of software development methodologies where user requirements and implementation evolve rapidly and in parallel (Beck et al., 2001; Hunt, 2006). It also adopts UCD (Detweiler, 2007), whereby MCDAS was compiled frequently to solicit user feedback, fine tune the high-level requirements, and test and refine features in development without breaking existing functionality. MCDAS is a Windows® application that was developed using Microsoft Visual Studio 2008® with the C#® programming language, and based on the ArcGIS 9.3® platform. The high-level software components underlying MCDAS consist of libraries made available by the Microsoft and ArcGIS development environments and custom-built components. MCDAS has been placed in the public domain with a small sample data set for download at http://arcscripts.esri.com/details.asp?dbid=16856. MCDAS has both back-end data and front-end tools running on a local computer, but the approach can be easily adapted to a variety of configurations depending on the need for scalability and the location of data.

Fig. 3.4 shows the resulting MCDAS user interface and its components.

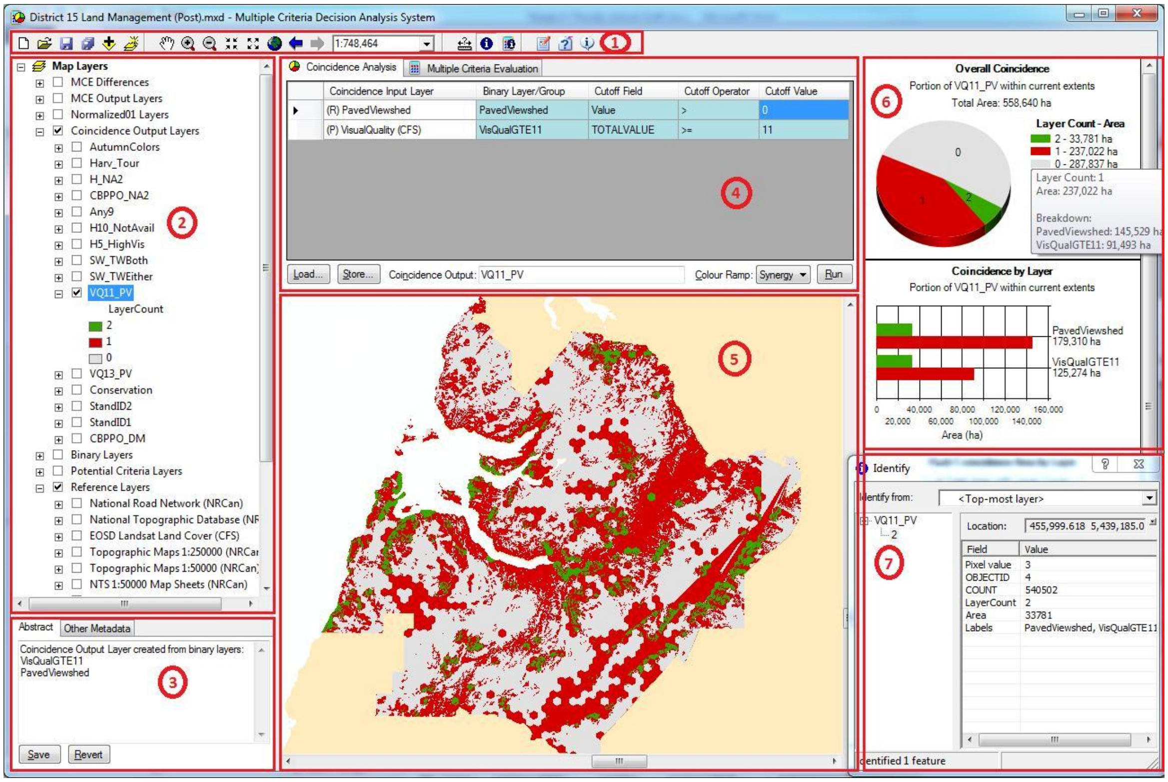

Fig. 3.4. Multiple-criteria decision analysis system (MCDAS) user interface, showing (1) top toolbar, (2) table of contents (available map layers) pane, (3) metadata pane, (4) analysis pane with two tabs (one each for coincidence analysis and MCE), (5) map pane, (6) charts pane, and (7) additional pop-up windows, such as the “Identify” window.

For coincidence analysis, users can select map colours from custom colour ramps based on traffic-light colours, where green implies favourable or desirable, red implies undesirable or unfavourable, and yellow implies intermediate or cautionary (Devillers et al., 2007). Interpolated shades of these colours are used when more than three layer count values are present in the coincidence output layer. A pie chart summarises the area of each layer count, and a bar chart shows how each input layer breaks down by layer count; both charts synchronise their colours with the map display. Zooming in on or panning the map causes the charts to recalculate based on the visible extents in the map display. Detailed drill-down is supported on the map to identify the input layers occurring at a particular location and on any chart bar or slice to show a further breakdown of its composition. Similarly for MCE, a variety of output colour ramps are available and the distribution of MCE output values are automatically summarised in a colour-synchronised histogram. An "Identify" tool uses a bar chart to breakdown the MCE score at a selected location into the weighted values of the input layers that contributed to the score.

3.4 Case study

3.4.1 Study area

To validate the proposed approach, MCDAS has been tested using a land-management case study that involved a group of experienced decision makers. The location of the case study is Forest Management District 15, which covers over 560,000ha, mostly within the Humber River Basin, in the province of Newfoundland and Labrador, Canada (see Fig. 3.5). Interest groups include forest and agriculture industries, domestic-use woodcutters, recreational users, tourism and outfitting operators, wildlife managers, conservation organisations, and municipalities. The largely rural character of the region means there is not excessive pressure toward urbanisation, so tension between forestry managers and conservation-oriented perspectives is perhaps the most critical land-management issue (CBCL Limited et al., 2010).

Fig. 3.5. Case-study location in the province of Newfoundland and Labrador, Canada.

3.4.2 Decision-making context

Corner Brook Pulp and Paper Limited (CBPPL), a subsidiary of Kruger, operates a paper mill in the city of Corner Brook. Forest harvesting and silviculture in support of wood fibre for the mill are the primary agents of landscape change in the region. The current planning process involves public consultations and takes into account both regulated and voluntary areas of non-harvest (CBPPL, 2008). However, incorporating more science-based information into the process is desired by all interest groups. Identification of specific areas for protection, beyond more general protection goals, can help fulfil sustainability and stewardship responsibilities.

A snowball method was used to make initial contacts in the Humber region and brainstorm about the project. Given the logistics of scheduling five group sessions, the anticipated time commitment of up to 25 hours per person, and the project's focus on methods and tools, it was decided that six participants would be a manageable number. Prospective participants were selected from among those who had been introduced to the project with a goal of ensuring a broad set of perspectives were represented. The six people who agreed to participate represented the following perspectives: pulp and paper industry, forestry regulation and management, wildlife/ecology, tourism, regional planning, and policy-focused research. The author acted as participant-observer (Johnson and Johnson, 2003; Kearns, 2005), facilitating design and application of the GIS-based MCDA approach and supporting data sets for the case study while also gathering feedback. Based on discussions with case-study participants and other interested parties, general decision-support requirements were identified and included capacities to integrate qualitative and quantitative factors, explore alternatives and their consequences, understand the impact of favouring different perspectives, and help reach consensus or compromise. Key steps in the case-study decision process included identifying potential criteria to represent different values, sourcing corresponding data, identifying and structuring the problem, evaluating a chosen objective using selected criteria, and gathering qualitative feedback from the participants using a formal process.

3.4.3 Data

Case-study data layers were divided into groups by layer type to organise the MCDAS table of contents. Reference layers included a variety of base maps to provide context for other layers. Potential criteria layers were those identified by the case-study participants as representing important values. Approximately 40 potential criteria layers were considered, which covered physical characteristics such as land elevation and slope, forest inventories, wildlife and plant habitats, and watersheds for drinking-water supplies as well as human activities such as farming, mineral exploration, waste management, conservation, outfitting, fishing, forest harvesting, hiking, snowmobiling, and driving. Four other layer types were outputs of the coincidence analysis and MCE processing: binary layers, coincidence output layers, normalised layers, and MCE output layers. A layer could have multiple designations, such as the output for one coincidence analysis scenario being used as input for another scenario, or a potential criteria layer being used as a reference layer in a different scenario, facilitating experimentation.

3.4.4 Decision analysis

Most decision analysis occurred in group meetings. The sessions were facilitated by the lead researcher, who provided introductory training and operated MCDAS. Some analysis scenarios were prepared before the meetings, and others were built and run by the group during the meetings. Case-study participants were also given access to the software and data for use outside the meetings. Group analysis began with an exploration of each potential criterion layer. Participants typically started with a discussion of the layer's meaning and general importance, followed by visualisation of its spatial extent and distribution of values. For instance, Fig. 3.6 shows "Visual Quality", a potentially important criterion for tourism. This layer provides an indication of the extent to which a given site is visually pleasing based on a study that used landscape photographs to question tourists and the general public about their opinions. The responses helped calibrate a model for assigning a visual quality rating to landscapes based on factors such as vegetative variety and topographic variety (Piercey, 2008). The map allows users to visualise which areas have higher visual quality (darker), and the histogram shows the overall distribution of values. Exploring potential criteria is an important step in preparing for evaluation.

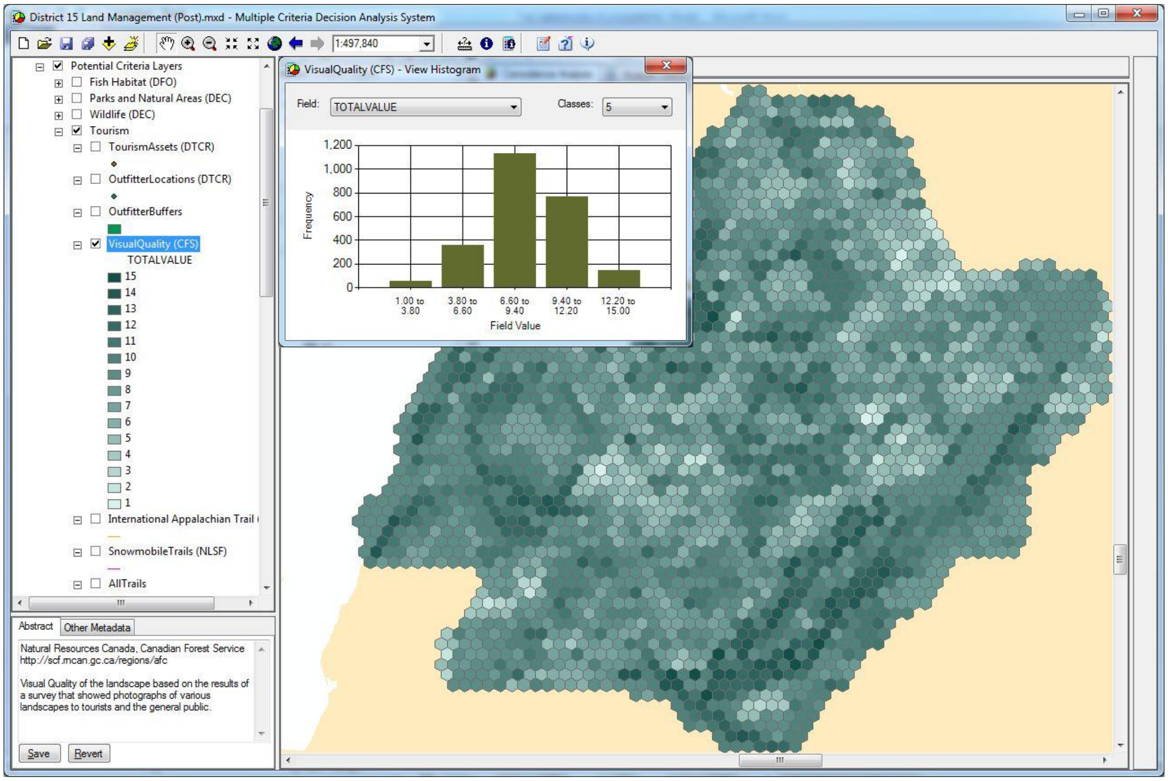

Fig. 3.6. Visual quality, a criterion that is potentially important for tourism.

After exploring individual criteria, the next step involved identifying where potential criteria coincide. Fig. 3.7 shows coincidence analysis inputs and outputs for a scenario that identifies stands for possible forest harvesting. Four input criteria and associated cut-off conditions are based on the attributes of forest stands contained in the inventory layer: “Age Class”, “Density”, “Site Quality”, and “Working Group” (species profile). Output areas with layer count of 4 (dark green) met all the criteria; those with layer count of 1 (dark red) met just a single criterion. More detailed information was provided in a drill-down information balloon above the bar chart at the bottom right of Fig. 3.7. Case-study participants tried various cut-off conditions and experimented with a variety of coincidence analysis scenarios covering tourism (e.g., Fig. 3.4 shows the coincidence between the “Visual Quality” layer and the “Viewshed from Paved Roads” layer), timber harvesting vs. tourism, and conservation. An enforcement scenario compared the industry’s 25-year harvest plan with areas of legislated protection (parks, wildlife reserves, ecological reserves, and riparian buffers around water bodies). Analysis confirmed that the harvest plan did not impinge upon any protected areas.

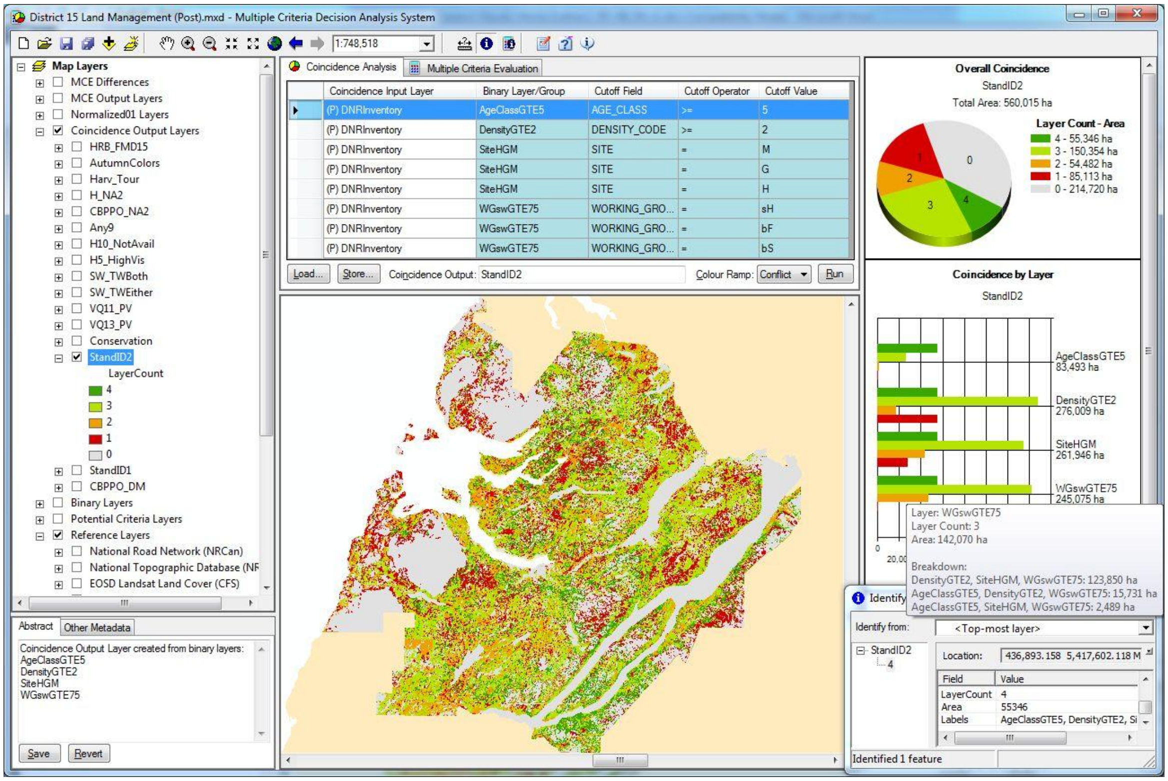

Fig. 3.7. Coincidence analysis of stands for possible timber harvesting.

The primary outcome of the exploration phase was a clear definition of the decision objective and a selection of supporting criteria in preparation for evaluation. Participants decided that the decision objective would be to rate the areas within the 25-year harvest plan based on their potential for conflict with conservation values. Participants felt it would be useful for the company to be aware of potential harvesting conflict hotspots as they roll out the long-term plan into annual operating plans. To measure this objective, thirteen criteria (Table 3.2) were chosen by participants based on the exploration activities. These represented a sufficiently broad set of land-management values to test the proposed tools and approach.

Table 3.2. Evaluation criteria selected for rating areas within the 25-year harvest plan based on their potential for conflict with conservation values.

Layer name	Description	Perspective	Data values
AllViewshed5K	Viewshed from paved roads, salmon rivers and trails	Tourism	Number of viewpoints up to 5km away
CaribouCalv	Caribou calving areas	Wildlife	Binary (presence/absence)
DomesticWater	Watersheds for domestic water supplies	Regional Planning	Binary (presence/absence)
MartenCore	Marten core area	Wildlife	Binary (presence/absence)
MartenAllHomeRanges	Marten home range probability	Wildlife	Probability of habitat within each home range supporting marten
MuniBounds	Municipal boundaries	Regional Planning	Binary (presence/absence)
MuniPlanOnly	Municipal planning areas	Regional Planning	Binary (presence/absence)
OutfitBuffers	Outfitter camp buffers	Tourism	Binary (presence/absence)
Plants	Rare plant habitat	Wildlife	Binary (presence/absence)
SpawnPct	Fish spawning habitat	Wildlife	Percent spawning habitat in adjacent river, inverse distance weighted up to 1km
TrailProximity	Trail proximity	Tourism	Distance from hiking and snowmobile trails up to 1km
VisualQuality	Landscape visual quality	Tourism	Landscape visual appeal measured on 0-15 scale
Waterfowl	Sensitive waterfowl habitat	Wildlife	Binary (presence/absence)

The evaluation phase proceeded based on the criteria selected during the exploration phase. Fig. 3.8 shows the initial MCE analysis output, whereby the 13 criteria shown in Table 2 are weighted equally. Input criteria values are normalised to a 0-1 continuous scale. The output is constrained to the area of the 25-year harvest plan (shown in shades of blue in Fig. 3.8). Darker areas reveal a higher conservation rating and lighter areas have lower conservation ratings. Note that the highest possible MCE rating is 1.0, but the highest obtained rating is 0.49, which means there are no areas that fully meet all 13 conservation criteria. Only 6.6% of the study area rates 0.30 or above and these are primarily smaller areas dispersed throughout the study area. Next, case-study participants evaluated several scenarios that gave higher weighting to select criteria, and it was noted that changing criteria weights could substantially change the conservation ratings. Sensitivity analysis comparing scenarios with different criteria weightings showed MCE rating value changes up to 0.35 for some locations. The primary evaluation challenge for case-study participants thus became deciding as a group on the weights to use.

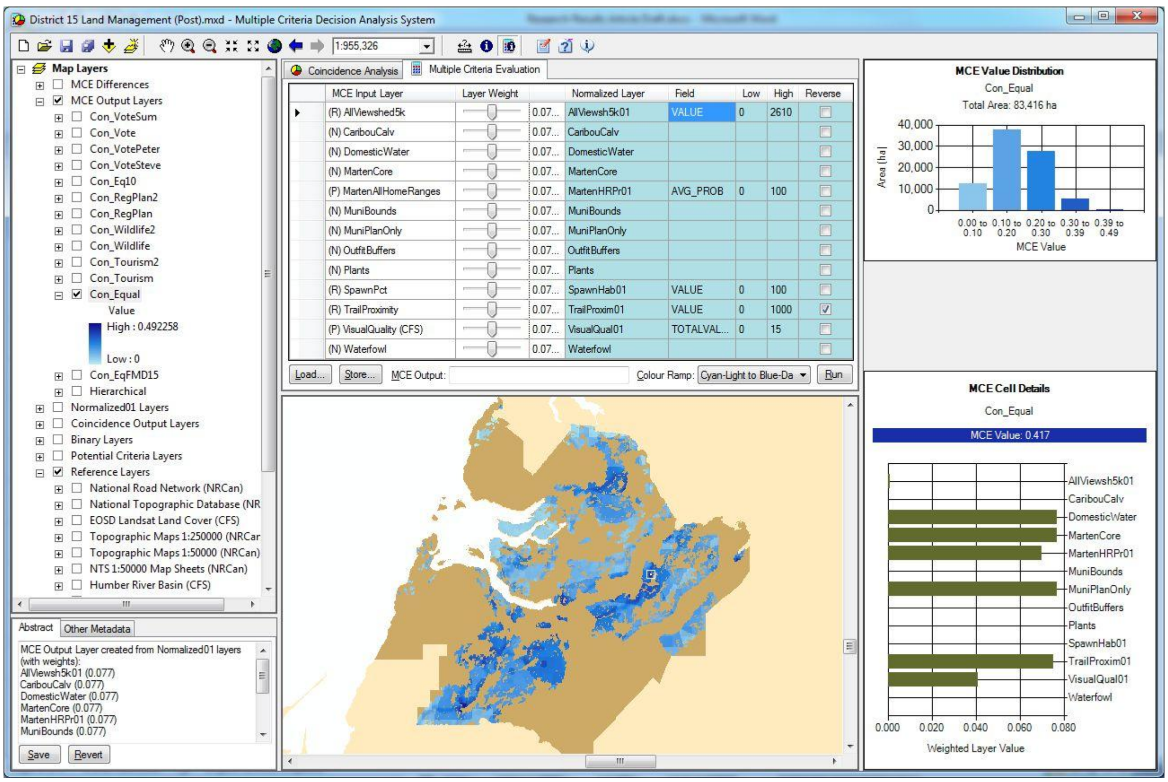

Fig. 3.8. Multiple-criteria evaluation (MCE) showing conservation rating of harvest plan areas using equal weights for all criteria.

One method for determining criteria weights in a group setting is to have each participant rank the criteria, and aggregate the rankings. Table 3.3 shows the outcome of a group ranking exercise where each participant provided criteria rankings from 1 to 13 (where a value of 1 is most important). The participant rank values for each criterion were then averaged, and z-scores and group rank values were calculated from the averages. Participants decided to use these rankings as the basis for a MCE scenario, which required converting the rank values to weights.

Table 3.3. Criteria ranking to derive group weights. Bold cells indicate average rank values and individual participant rank values that were substantially more important (↑) or less important (↓).

	Participant Rankings					Avg Rank	Z-Score	Group	Group
Criterion	**A**	**B**	**C**	**D**	**E**	**(AR)**	**of AR**	**Rank**	**Weight**
Caribou Calving Areas	↓**10**	4	↑**1**	↓**10**	5	6.0	-0.328	5	0.099
Fish Spawning Habitat	9	3	↑**1**	9	5	5.4	-0.612	4	0.110
Marten Core Area	11	5	↑**1**	11	10	7.6	0.430	9	0.049
Marten Home Range	12	12	7	12	11	10.8	↓**1.946**	13	0.011
Municipal Boundaries	↑**2**	6	10	↑**2**	↓**13**	6.6	-0.044	8	0.066
Municipal Planning	↑**3**	11	9	↑**3**	↓**12**	7.6	0.430	9	0.049
Outfitter Camp Buffers	13	13	8	13	↑**3**	10.0	↓**1.567**	12	0.022
Rare Plant Habitat	6	2	1	6	5	4.0	↑**-1.275**	2	0.132
Sensitive Waterfowl	7	8	5	7	5	6.4	-0.138	7	0.077
Trail Proximity	8	9	10	8	4	7.8	0.525	11	0.033
Viewshed from Paved Roads, Salmon Rivers and Trails	4	7	↓**10**	4	↑**1**	5.2	-0.707	3	0.121
Visual Quality	5	10	10	5	↑**1**	6.2	-0.233	6	0.088
Watersheds for Domestic Water Supplies	1	1	5	1	↓**9**	3.4	↑**-1.559**	1	0.143

There are a number of techniques for converting ranks to weights (Malczewski, 1999a; Nyerges and Jankowski, 2010). The formula for the rank sum technique used is

$$W_J = (N - R_J + 1) / \Sigma_J J$$

where W_J is the weight and R_J is the rank of the Jth criterion (J = 1 to N criteria). This formula was used to calculate group criteria weights in the final column of Table 3.3, and these weights were used to generate the MCE output shown in Fig. 3.9. In comparison with the equal weighting scenario, the group weights result in a clustering of hotspots (darker blue). These clusters occur mostly around municipalities, reflecting the high rank values given to domestic water supplies. The proportion of the study area with MCE rating values 0.30 or higher decreased from 6.6 % to 1.3%. These scenarios illustrate the flexibility of MCDAS in supporting experimentation with multiple criteria and weighting of values. It demonstrates the power of such systems to help decision makers and analysts visualise and discuss openly the rationale and basis for their decisions, in particular the influence of relative weightings (value judgments) made by interest groups with different perspectives.

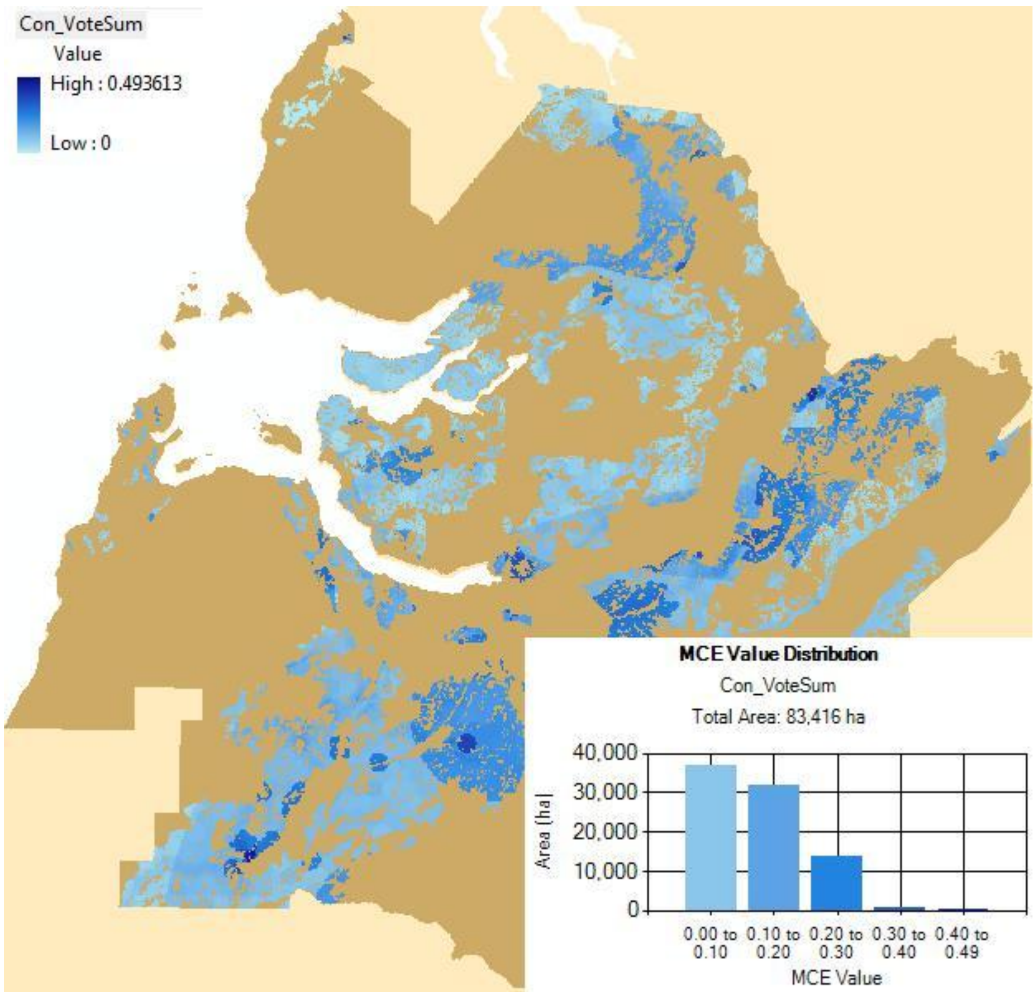

Fig. 3.9. Multiple-criteria evaluation (MCE) showing conservation rating of harvest plan areas using group-derived weights.

3.4.5 Participant feedback

The goal of the case study was to test the GIS-based MCDA approach, which combines an exploration phase with an evaluation phase in an integrated SDSS. Two formal mechanisms for gathering qualitative feedback were used for the validation. The final meeting had a focus group format, guided by a number of questions about the approach. This was followed by a questionnaire that participants completed on their own time.

Participants were unanimous in concluding that an exploration phase was effective in helping to understand a decision problem and to select criteria for the evaluation phase. Participants also felt that coincidence analysis, the primary exploration tool, provided the ability to quickly analyse many scenarios with variations in the input layers and cut-off choices. Although they found the coincidence analysis output (layer counts) easy to interpret, having to choose binary cut-off conditions was challenging for some participants. This feedback is not surprising given that having to make cut-off choices is a known limitation of binary methods (Eastman, 2005; Store, 2009). However, once participants understood criteria are not converted to binary in the evaluation phase, they were more comfortable seeing coincidence analysis as an exploration and learning tool. They agreed that an exploration phase helped them focus their evaluation objective and decide which criteria to include in the evaluation phase. Some criteria, such as layers representing legislated protection that had already been considered in the harvest plan, were excluded from the MCE as a result of the coincidence analysis. Based on discussions initiated by exploration activities, participants decided that other potential criteria, such as mineral exploration claims and proposed dump sites, do not impact harvesting decisions and were therefore also excluded from the evaluation phase.

Regarding the transparency of MCDA methods and a simplified and integrated GIS-based user interface, participants provided mixed feedback. In the questionnaire more than half of the participants “disagreed somewhat” with the assertion that “analysis tools (coincidence analysis and MCE) were transparent (easily understood).” Some participants qualified their responses, indicating they would likely become more comfortable with increased exposure to the software. Similarly, in terms of usability, the questionnaire item “MCDAS is easier to use than a full-featured GIS” met with a generally neutral response, but it was noted that additional training would be required for users without GIS experience. Participants also felt that the MCDAS software is too complex to bring into a public meeting, but scenario outputs or a simplified tool that dynamically shows the effect of changing weights may be effective in such forums. There was consensus that synchronising the colours and content of summary charts with output maps and providing drill-down capabilities were effective in helping make manageable the large volume of data.

Other feedback confirmed a number of well-known strengths and weaknesses of GIS-based MCDA. Participants felt that these types of methods are useful for continuously incorporating new data and for monitoring changing values over time, and provides a motivation for organisations to develop and maintain data sets. Exploring and analysing problems spatially with maps and linked charts allows participants with different objectives to see that conflicts are often location specific, and that location-based compromises are possible in the interest of larger goals. Participants generally agreed with the assertion that "MCDA documents and makes explicit the value judgments that lead to a decision." However, the subjectivity of decision-making processes was also seen as a weakness of MCDA, in that models can be manipulated to support desired outcomes by including or excluding criteria and changing weights. Another identified weakness was the potential impact of MCDA model biases that would be hidden from uninformed users.

3.5 Discussion and conclusions

This paper presents a conceptual approach to GIS-based MCDA that proposes the addition of an exploration phase prior to the traditional evaluation phase and integration of the exploration and analysis phases in a single software system with transparent, easy-to-use tools. The approach was designed and developed following UCD principles and the Agile software development methodology. It was assessed based on its application to a decision-making case study in a region with a dominant forestry industry and a variety of other land-management interests.

The case-study assessment concluded that in-depth exploration using coincidence analysis is effective for helping to better understand a problem and structure it for evaluation. This result contributes to the GIS-based MCDA literature by explicitly addressing the exploration phase inherent in all decision-making processes. The capacity to explore and visualise the decision problem provides a basis for discussion among interest groups on the relevance of particular input layers and which criteria may be included or excluded from a systematic evaluation. In the case study, it was constructive to observe how, out of the exploratory analysis, participants came to formulate their evaluation objective of giving a conservation rating to areas of planned timber harvest. One of the benefits of an extended and well-supported exploration phase is the ability to minimise the degree of pre-judgment of a problem at hand (Ramsey, 2009). Addressing the broad basis of EBM principles requires such an open-minded approach. As EBM encompasses ecological, social, and economic factors, identifying and incorporating relevant perspectives and criteria to measure those perspectives is an on-going task that takes time. A decision analysis process with an explicit exploration phase encourages allocation of the needed time.

Having the exploration and evaluation phases integrated in a single system allows the exploration layers to be made immediately available for evaluation, and for all layers to be visually compared with reference layers of interest. An integrated exploration phase also supports iterative sensitivity analysis, which involves performing multiple evaluations to test the sensitivity of outputs to changes in selection and weighting of criteria (Malczewski, 1999b; Store and Kangas, 2001; Feick and Hall, 2004). In the case study, sensitivity analysis showed that giving extremely high weights to the criteria that represent a particular perspective drastically changed the resulting MCE outputs relative to the equal weighting case. However, slightly favouring one perspective caused more subtle changes in the location of conservation hotspots within the 25-year harvesting plan. Despite substantial discussion about the effects of changing weights, participants decided to use their original independent criteria rankings to derive overall group weights for the “final” MCE output.

Regarding the identified need for transparency, MCDA methods used in this study were selected in part for their simplicity (Belton and Stewart, 2002; Kangas and Kangas, 2005; Løken, 2007) in order to comply with a UCD approach. The mixed feedback on transparency underscores the need for additional instruction on MCDA terminology and methodology. Although the underlying algorithms were the subject of group discussion and were covered in software documentation, perhaps they could be communicated directly in the MCDAS user interface using a wizard that documents each step. Usability of the GIS-tools (Jankowski and Nyerges, 2001; Haklay and Tobón, 2003; Balram and Dragićević, 2006) was also an important element of the research objectives. The generally neutral feedback on usability was influenced by the mixed GIS experience (from none to substantial) of the case-study participants and also by the intention to design MCDAS generically, so that it is applicable to other data sets and study areas. Including additional functions for managing map documents, adding and removing layers, changing layer display settings, and managing analysis settings added to the complexity of the user interface design without any benefit in the case-study setting. However, as with other types of analytical mapping tools, GIS-based MCDA will almost always require some degree of technical expertise for preparation of the input data layers. In short, complexity may never be removed entirely; however, I believe that the proposed approach reduces substantially the degree of complexity for users compared with many conventional practices.

A number of limitations of the GIS-based MCDA approach and case study, with corresponding opportunities for further research, have been identified: (i) because case-study participants had no previous MCDA experience, it was not possible for them to compare the approach with other GIS-based MCDA approaches that do not integrate an exploration phase and begin with the evaluation model. Such a comparative analysis is a possible topic for a future study. (ii) There is also room for further exploration of alternatives to arrive at criteria weights in a group setting. The private, individual criteria ranking method used might help avoid direct conflict, but a discussion-based method could lead to a compromise or consensus with greater participant buy-in. Another possibility is to use an open-ballot voting method, but one participant thought it would be unwise because it often polarises a group into voting camps. (iii) Coincidence analysis can be used to compare multiple competing objectives during exploration, but the chosen MCE weighted overlay method can only be applied to a single objective per scenario during evaluation. Simultaneous evaluation of multiple conflicting objectives typically requires a mathematical optimisation or heuristic method, both of which are algorithmically and computationally more intensive and often implemented outside the GIS software. The use of constraints with weighted overlay allows a limited form of incorporating additional objectives, as was done in the case study by constraining the conservation rating objective to areas within the 25-year harvest plan. It is also possible to run multiple MCE scenarios with different objectives and compare their outputs. Systematic conservation planning researchers, however, generally recommend methods that help identify areas simultaneously meeting multiple objectives over single-objective scoring methods such as weighted overlay (Margules and Sarkar, 2007). Integration of exploration tools with multiple objective evaluation methods thus represents a research opportunity. (iv) Uncertainty needs to be managed at multiple levels in MCDA: in input layers, in criteria weightings, and in reconciling competing values. Although binary coincidence analysis is limited in its ability to incorporate uncertainty, it proved sufficient for the case-study participants to identify areas of competing values. However, the design is sufficiently open and flexible to incorporate uncertainty such as the use of probability models and fuzzy logic, and this represents another research opportunity.

Participant confirmation of some of the well-known strengths of GIS-based MCDA was balanced by concern regarding potential model biases. For instance, some MCE input layers are represented by binary values (with 1 indicating presence and 0 meaning absence) whereas others are continuous (with the only highest value assigned 1 and other values ranging between 0 and 1). Binary input layers, therefore, tend to exert more influence on the MCE output values, and should only be used when continuous-valued data are not available (Bonham-Carter, 1994). There is also greater influence from layers covering a larger spatial extent. This greater influence is, perhaps, undue and could be corrected (for instance, by assigning layers of greater spatial extent lower weights to compensate for their pervasiveness). It may also simply reflect the greater importance of such expansive layers, although this is a topic that does not appear to have been studied. Bias can also result from the MCE aggregation method. When a flat weighting and aggregation structure are used (with the weighted criteria being summed in a single step), greater influence is exerted by perspectives with a larger number of criteria (in the case study, there were three regional planning criteria layers, four tourism, and six wildlife). Hierarchical aggregation techniques (Saaty, 1980; Malczewski, 1999a) combine input layers for each perspective and then perform a weighted aggregation of the perspective scores, and these techniques can help overcome biases associated with flat aggregation. In general, I do not view the existence of model biases as a weakness per se, but conclude that it is important to explicitly inform model users of as many potential biases as possible. This is in keeping with the openness of MCDA, which is further reinforced through the ability to re-trace steps in an analysis and to make explicit all assigned values and weights.

In summary, the research presented here is relevant on both practical and theoretical levels. On a practical level, the specific case-study outputs, as well as the tools and input data sets, were made available (some under the limitations of data-sharing agreements) to the participating organisations, and could be used to support adjustments in the 25-year harvest plan. Case-study participants expressed a desire to see such an approach adopted in land-management practices in the Humber region, and to include additional conservation criteria as input to future harvest plans. In describing its ability to integrate many perspectives and criteria, one of the participants likened the MCE output maps to a group CAT scan that illustrates what the “thinking” of various interest groups looks like when their values are projected spatially (Fig. 3.10). Forestry and conservation management are but two of many applications of integrated land management that can be analysed using EBM principles. However, EBM requires methods for evaluating specific situations in terms of its broadly-based principles. The case study demonstrates how GIS-based MCDA methods can support this requirement. The MCDAS software that embodies the approach is generic and can be applied to a variety of spatially continuous land management problems in other geographic locations.

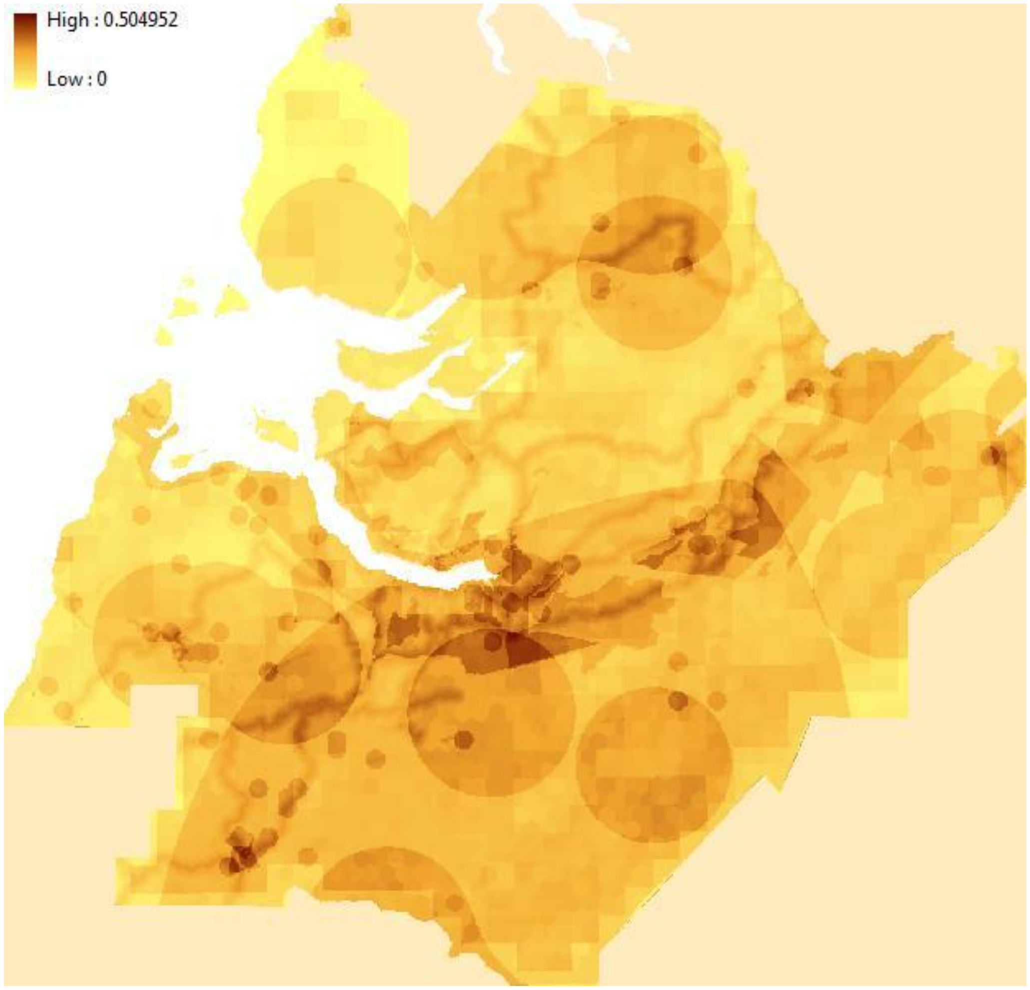

Fig. 3.10. "CAT Scan" multiple-criteria evaluation (MCE) showing conservation rating of entire study area using equal weights for all criteria. Many input layers are clearly visible, including large circles for outfitter camp buffers, polygons representing municipal boundaries, lines showing trail buffers, and small squares for marten home ranges.

On a theoretical level, this study highlights the importance of supporting an exploration phase in GIS-based MCDA and demonstrates one way of integrating it into the analysis process. Other ways of supporting problem exploration and structuring, such as "strength, weakness, opportunity, threat" (SWOT) analysis, idea generation and capture sessions, and cognitive mapping exercises are discussed in the MCDA literature (Belton and Stewart, 2002). The exploration approach complements these techniques by providing a spatially explicit view of the problem and facilitating analysis of areas of spatial coincidence among potential criteria. It is the author's hope that highlighting the exploration phase sparks an interest in integrating other problem exploration and structuring techniques into more comprehensive GIS-based MCDA tool suites and SDSSs.

I believe the proposed approach represents a step towards less fragmented forest management. As Yaffee (1999, p. 722) observes:

> "Landscape fragmentation also is reinforced by fragmentation of information, values, legal structures and responsibilities; integration across bodies of knowledge, interests, space and time is difficult."

Our ability to deal with information fragmentation and similar problems is in part related to how we make use of scientific information in forest-management decisions, especially with respect to mitigating competing values and interests. GIS-based MCDA helps bring scientific information about forest ecosystems into decision-making environments without watering down the data. This allows forest managers to deal with the complexities of competing values on a location-by-location basis, as opposed to implementing widespread general policies that reinforce landscape fragmentation and dominant-use scenarios.

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Chapter 4 Conclusions

4.1 Summary

Land management is an important and complex activity that requires numerous and often conflicting perspectives to be considered. While traditional GIS-based MCDA can be useful in such a context, it can be limited in its accessibility to land-management decision makers and analysts, where accessibility is defined as the ease of understanding and use of available tools and methods. This research aimed to better support land-management decision makers and analysts in simultaneously considering multiple values by improving the accessibility of GIS-based MCDA. An approach which addresses a number of accessibility challenges was developed, implemented in a customized software system and validated using a case study. Analysis of the case-study feedback supports the conclusion that the proposed approach, which specifically addresses the exploration phase of decision analysis, facilitates understanding of land-management decisions in preparation for a more comprehensive multiple-criteria evaluation phase. This is an important result, given that non-spatial MCDA research has considered methods and tools for problem exploration and structuring, but the exploration phase has received little attention in GIS-based MCDA research.

Four research questions were posed in section 1.3 and have been addressed as follows:

- **What are some of the accessibility challenges of GIS-based MCDA for land management?**

Analysis of the existing literature helped identify a number of accessibility challenges. The main ones considered in this research are (1) the breadth and complexity of the GIS and MCDA fields, (2) the lack of support for the exploration phase of decision analysis, and (3) the lack of transparency of some tools and techniques. Chapter 2 helped address the first challenge by introducing GIS-based MCDA in a way that is accessible to people without any prior MCDA knowledge and by providing guidance for applying available methods. It also helped place GIS-based MCDA and its terminology within the wider field of SDSS. Chapter 3 introduced an approach to GIS-based MCDA that integrated simple and easy-to-use exploration tools, thereby showing one way of addressing the second and third challenges. Chapter 2 concluded by identifying two other GIS-based MCDA accessibility challenges: developing effective web-based delivery to facilitate broader and more effective interest group involvement, and improving geovisualisation capabilities to facilitate a rich and engaging experience.

- **How can the process of selecting appropriate GIS-based MCDA methods for a particular land-management problem be guided?**

Guidelines are necessary for the process of selecting appropriate GIS-based MCDA methods for a particular land-management problem. As models are intended to be a representation of reality, it is critical to understand the decision problem being modelled. An exploration phase with appropriate analysis tools, such as those suggested in the designed approach and described in chapter 3, can be very helpful in developing problem insight. This knowledge can then be used to help select an appropriate set of GIS-based MCDA methods. One set of guidelines for selecting GIS-based MCDA methods is described in the literature review (sections 2.3 and 2.4), and it requires that the problem has been explored sufficiently to know, at least in rough terms, the decision objective(s), alternatives, and potential criteria. The selection process should also consider method transparency as well as the sensitivity analysis strategy of using more than one GIS-based MCDA method. These considerations support the MCDA philosophy that emphasises that 'people' make decisions, while computational tools like GIS-based MCDA provide supporting information.

- **Which usability enhancements from other areas of GIS research might be incorporated in a customised software system to improve the accessibility of GIS-based MCDA?**

A number of usability enhancements from other areas of GIS research can improve the accessibility of GIS-based MCDA. As described in sections 2.7 and 3.2, geovisualisation and cybercartography offer ideas for many potential enhancements that balance richness and simplicity in user interaction. One technique is automatic synchronisation of maps and charts that summarise those maps, as used in geovisualization and SOLAP systems and implemented in the MCDAS software (appendix E). It can apply to the colour palettes, so that selecting a new palette for the map results in an updated chart that reflects the new colours. It can also apply to the content, for instance by automatically recalculating charts based on the visible extent of the corresponding map. Another geovisualisation technique also inspired from SOLAP systems is to initially present a summary view, such as the overall rating at a particular location, then drill down for details, such as information showing how the rating at that location was derived. Case-study participants found these techniques effective in visualising multiple-criteria problems.

- **How can a generic approach that addresses accessibility challenges be validated?**

Presenting the design of a GIS-based MCDA approach would have been sufficient to communicate how the concept addresses some of the accessibility challenges. However, validating the approach with a real problem for users inexperienced in GIS and MCDA required the approach to be implemented as software. Because of the usability-oriented research objectives and the user-interface complexities of full-featured GIS, a custom user interface was developed and presented in chapter 3 and in appendices C, D, and E. This also facilitated the research objective of integrating exploration tools. With a software system to demonstrate the approach in place, a hands-on case study could then be used to provide feedback and validate the original design concepts.

The research hypothesis questioned whether this approach "**will improve the ability of land-management decision makers and analysts to simultaneously consider diverse values**." Case study participant feedback confirmed directly that MCDA approaches generally are useful in combining diverse criteria, both quantitative and qualitative, in an integrated analysis. All questionnaire respondents agreed with the statement that MCDA "can incorporate multiple diverse perspectives and factors", with the majority of them agreeing strongly. Participants also agreed that the weakness that MCDA can support virtually any decision by manipulating the criteria and weights, identified in section 3.4.5, was adequately balanced by MCDA's ability to make explicit those value judgements. Further validation for the hypothesis can be found in the primary research result stemming from the case study, that exploration facilitates problem understanding and structuring in GIS-based MCDA. It is an important phase in the process of integrating diverse values in decision analysis for land-use and natural-resource management.

4.2 Limitations and opportunities

Although this research confirms the hypothesis that the GIS-based MCDA approach can improve land managers' analysis of decisions involving multiple values, there remain a number of aspects in the current approach that could be explored further. These relate to the decision-analysis methods used, as well as the research methodology and scope. Research opportunities can also arise from considering different approaches to the accessibility challenges addressed here as well as from considering other accessibility challenges, such as how to help support public participation in land-management decisions with GIS-based MCDA and how to incorporate advanced visualisation techniques, as indicated in chapter 2.

Given the transparency and usability objectives as well as the input and feedback from case-study participants and other interested parties, relatively simple GIS-based MCDA methods were used in the approach. Although decision makers tend to avoid overly-complex decision models (Malczewski, 2006b), limitations exist in the binary overlay and WLC (also known as simple additive weighting) multiple-criteria methods used (Bonham-Carter, 1994; Roy and Vanderpooten, 1996; Bouyssou et al., 2006). There are potential biases associated with flat, or single-level, aggregation, and as introduced in section 2.4.2 and described in section 3.5, hierarchical aggregation techniques could help overcome these.Hierarchical aggregations are, however, operationally more complex because weights must be established at each level of the hierarchy and they require a decision whether to normalise the aggregated scores for each perspective. In the case study presented here, several hierarchical aggregation scenarios were run, but because the intermediate perspective-level scores were normalised, the overall scores could not be compared to the non-hierarchical scenario results. The research could be advanced by comparing outputs from flat and hierarchical evaluation techniques.

Limitations also exist in the independent ranking method used to determine the "final" criteria weights for the case study group (section 3.4.4), particularly the inflexibility of the sequential integer scale used for ranking. There are many other possible approaches to aggregation of individual judgements, such as point allocation and vote-trading models (Hwang and Lin, 1987; Mendoza and Martins, 2006). Of course, as pointed out by one case-study participant, any public voting method can lead to “bad blood”. Another approach is attempting to find consensus, if possible, through in-depth discussion and negotiation. GIS-based MCDA exploration activities can certainly support this process by helping identify similarities and differences in values across the group. However, historical differences in levels of power among the individuals at the table and the interest groups they represent can have a strong influence in open negotiations. One questionnaire respondent also felt that the group weighting approach used (mathematical aggregation of independent rankings) was substantially more expedient than negotiating. Regardless of the method chosen for aggregating individual preferences and judgements, in keeping with the theme of promoting transparency in MCDA it is recommended that the mechanics be clearly communicated to the group.

From a methodology perspective, it would be desirable to work with a larger group of participants (and therefore questionnaire respondents) to facilitate testing of statistical significance of the responses. Also, although few decision makers have an in-depth knowledge of MCDA approaches, having a group with minimal GIS-based MCDA experience limited the type of validation possible. For instance, the participants were forced to compare the approach used here with non-MCDA approaches. Participants with more GIS-based MCDA experience would be able to compare the approach developed in this thesis to GIS-based MCDA approaches without explicit support for an exploration phase. Due to constraints of time and other resources, the case study scope was limited to a single geographic region, one group of participants, and a single decision problem. Practicality also limited the number and types of accessibility challenges that could be addressed. For instance, more comprehensive approaches could involve participants in addition to decision makers and analysts acting in professional roles, such as public participation through information sessions and workshops or via the internet. Public participation must be thoughtfully crafted, however. For example, the design rigour of survey-based data gathering can be easily compromised in a web implementation (Duda and Nobile, 2010). Decision makers must also be open minded in receiving broad input, even if it is contrary to prevailing wisdom. For instance, a recent public-attitudes survey regarding forest management in Newfoundland found that there was very little public support for hunting outfitters, even though they are a substantial part of the tourism sector and a powerful lobby group (Bath, 2006). Adding to the policy-making challenge is the fact that messages from the public can be contradictory. For instance, even where public attitudes appear to favour wildlife protection, it has been shown that there is a limit to how much the public are actually willing to risk their own perceived safety and comfort (Carpenter et al., 2000). There is a research opportunity in further studying such human-dimension implications of GIS-based MCDA for land and resource management.

Another opportunity exists in investigating the many ways to potentially enhance support for data-exploration activities in GIS-based MCDA generally and MCDAS in particular. For instance, coincidence analysis could be augmented to automatically search among all available binary layers to determine which ones coincide spatially with areas of interest. The process of specifying cut-off criteria could be made more flexible by allowing more sophisticated logic expressions. Opportunities for user interface improvement include the ability to automatically carry analysis layer selections from coincidence analysis to MCE, instead of having to make layer selections again. Interactive geovisualisation capabilities could be enhanced by adding more chart types and through "brushing" of chart sections, which automatically highlights in the map pane data related to the selected chart section (Jankowski et al., 2001).

The coincidence analysis and geovisualisation elements of our approach, as well as other exploration tools, could potentially enhance existing GIS-based software toolkits. Some toolkits include more complex MCDA evaluation methods like multiple-objective optimisation, to allocate land efficiently among economic, social, ecological, and other goals. Some toolkits have been customised for a specific land-management interest such as forestry (for instance Remsoft's Woodstock, Stanley, and Allocation Optimizer - http://www.remsoft.com/), conservation planning (such as Marxan from the University of Queensland - http://www.uq.edu.au/marxan/), or urban planning (like placeways' CommunityViz - http://www.placeways.com/). There is an opportunity to continue developing and improving such integrated toolkits, which would also contribute to the goal of increasing accessibility of GIS-based MCDA.

In addition to integrating easy-to-understand spatial exploration methods such as coincidence analysis, less quantitative and non-spatial approaches could also help in GIS-based

MCDA problem structuring. Several of these were identified in the conclusions to chapter 3, and they fall into a class called "soft systems" or soft operations research (Soft-OR) methods (Rosenhead, 1989; Belton and Stewart, 2002; Mendoza and Martins, 2006). Robustness analysis is another Soft-OR method, and it manages uncertainty about the future by repeatedly modelling a decision to be made in the short term with respect to several alternative scenarios of how the future may unfold. The Delphi technique is a facilitated approach to achieving consensus among a group of experts (Linstone and Turoff, 1975). It is intended reduce the potential for group dynamics to lead to "group think", and highlights a possible weakness of the group meetings and focus-group session employed in this project. Individually-completed questionnaires were used with the intention of balancing this potential bias and it is therefore noteworthy that all of the questionnaire respondents identified the need for additional training, even though this issue had not been raised with the group.

Finally, the research described in this thesis is potentially significant on several levels. For GIS-based MCDA generally, the thesis provides new focus on accessibility, particularly on the benefits of integrating exploration tools. For land and natural resource management, enhanced accessibility to GIS-based MCDA means opening up this family of analysis methods to additional interest groups and the new criteria and priorities they will bring. It also facilitates use of GIS-based MCDA as an analysis tool for ILM and EBM. For the Humber region, the significance goes well beyond the harvest plan conservation ratings that resulted from the case study decision analysis. Having the case study based on local perspectives and data should help such approaches gain credibility more easily than if the same research had occurred in another region. The research and application opportunities at each of these levels will continue to evolve. At a regional level, for instance, as decision makers and analysts become familiar with these types of tools, there may be a focus on the currency and quality of input data or on using more complex MCDA techniques for their modelling advantages. Approaches targeted at more sophisticated users can still take advantage of many of the accessibility enhancements and related opportunities described here, and they are likely to reveal new and different accessibility challenges.

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Appendix A – Case-study focus group questions

- What do you see as the strengths and weaknesses of the approach we've taken to land management decision making?
- From your professional experience, compare the process used in this case study with decision making processes for similar scenarios that did not employ similar tools and approaches.
- Did you have sufficient understanding of the tools used (both Coincidence Analysis and Multiple Criteria Evaluation) to be confident in interpreting their output and recommendations?
- Was sufficient insight gained through Coincidence Analysis alone to identify the conservation hot spots?
- Did MCE help identify the conservation hot spots?
- Do you believe the tools and approaches are applicable to other land management scenarios you are likely to face?
- For what types of land management decisions are they not applicable?
- Would your organization accept the conservation priority areas identified?
- Would this approach work in reality, outside the case study setting?

Appendix B – Case-study participant questionnaire

Land Management Decision Making Case Study Follow-up Questionnaire

1. Rate the following weaknesses and strengths of the approach used in the case study. Disagree Strongly means you do not believe it is a weakness or strength at all. Neutral means you agree that it is a weakness or strength, but are unconvinced that is has significant consequences. Agree Strongly means you agree that it is a weakness or strength, and that is has very significant consequences. Add and rate any weaknesses or strengths you feel are missing.

Tool (MCDAS) Weakness	**Disagree Strongly**	**Disagree Somewhat**	**Neutral**	**Agree Somewhat**	**Agree Strongly**
There is a requirement for training for any new user of MCDAS.					
There is a requirement for an ESRI software license for each workstation that runs MCDAS.					
Generally speaking, Multiple Criteria Decision Analysis provides a variety of methods for cutting off (when converting to binary), normalizing (when converting to a continuous scale), weighting (such as ranking, rating, voting, pair wise comparison), and ordering alternatives (for instance single level aggregation, hierarchical aggregation, outranking, ideal point). MCDAS, however, supports only a limited number of these methods.					
MCDAS can require significant computing power for responsive processing, depending on the scale of analysis and resolution of data.					
MCDAS was designed to be flexible in supporting various decisions and datasets, but this introduces a requirement for GIS expertise in data preparation.					

Process Weakness	**Disagree Strongly**	**Disagree Somewhat**	**Neutral**	**Agree Somewhat**	**Agree Strongly**
The human network that typically surrounds a multiple criteria decision making process in practice can be complex or even unwieldy.					
There is substantial subjectivity in the process of weighting or ranking criteria.					
Constraints of data availability and quality significantly limit the completeness of the analysis and trustworthiness of the outputs.					

There is a tendency for input layers with large spatial extent to dominate in the outputs, independent of their importance or relative weighting.					
Errors in data preparation or other early steps can cascade through later steps.					
Multiple Criteria Decision Analysis can support many different views or recommendations for the same problem by including/excluding layers and manipulating cut offs, normalization values, and weights.					
There is a lack of transparency in the data preparation and processing, especially for the public, for high-level decision makers, and for others who are not close to the process or don't have time to be informed about the inputs and analysis methods.					

Tool (MCDAS) Strength	**Disagree Strongly**	**Disagree Somewhat**	**Neutral**	**Agree Somewhat**	**Agree Strongly**
MCDAS' analysis tools (Coincidence Analysis, MCE) are transparent (easily understood).					
MCDAS provides a robust of framework, for instance to incorporate future issues and changes to current issues.					
MCDAS easily incorporates new data as it becomes available.					
MCDAS is easier to use than a full-featured Geographic Information System (GIS) package.					
MCDAS' use of charts/graphs dynamically linked to maps is an effective visualization technique.					
MCDAS' use of colour in maps and chart/graphs is intuitive.					

Process Strength	**Disagree Strongly**	**Disagree Somewhat**	**Neutral**	**Agree Somewhat**	**Agree Strongly**
Multiple Criteria Decision Analysis can incorporate multiple diverse perspectives and factors.					
It helps objectify decision making.					
It helps quantify the decision process, particularly for more qualitative values.					
Multi-stakeholder decision making provides motivation for development and maintenance of better data by participating organizations.					

Multiple Criteria Decision Analysis makes explicit the value judgements that lead to a decision, thereby balancing the criticism that it can help support virtually any decision or outcome.					

2. Was sufficient time allotted for the case study meetings?

3. Were the software tools easy to use? How can they be improved?

4. Did you have sufficient understanding of the tools and approaches used (both Coincidence Analysis and Multiple Criteria Evaluation) to be confident in interpreting their outputs and recommendations?

5. Was the preliminary exploration phase (using Coincidence Analysis) effective in helping understand the situation and the criteria available to model it?

6. Was the systematic evaluation phase (Multiple Criteria Evaluation) useful in helping identify conservation hotspots within the harvest plan areas?

7. Which approach to determining criteria weights (voting, ranking, negotiation/compromise) would be most effective in a group setting?

8. Do you have any others comments or feedback?

Appendix C – Coincidence analysis preliminary design

Coincidence Analysis Design

Randal Greene

June 2009

DRAFT

1 Introduction

In the spirit of flexibility and brevity, this is a high-level software design. It documents the software requirements and provides high-level suggestions for their implementation, but not implementation details. It is intended to be a focal point for discussion and refinement.

Coincidence analysis supports the exploratory visualization phase for the MSc research project *A GIS-based Multiple Criteria Approach to Support Integrated Land Management Decision Making within the Humber River Basin*. The goal of coincidence analysis is to spatially visualize the number of coincident layers for each location within a study area, and the extent of coincidence for the study area overall. The input layers can represent any spatial phenomenon, such as potential criteria layers for a decision-making scenario. But coincidence analysis is intended to be flexible in its use, and not tied specifically to multiple criteria decision making. Depending on the application, the input layers may represent complementary or conflicting phenomena. Each input layer defines presence/absence of the spatial phenomenon, so it must either be binary or capable of being converted to binary.

Two logically separate software components are envisioned. The *Coincidence Tool* is a geoprocessing tool that accepts input parameters and creates output map layers. ArcGIS is the targeted geoprocessing environment, but this design should be flexible enough to be implemented in most automatable GIS software. The *Coincidence Analysis System* (CAS) is a custom GIS application that uses the Coincidence Tool, adding functionality for map layer control, panning and zooming, and for graphing of the coincidence tool results. The targeted platform for CAS is either a desktop application (such as a standalone Windows application built on ArcObjects) or a web-based application (such as a browser application built on ArcGIS Server), but this design should be flexible enough to be implemented on any platform that can access the targeted geoprocessing environment. Separating the Coincidence Tool geoprocessing into its own component allows it to be reused outside CAS, for instance as a custom ArcGIS Desktop (ArcMap) tool.

2 Use Cases

Use cases are a software design technique for documenting system requirements textually and graphically. They describe and depict the scenarios in which actors interact with (use) a system, and the dependencies of the various use cases on each other. The diagrams are based on the Unified Modeling Language (UML) family of diagrams, and each use case represents a goal at a specific level. *Kite Level* goals show how the other use cases fit into broader purposes. *Sea Level* goals describe a discrete interaction between a primary actor and the system. *Fish Level* goals support Sea Level use cases.

Figure 1 is a UML diagram of the use cases identified for Coincidence Analysis, and their textual descriptions follow. Line segments with no arrowheads show actors participating in use cases, and line segments with arrowheads show dependencies among use cases.

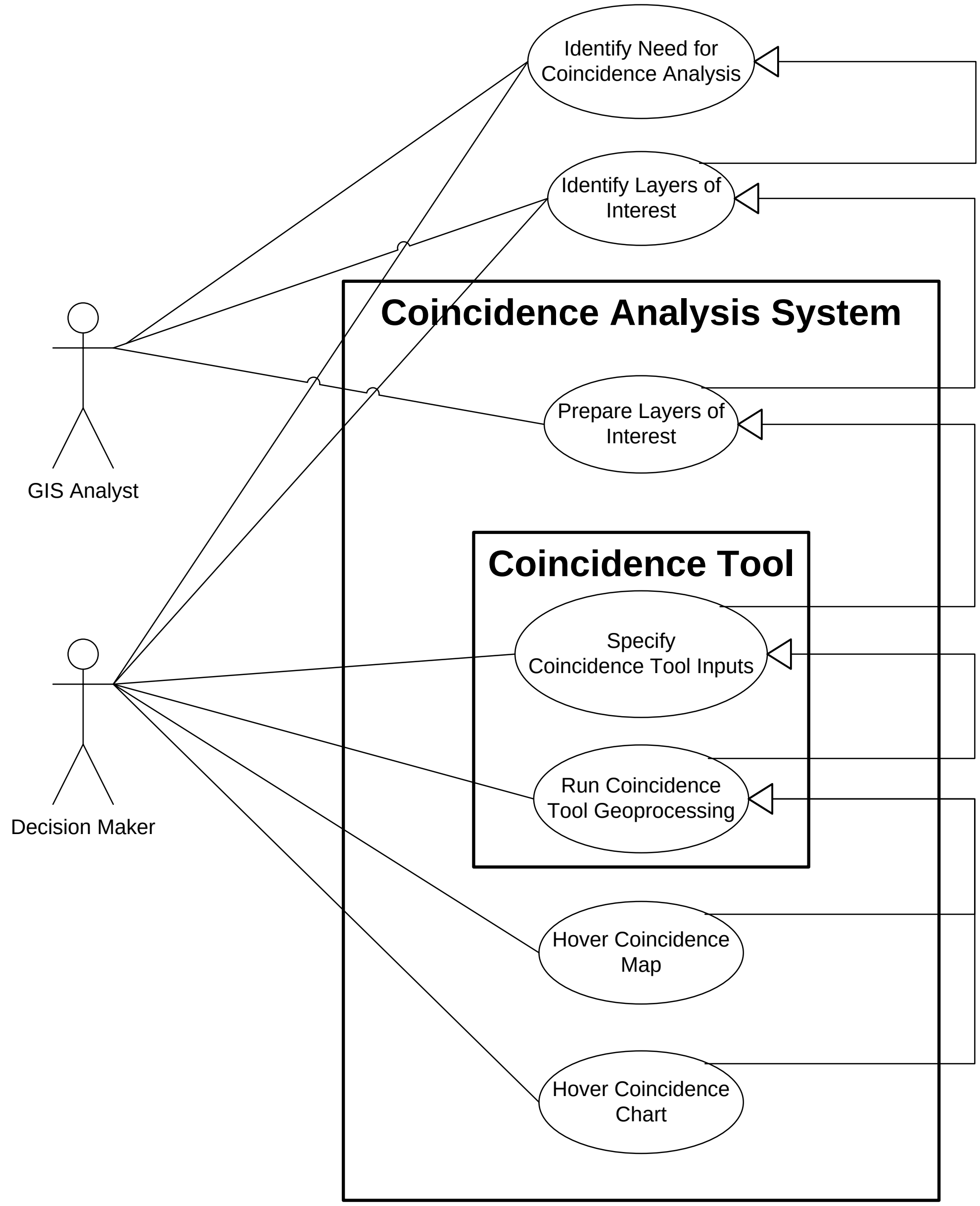


Figure 1 - Coincidence Analysis Use Cases

2.1 Identify Need for Coincidence Analysis

Goal Level: Kite Level

Scenario:

1. Decision Maker (end user) identifies possible use of coincidence analysis, and contacts GIS Analyst for assistance.

Decision Maker and GIS Analyst define clear analysis objective.

2.2 Identify Layers of Interest

Goal Level: Kite Level

Scenario:

1. Decision Maker and GIS Analyst discuss possible spatial data layers that can contribute to the analysis objective.
2. For each layer of interest, sources, nature and quality of data are identified.

2.3 Prepare Layers of Interest

Goal Level: Fish Level

Scenario:

1. GIS Analyst follows up on each layer of interest.
2. As required, data for each layer is created or imported into an appropriate format for use with CAS.
3. As required, data for each layer is transformed to account for issues such as spatial reference system and scale.
4. Metadata for each layer is created or updated.
5. Each layer is made available for use in CAS.

Comments:

The *Abstract* metadata element should be filled for each layer with informative text and links to academic literature and related web sites, as it will become the primary documentation source for that layer in CAS.

2.4 Specify Coincidence Tool Inputs

Goal Level: Sea Level

Scenario:

1. Decision Maker opens Coincidence Tool dialog.
2. Layers or groups of layers to be analyzed are selected.
3. For non-binary layers, the attribute name and cut-off value for converting to binary are specified.
4. Analysis geographic extent and mask are specified/selected.
5. Spatial resolution of output coincidence layer is chosen.
6. Name of output coincidence layer is chosen.
7. An optional layer defining regions into which the analysis is sub-divided may be chosen.

Comments:

Additional details can be found in the Coincidence Tool User Interface section below.

2.5 Run Coincidence Tool Geoprocessing

Goal Level: Fish Level

Scenario:

Decision Maker starts geoprocessing based on inputs described in previous section.

Comments:

Additional details can be found in the Coincidence Tool Geoprocessing section below.

2.6 Hover Coincidence Map

Goal Level: Sea Level

Scenario:

1. User hovers mouse over output coincidence map.
2. Pop-up text indicates names of coinciding layers under mouse.

2.7 Hover Coincidence Chart

Goal Level: Sea Level

Scenario:

1. User hovers mouse over pie chart corresponding to coincidence map.
2. Pop-up text indicates names and areas for each unique combination of coinciding layers for the pie slice under the mouse.

3 Coincidence Analysis System User Interface

Figure 2 presents a mock-up of the CAS user interface to show how the required functionality may be organized.

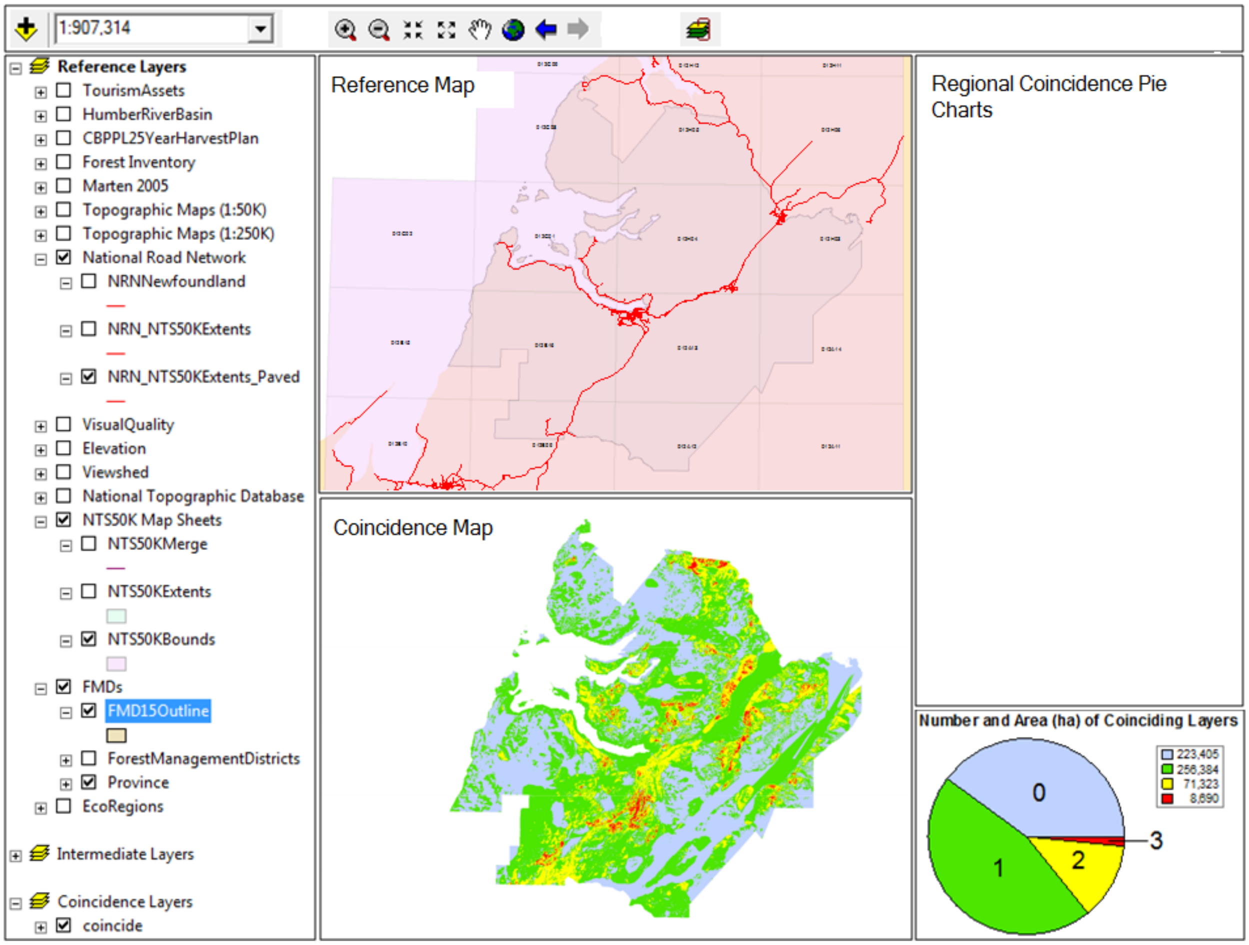


Figure 1 - Coincidence Analysis System User Interface

3.1 Table of Contents

The left side of the CAS user interface presents an ArcMap-style Table of Contents for interacting with layers: turn on, turn off, layer drawing order, symbol, colour, label and view abstract. The Table of Contents will include data frames (top level groups with yellow layers icons) for Reference Layers (available in the Reference Map window and as input to the Coincidence Tool geoprocessing), Intermediate Layers (created by the Coincidence Tool in an intermediate step) and Coincidence Layers (created by the Coincidence Tool and available in the Coincidence Map window).

3.2 Reference Map

The top centre section of the CAS user interface contains the Reference Map window. Its layers are controlled using the Reference Layers data frame of the Table of Contents. Panning and zooming are controlled using toolbar icons, and the spatial extents of this window are linked to the spatial extents of the Coincidence Map window (i.e. pan/zoom in one Map window will cause the same pan/zoom in the other Map window).

3.3 Toolbar

The toolbar along the top of the CAS user interface will provide buttons for adding data layers, panning/zooming, and opening the Coincidence Tool.

3.4 Coincidence Map

The bottom centre section of the CAS user interface contains the Coincidence Map window. Its layers are controlled using the Coincidence Layers data frame of the Table of Contents. Panning and zooming are controlled using toolbar icons, and the spatial extents of this window are linked to the spatial extents of the Reference Map window (i.e. pan/zoom in one Map window will cause the same pan/zoom in the other Map window). When the Coincidence Tool is run, the Coincidence Map window will automatically show the results of that run. The user can manually select an earlier Coincidence Layer for display, if desired. Coincidence Layers are coloured/shaded based on the number of coinciding input layers/groups at each location. Hovering over the Coincidence Map presents pop-up text with the names of the input layers/groups coinciding at that location.

3.5 Overall Coincidence Pie Chart

Linked to the active Coincidence Map, the bottom right section of the CAS user interface presents the Overall Coincidence Pie Chart. It has one pie slice for each colour from the active Coincidence Map, and its size the represents the relative area of that colour (number of coinciding layers). The pie chart legend displays the total area for each colour (number of coinciding layers). Hovering over the Pie Chart presents pop-up text indicating names and areas for each unique combination of coinciding layers for the pie slice under the mouse.

3.6 Regional Coincidence Pie Charts

If the user selects the optional regional polygon layer for subdividing the analysis (see the use case in 2.4 above), the region polygons will be shown on the Coincidence Map and a set of pie charts (one for each region) will be shown in the top right section of the CAS user interface. Regional Coincidence Pie Charts will appear and behave like the Overall Coincidence Pie Chart, except there will one chart for each region.

4 Coincidence Tool User Interface

When the user opens the Coincidence Tool, it will present a dialog box for specifying the inputs. This is depicted in Figure 3, and the inputs correspond to those described in use case 2.4 above.

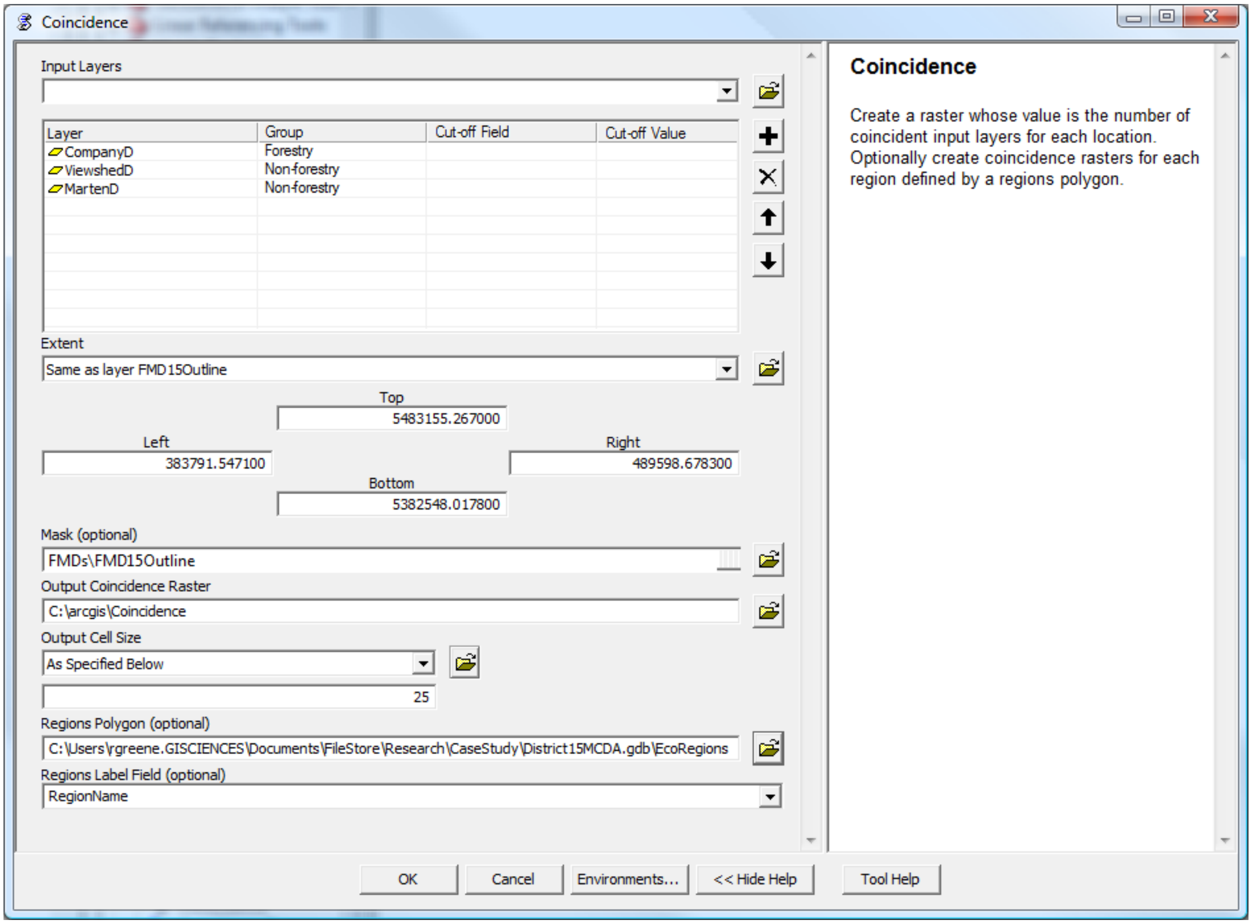


Figure 1 - Coincidence Tool Inputs Dialog

4.1 Input Layers

The primary input is a list of two or more rasters or polygon feature classes. The user can optionally group the layers by providing a Group label, so that the layers of a group are combined into a single input layer. Alternative user interfaces for grouping, such as a matrix, will be investigated.

If the input layer is not a binary raster, the user must specify the Cut-off Field and Cut-off Value for converting the layer to a binary raster.

4.2 Extent

The spatial extent of the output raster to be created. By default, this is the intersection of the spatial extents of the input layers.

4.3 Mask

An optional layer that defines a mask for the output raster to be created. All cells of the output raster outside the Mask will be set to NoData.

4.4 Output Coincidence Raster

The name and location of the output raster to be created. A default name will be provided.

4.5 Output Cell Size

The cell size, or spatial resolution, of the output raster to be created. By default, this will be a function of the extent.

4.6 Regions Polygon and Label Field

An optional layer that defines regions for sub-dividing the analysis. If specified, the tool will create an additional output raster for each region, using the Label Field to name the additional output rasters. This will facilitate creation of regional coincidence pie charts by CAS.

5 Coincidence Tool Geoprocessing

Figure 4 outlines the approximate geoprocessing model required by the Coincidence Tool.

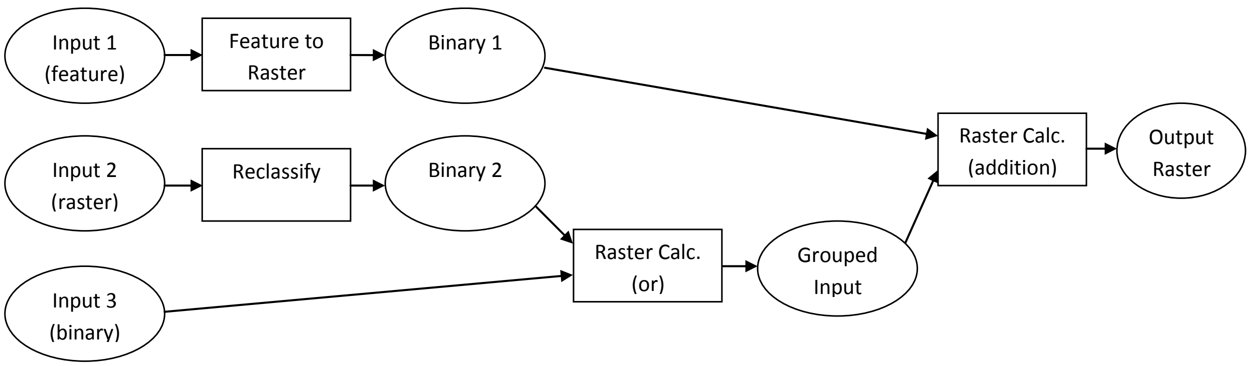


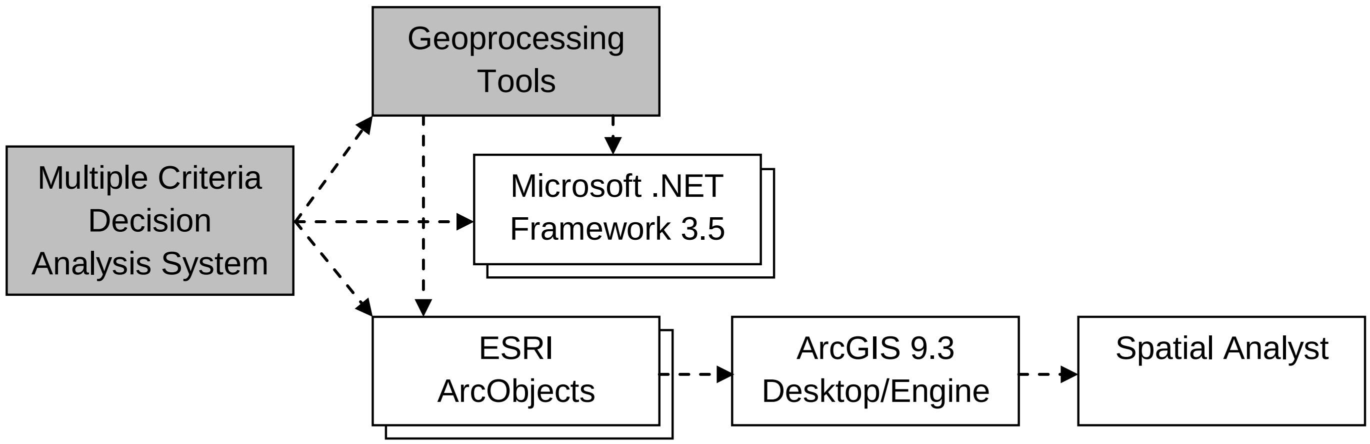
Figure 1 - Coincidence Tool Geoprocessing Model

There are 3 possible types of input layers. Feature polygons (Input 1) must be converted to a binary raster (Feature to Raster) based on the user-specified cut-off field and cut-off value. Non-binary rasters (Input 2) must be converted to binary (Reclassify) based on the raster value and a user-specified cut-off. Binary rasters (Input 3) can be used directly.

Two or more input layers can be grouped (Raster Calculator with the logical or operator) into a single binary grouped input.

Two or more input layers or grouped inputs are then overlaid (Raster Calculator with the addition operator) to build the output raster, where each pixel contains the count of coincident layers/groups at that location.

Appendix D – MCDAS high-level architecture



Note: shaded boxes indicate custom-developed components.

Appendix E – MCDAS user documentation

Multiple Criteria Decision Analysis System

Introduction

Multiple Criteria Decision Analysis System (MCDAS) is a Geographic Information System (GIS) that aids decision makers explore complex scenarios. It includes two sets of analysis tools:

1. Coincidence Analysis, to help visualize and analyze the extent and locations of spatial coincidence (overlap) among user-specified input layers, normally representing conflict or synergy. It first converts input layers to a binary 0-1 value, then counts the number of layers at each location (cell/pixel). It supports the preliminary exploration phase of spatial Multiple Criteria Decision Analysis (MCDA), and can also be used for screening or selection based on a simple binary approach.

2. Multiple Criteria Evaluation (MCE), to help evaluate locations (cells or pixels) in a single-objective scenario, based on user-specified criteria layers, with spatially continuous inputs and outputs (i.e. not discrete locations). It first normalizes inputs to a continuous 0-1 scale, then applies weights to each criterion (where all the weights sum to 1), and finally aggregates the weighted normalized scores for all criteria layers to calculate an overall score for each location. MCE supports the evaluation phase of spatial MCDA, for screening or selection.

MCDAS is built on ESRI ArcObjects 9.3.1 SP1, and is two-way compatible with map documents (.mxd files) and data layers (raster and vector) from ESRI ArcGIS 9.3.1 SP1.

Installation

The system requirements for running MCDAS are a Windows workstation with ArcGIS Desktop or ArcGIS Engine Runtime 9.3.1 SP1 plus the Spatial Analyst extension pre-installed. The application has also been lightly tested against 9.3 SP1, but is not officially supported against this or any version of ArcGIS other than 9.3.1 SP1.

MCDAS can be downloaded from the ArcScripts section of ESRI's web site: http://arcscripts.esri.com, http://arcscripts.esri.com/details.asp?dbid=16856.

To install MCDAS, run Setup and follow the instructions. If the Microsoft .NET Framework version 3.5 is not installed, it will be downloaded and installed by Setup. Run MCDAS from the Desktop icon, or from the Multiple Criteria Decision Analysis System program group under the Windows Start menu. If you have ArcGIS Desktop, you can also directly use two geoprocessing tools underlying MCDAS (the Coincidence tool and the FeaturePolygonToBinaryRaster tool) from ArcMap or ArcCatalog. To uninstall MCDAS, go to Control Panel, Add/Remove Programs, Multiple Criteria Decision Analysis System and select Remove.

User Interface

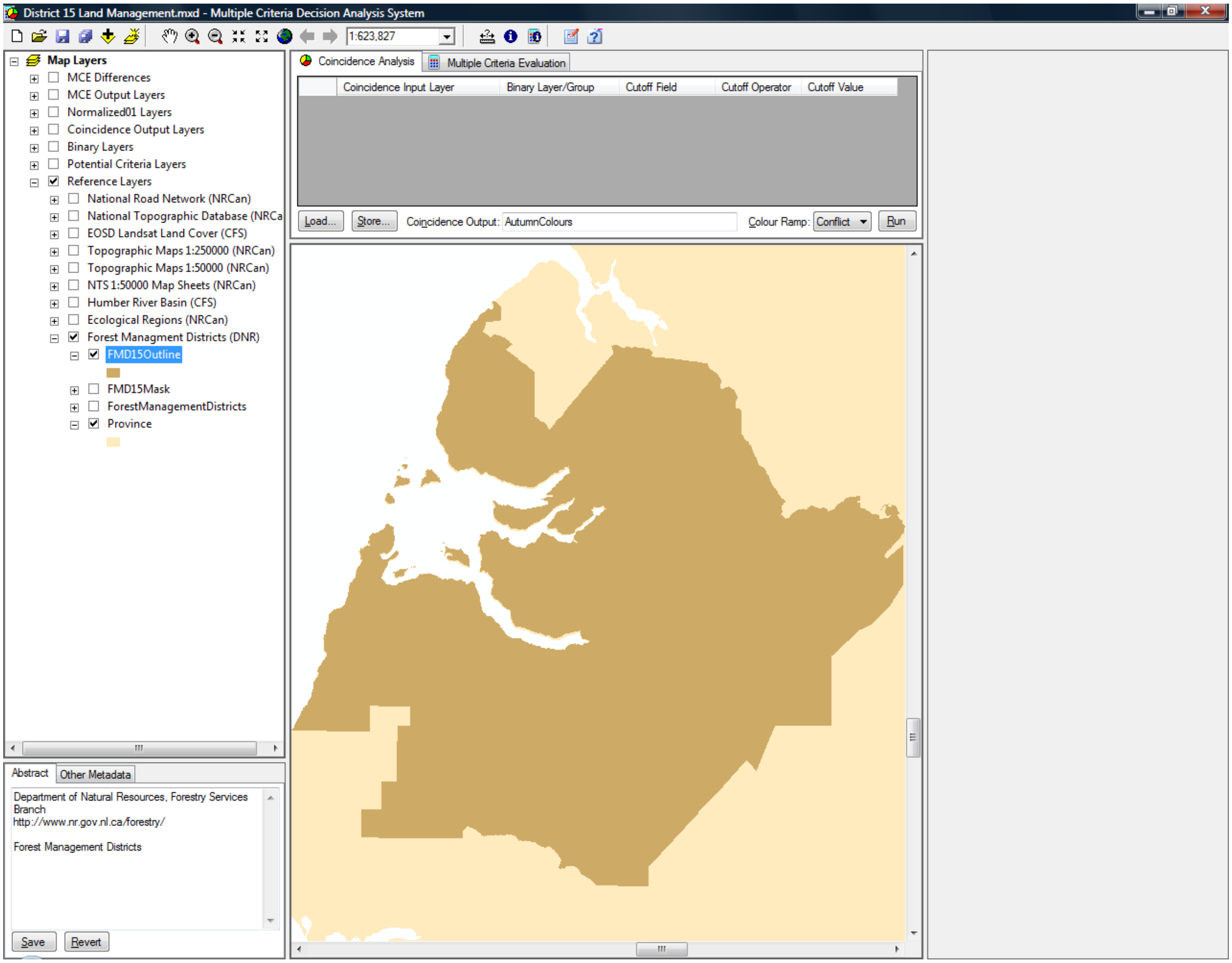


Figure 1 - MCDAS Main Window

The MCDAS main window is depicted in Figure 1 above. It is divided into the following Panels:

- Toolbar – the panel along the top of the main window, containing graphical buttons representing available commands and tools.
- Map Layers – the panel along the left side of the main window, containing a hierarchical table of contents of available data layers.
- Metadata – the panel in the lower left corner of the main window, showing selected metadata (background information) about the currently selected Map Layer.
- Map – the panel in the bottom center of the main window, showing all layers that are currently turned on.
- Analysis – the panel above the Map, where the user specifies the input layers and other parameters for creating Coincidence or MCE output layers.
- Charts – the panel along the right side of the main window, which shows summary information in chart format related to the current top-most turned on Coincidence or MCE Output Layer. The Charts panel is blank in Figure 1 because no Coincidence or MCE Output Layer is currently turned on.

All panels except the toolbar can be resized at the user's discretion by dragging the panel dividers.

Map Navigation

The middle section of the Toolbar panel contains commands and tools related to map navigation, as shown in Figure 2. "Extent" and "View" refer to the visible portion of the map.

Figure 2 - Map Navigation Commands and Tools

- Pan tool (hand icon) – re-centre the Map by dragging. You can also re-centre the Map using the scroll bars to the right and bottom of the Map.
- Zoom In tool (+ icon) – zoom the Map to a more local scale (show a smaller area in more detail) by clicking the center point or dragging a box around the approximate extents of the desired view.
- Zoom Out tool (- icon) – zoom the Map to a more regional scale (show a larger area in less detail) by clicking the center point or dragging a box around the approximate extents of the desired view.
- Fixed Zoom In command (4 inward-pointing arrows icon) – zoom the Map to a more local scale (show a smaller area in more detail).
- Fixed Zoom Out command (4 outward-pointing arrows icon) – zoom the Map to a more regional scale (show a larger area in less detail).
- Full Extent command (world icon) – zoom the Map to show the extents of all available layers.
- Go Back to Previous Extent command (left arrow icon) – zoom the Map to the extents visible before the most recent pan or zoom action.
- Go to Next Extent command (right arrow icon) – zoom the Map to the extents visible before using Go Back to Previous Extent.
- Map Scale command (combo box showing current scale, such as 1:500,000) – zoom the Map by selecting from the drop-down list or typing a desired map scale.

Layer Management

The Map Layers panel presents a table of contents for control and management of the layers available to comprise the map display. Layers are turned on and off by checking/unchecking the checkbox to the left of the layer name. Layers are drawing from the bottom up, with layers closer to the bottom of the Map Layers list drawn underneath layers higher in the list. Layers can be organized in a hierarchy using Group Layers. A layer will only be shown on the map if the Group Layers that contain it are also turned on. A Group Layer or Layer Legend is expanded/collapsed by clicking the +/- sign to its left.

Right-clicking a layer in the Map Layers presents the menu shown in Figure 3. The menu items are organized by feature set.

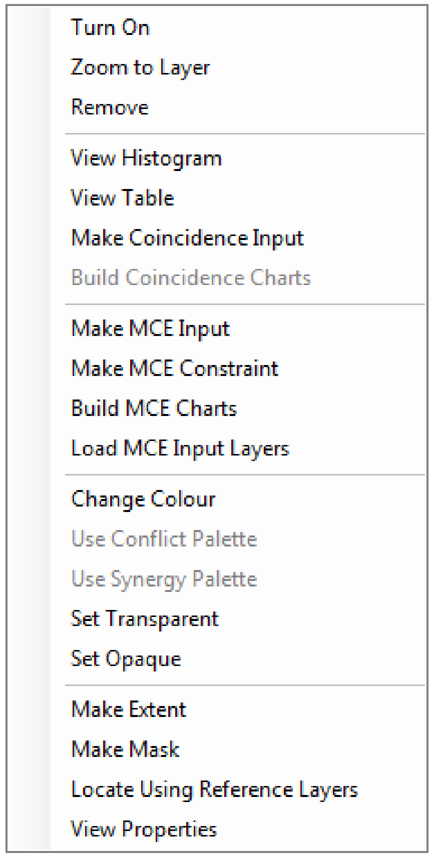


Figure 3 - Map Layers Right-click Menu

Layer Control Features:

- Turn On/Off – make the selected map layer visible/invisible (same as checking/unchecking its checkbox).
- Zoom to Layer – zoom the Map to show the extents of the selected layer.
- Remove – remove the layer from the Map and Map Layers list. If the selected layer is a Group Layer, all its contained layers will also be removed.

Preliminary Exploration Features:

- View Histogram – view a column chart histogram of the table underlying the selected layer. The field and number of classes can be changed dynamically.
- View Table – view the attribute table underlying the selected layer, if any.
- Make Coincidence Input – add the selected layer to the list of Coincidence Input Layers (see Coincidence Analysis below for more details).
- Build Coincidence Charts – build Coincidence Charts for the selected layer, if it is a Coincidence Output Layer. Coincidence Charts are built automatically for a newly created Coincidence Output layer. Charts will also be automatically built when the top-most Coincidence Output Layer changes or the map extents change, but only if the "Automatically Rebuild Coincidence Charts" environment setting is selected.

Multiple Criteria Evaluation features:

- Make MCE Input – add the selected layer to the list of MCE Input Layers (see Multiple Criteria Evaluation below for more details).
- Make MCE Constraint – make the selected layer the optional constraint layer for MCE (see Multiple Criteria Evaluation below for more details).
- Build MCE Charts – build MCE Charts for the selected layer, if it is a MCE Output Layer. MCE Charts are built automatically for a newly created MCE Output layer. This will also be automatically built when the top-most MCE Output Layer changes or the map extents change, but only if the "Automatically Rebuild Coincidence Charts" environment setting is selected.
- Load MCE Input Layers – load the list of MCE Input Layers and weights that was used to create the selected MCE Output Layer.

Layer Colour Control Features:

- Change Colour – show a dialog for changing the selected colour. It allows selection of an individual colour if the selected item is a unique value, or selection of a color ramp for continuous values or a range of values.
- Use Conflict Palette – a special colour set for Coincidence Output Layers, which uses gray for value 0, and a range of colours from green to yellow to red for values 1 and higher.
- Use Synergy Palette – a special colour set for Coincidence Output Layers, which uses gray for value 0, and a range of colours from red to yellow to green for values 1 and higher.
- Set Transparent – set the selected layer to 50% transparent.
- Set Opaque – set the selected layer to 0% transparent.

General Layer Features:

- Make Extent – use the rectangular extents of the selected layer to limit the locations of analysis and output for newly created Binary, Coincidence, Normalized01 and MCE layers.
- Make Mask – use the presence of data in the selected layer to limit the locations of analysis and output for newly created Binary, Coincidence, Normalized01 and MCE layers. To delete the Mask, go to View/Edit Environment Settings.
- Locate Using Reference Layers – assist the user to locate the selected layer in its geographical context by setting it to 50% transparent, turning on the Reference Layers group, and turning off all other layers.
- View Properties – view key properties of the selected layers, including its type, path, spatial reference, cellsize (for rasters only) and number of cells/pixels (for rasters only).

The drawing order and position with the hierarchy of any layer can be changed by dragging it to a new location in the Map Layer list.

A layer can be relabelled by clicking in its label in the Map Layer list. This does not change the name of the file or class that stores the layer on disk.

Coincidence Analysis

Coincidence Analysis first involves selecting or generating binary input layers – those containing values of only 1 and 0 representing on/off or yes/no. Non-binary input layers can be converted to binary by specifying optional cutoff parameters to limit the locations included in that layer. Multiple input layers can be combined into a single input layer by giving them the same Layer/Group Label.

Then, running the Coincidence Tool overlays the binary Coincidence Input Layers and determines the count and name(s) of the layer(s) at each location. Locations with higher layer counts are said to have higher coincidence among the input layers. Higher coincidence may represent synergy or conflict, depending on the nature of the input layers. The new Coincidence Output Layer is displayed as a map layer along with charts to aid interpretation and help identify additional scenarios of interest.

Coincidence Input Layers

A layer is added to the list of Coincidence Input Layers by right-clicking it in the list of Map Layers, and selecting Make Coincidence Input. Figure 4 shows a number of Coincidence Input Layers, intended to help identify good areas for viewing autumn colours.

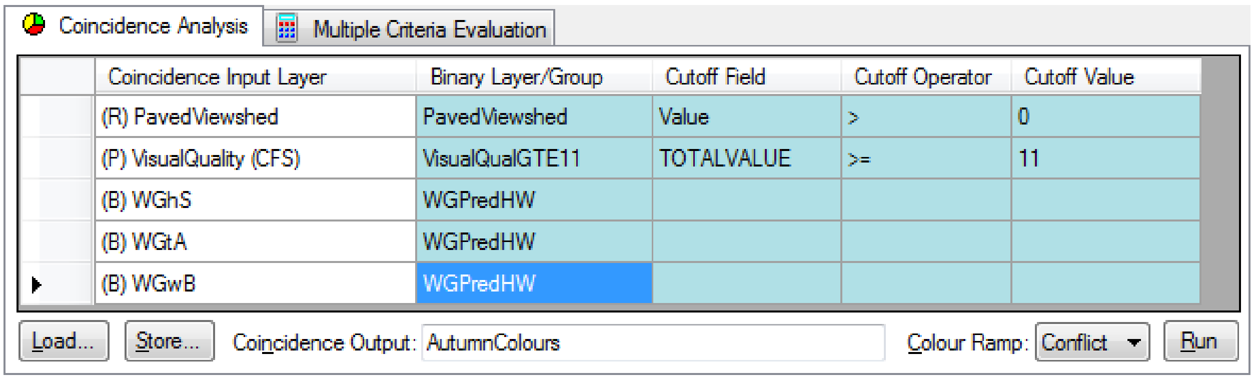


Figure 4 - Coincidence Input Layers

In this example, PavedViewshed is a raster layer (R) where the Value counts the number of road points from which that location can be seen. It will be converted to a binary layer of the same name by converting any “visible” cells (those with Value > 0) to 1 and all other cells to 0. VisualQuality is a vector polygon feature layer (P) which measures the visual desirability of the landscape. It is based on the results of a survey that showed photographs of various landscapes to tourists and the general public. VisualQuality will be converted to a binary layer called VisualQualGTE11 (this name is specified by the user) by converting areas with TOTALVALUE >= 11 (on a scale of 0-15) to 1 and all other cells to 0. Working Group (WG) is from the forest inventory layer and identifies the types of trees in each area. WGhS (mostly hardwood with some software), WGtA (trembling aspen) and WGwB (white birch) are all binary raster layers (B). Because they are already binary they do not need to be converted using cutoff parameters. Note that they have all been given the same Layer/Group Label by the user, and thus will be converted to a single binary layer (WGPredHW for Working Group Predominantly Hardwood) using the union (logical or) operator.

A layer can be added to the list of Coincidence Input Layers multiple times if desired, for instance to have it generate multiple binary layers using different cutoff parameters. The following features are also shown in Figure 4:

- Store – save the list of input layers to a file.
- Load – load the list of input layers from a file.
- Coincidence Output layer name – the name of the layer to be created when the Coincidence Tool is run.
- Colour Ramp –the colours to be applied to the Coincidence Output Layer; select Conflict (gray for value 0, and a range of colours from green to yellow to red for values 1 and higher) or Synergy (gray for value 0, and a range of colours from red to yellow to green for values 1 and higher).
- Run – execute the Coincidence Tool based on the current Coincidence Input list.

Right-clicking a layer in the Coincidence Input List shows a menu with the following options:

- Clear – remove the selected layer from the Coincidence Input List.
- Clear All – remove all layers from the Coincidence Input List.
- Select in Map Layers – locate the selected layer in the Map Layers list and select it.

Binary Layers

Any binary layers newly created by the Coincidence Tool are added to the Map Layers list at the top of the Binary Layers group. They are available to be reused for future Coincidence Analyses.

Coincidence Output Layers

Figure 5 shows the Coincidence Output Layer based on the scenario shown in Figure 4. Each Coincidence Tool run creates a new raster layer, and it is added to the top of the Coincidence Output Layers group. The name of the layers occurring at each location (raster cell) can be found by selecting the Identify tool (i icon in the toolbar) and clicking on the desired cell. Each cell also contains a count of the number of layers at that location, and information about the layer counts is summarized in the Coincidence Charts panel to the right.

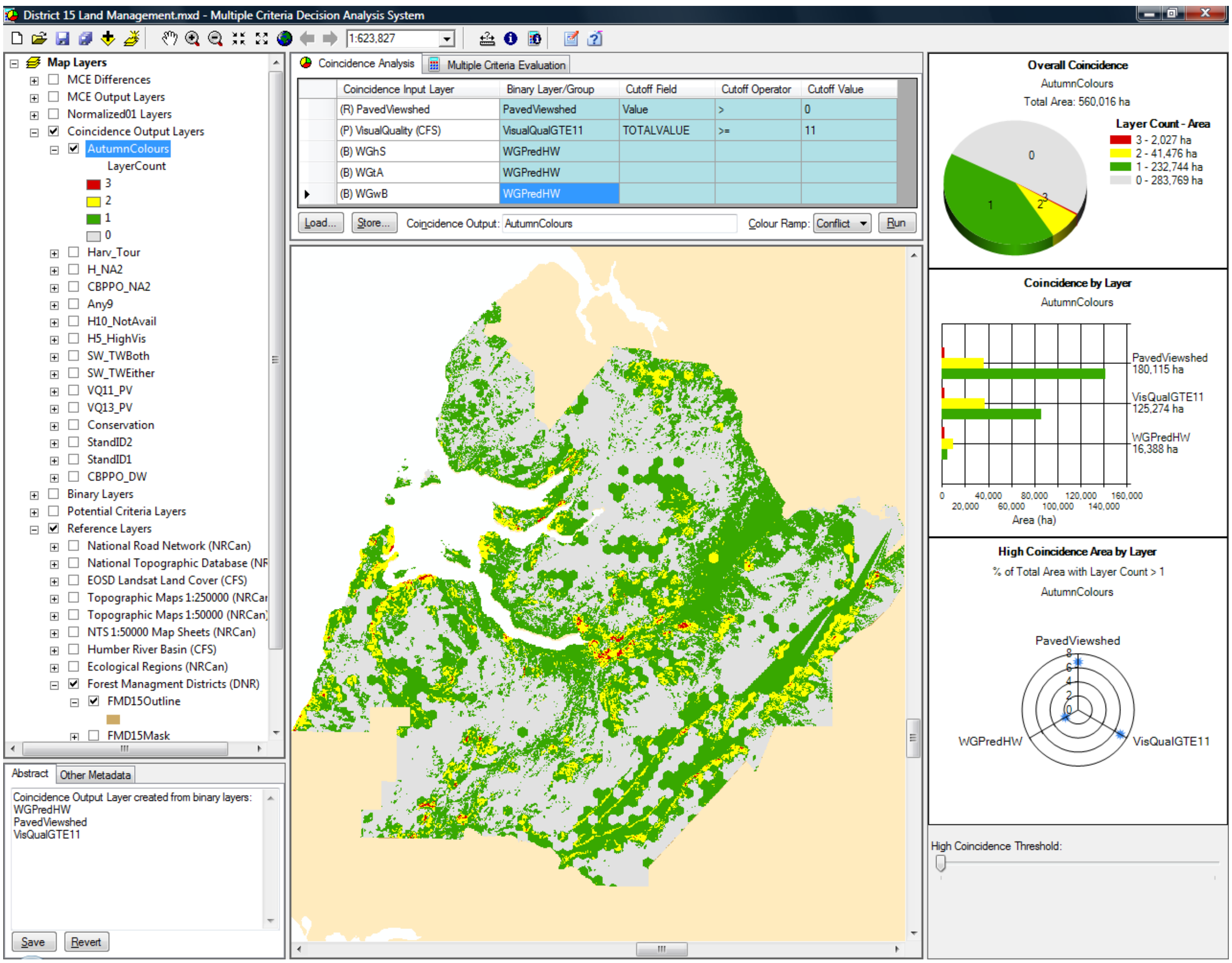


Figure 5 - Coincidence Output Layer and Charts

Coincidence Charts

Three Coincidence Charts correspond to the active Coincidence Output Layer:

- The Overall Coincidence pie chart summarizes the layer counts by area. Hovering the mouse over a pie slice or a legend item shows a breakdown of all combinations of layers with that layer count.
- The Coincidence by Layer bar chart summarizes each Coincidence Input Layer. Hovering the mouse over a bar shows a breakdown of all combinations of that particular layer with that layer count.
- The High Coincidence Area by Layer radar chart shows for each Coincidence Input Layer the percent of the total area with a high layer count. The High Coincidence Threshold slider allows selection of the layer count threshold used to calculate this information.

Coincidence Charts are calculated based on the visible extents of the Coincidence Output Layer. They are automatically recalculated on map pan and zoom, but only if the "Automatically Rebuild Coincidence Charts" environment setting is selected.

Coincidence Cell Details

The Coincidence Input Layers occurring at a specific location in the Coincidence Output can be identified by selecting the Identify tool on the toolbar (i icon), then clicking the desired location on the map. The Labels field lists the names of the Coincidence Input Layers at that location.

Multiple Criteria Evaluation

The MCE features of MCDAS are designed to support a spatial multiple criteria problem with the following attributes:

- Spatially continuous inputs (polygons or rasters) and outputs (rasters), such that all locations (raster cells) within the analysis extent/mask are assigned an MCE output value.
- A single objective in the form of a maximization or minimization goal. Examples include:
  - Identify locations with the highest conservation values (to be excluded from development, for instance).
  - Rank sites based on their potential for mineral exploration.
  - Search for areas with the lowest potential for crime.
- Availability of measurable criteria supporting the objective.

Criteria Input Layers are processed using these basic two steps:

- Criteria normalization, if required, which converts continuous criteria values to a continuous 0-1 scale, where the lowest value is assigned 0 and the highest value is assigned 1 using the formula *(value-low)/(high-low)*. The scale can be reversed if desired (for criteria where less is better), which applies the formula *1-(value-low)/(high-low))*. By default, the Low and Hi values are based on the values found in the dataset, but the user can override these to reflect the range of possible values (for instance, 0 to 100 for percentages). Contrary to appearances, this normalization is non-linear when the original low value is non-zero, because it does not preserve the proportionality of the original scale.
- Aggregation of criteria scores into MCE scores for each cell/pixel using weighted summation. The user selects relative criteria weights using sliders, and the numeric weights are calculated so that all weights sum to 1. Aggregation into MCE Scores for each location is performed using the formula $\sum i=1 \text{ to } n \ (V_i * W_i)$, where i is the i^{th} criteria, n is the total number of criteria, V is the value of the i^{th} criteria and W is the weight of the i^{th} criteria.

The MCE Output is a Raster Layer (continuous cell/pixels) of MCE scores, often called a suitability map. Because of the 0-1 normalization and total weighting of 1, the MCE output scores are always in the range 0-1.

MCE Input Layers

A layer is added to the list of MCE Input Layers by right-clicking it in the list of Map Layers, and selecting Make MCE Input. Figure 6 shows a number of Coincidence Input Layers, intended to help identify good areas for hikers to see Marten.

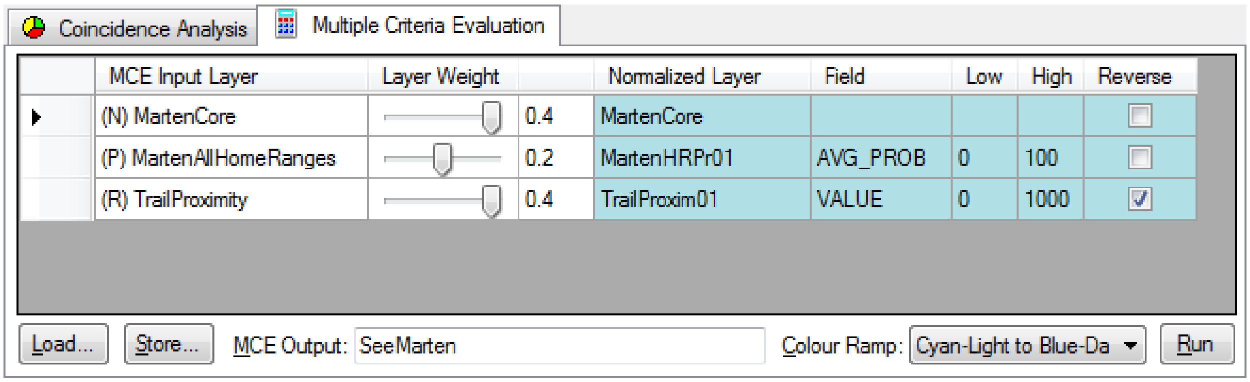


Figure 6 - MCE Input Layers

In this example, MartenCore is a Normalized01 raster layer (N), which denotes areas of known Marten population with the value 1 and all other areas with the value 0 (note that it is actually a Binary Layer, which also qualifies as a Normalized01 Layer). Because it is previously normalized, no normalization parameters are specified. MartenAllHomeRanges is a vector polygon feature layer (P) that breaks the landscape into rectangles approximating the size of the home range of a mating pair of Marten, and assigns each a probability value that the landscape in that home range can support the pair. These values will be normalized to a 0-1 value based on a Low value of 0 and High value of 100, to create a Normalized01 Layer called MartenHRPr01. Trail Proximity is a raster layer (R) that measures the distance from trails in meters, up to 1000m. Because trails are the most accessible for humans, this layer will be reversed as it is normalized so that areas closer to the trails score higher, to create a Normalized01 Layer called TrailProxim01.

The Layer Weight slider indicates the relative importance of each criterion, which is used to calculate the weight values to be used for weighted summation. In this case, the decision makers felt the probability of the landscape supporting Marten (MartenHRPr01) was only half as important as the other criteria in determining good areas for hikers to see Marten.

The following features are also shown in Figure 6:

- Store – save the list of input layers to a file.
- Load – load the list of input layers from a file.
- MCE Output layer name – the name of the layer to be created from Running the Multiple Criteria Evaluation.
- Colour Ramp –the colours to be applied to the MCE Output Layer.
- Run – execute the Multiple Criteria Evaluation based on the current MCE Input list.

Right-clicking a layer in the MCE Input List shows a menu with the following options:

- Clear – remove the selected layer from the MCE Input List.
- Clear All – remove all layers from the MCE Input List.

- Select in Map Layers – locate the selected layer in the Map Layers list and select it.

MCE Constraint

The MCE Constraint is an optional binary layer that indicates cells to be included and excluded from the MCE analysis. Included cells should be given a value of 1. Excluded cells should be given a value of either 0 (which causes those cells to have an MCE value of 0) or NoData (which causes those cells to have an MCE value of NoData).

Normalized01 Layers

Any normalized layers newly created by the MCE are added to the Map Layers list at the top of the Normalized01 Layers group. They are available to be reused for future MCE runs.

MCE Output Layers

Figure 7 shows the MCE Output Layer based on the scenario shown in Figure 6. Each MCE run creates a new raster layer, and it is added to the top of the MCE Output Layers group. Each pixel/cell contains the MCE score at that location, and information about the MCE scores is summarized in the MCE Charts to the right.

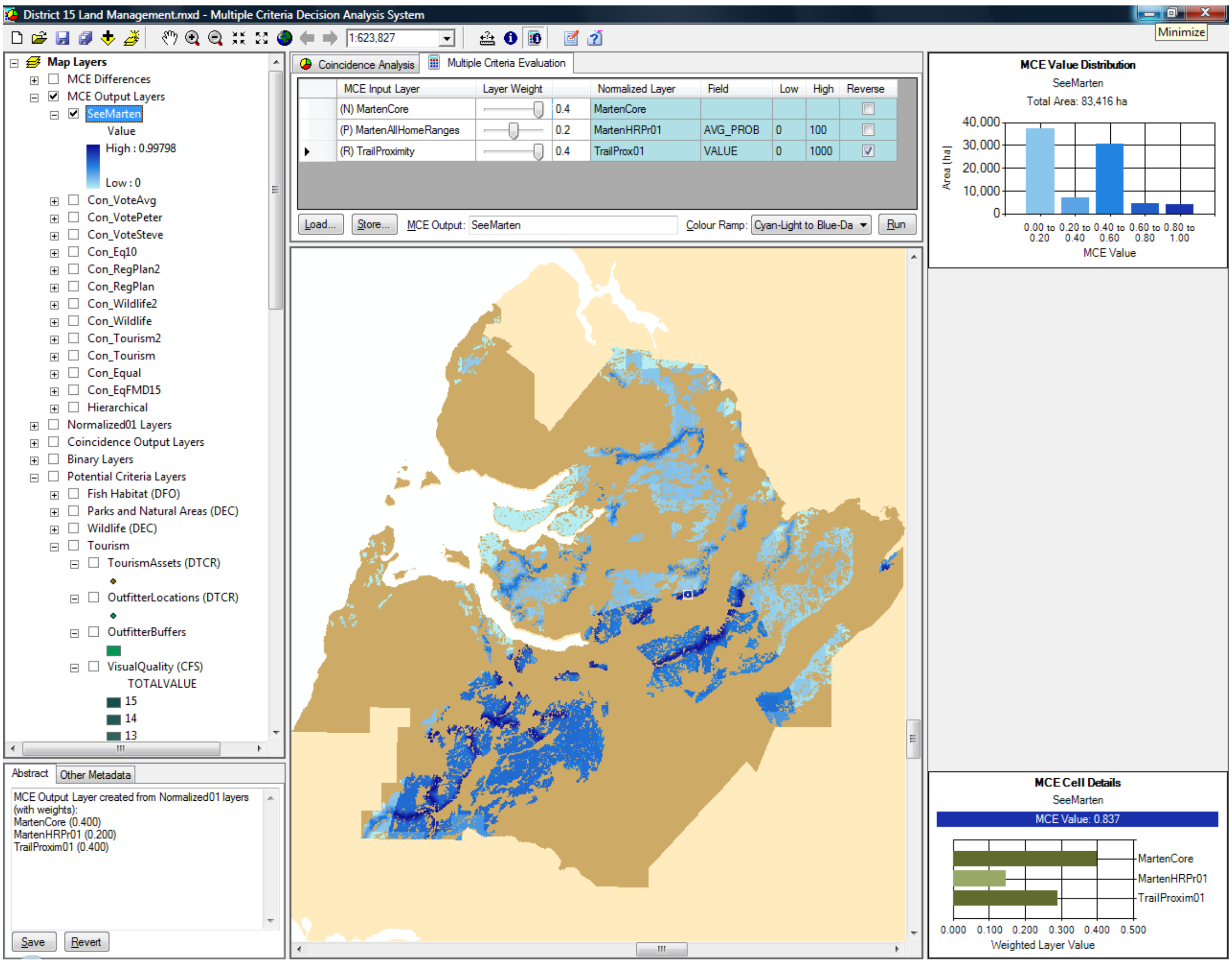


Figure 7 - MCE Output Layer and Charts

Note that when an existing MCE Output Layer is turned on and becomes the topmost layer, the list of MCE Inputs will not be automatically updated. To load the list of MCE Inputs, right-click the MCE Output Layer in the list of Map Layers and select Load MCE Inputs.

MCE Charts

The histogram/distribution at the top right of the MCDAS screen in Figure 7 shows the distribution of the MCE values across five equally spaced classes. The classes are coloured to match the MCE Output Layer colours. Hovering over a histogram bar gives the exact area of the cells it includes.

When an existing MCE Output Layer is turned on and becomes the topmost layer, the MCE histogram/distribution Chart will rebuild for that layer (if the Automatically Rebuild Charts setting is on).

MCE Cell Details

To see the details of the MCE value for a particular cell, select the Identify MCE Cell Details tool in the toolbar (i over calculator icon), then click the desired location on the map. This will produce the bar chart at the bottom right of the MCDAS screen in Figure 7. The MCE Value is coloured to match the MCE Output colour for the chosen cell. The size of the bar measures that criterion's contribution to the MCE Cell Value, and the bars are coloured relative to their weight (darker is higher weight). The breakdown of that criterion's contribution to the MCE Cell Value can be seen by hovering the mouse over the bar.

Performance Tips

Use existing Binary Layers when available for Coincidence Input Layers. Use existing Binary Layers or Normalized01 Layers when available for MCE Input Layers. Also, the following Environment Settings can affect system performance when running the Coincidence Tool or building Coincidence Charts:

- Use appropriate Cell Size for the scale of the analysis. A larger cell size will result in smaller Binary Layers and Coincidence Output Layers.
- Set the Extents to cover only the area required.
- Only use a Mask when input layers are not already masked.
- Use a raster Mask, which performs better than a vector Mask.
- Turn off Automatically Rebuild Charts to speed up panning and zooming with a Coincidence Layer visible.
- Ensure all input and output layers use the same spatial reference system (datum and projection) to avoid transformations during geoprocessing and display.

Environment Settings

Figure 8 shows the Environment dialog, accessed via the Environment Settings toolbar command (paper and pencil icon).

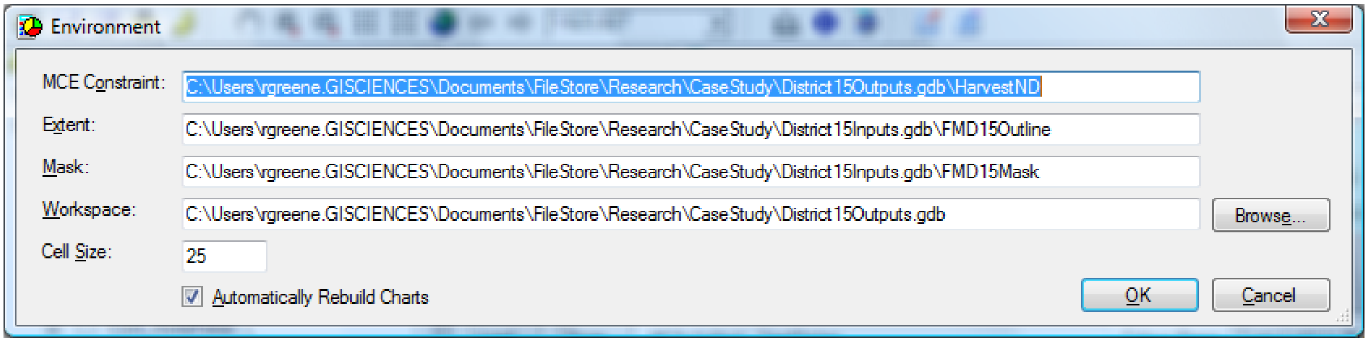


Figure 8 - Environment Settings

- MCE Constraint – a binary layer that specifies layers to be included and excluded from MCE processing. Set this by typing or copying/pasting, or by right-clicking the desired layer in the list of Map Layers and selecting Make MCE Constraint.
- Extent – a layer that specifies the rectangular area to which all input layers will be trimmed before processing. Set this by typing or copying/pasting, or by right-clicking the desired layer in the list of Map Layers and selecting Make Extent.
- Mask – a layer that specifies the exact area to which all input layers will be trimmed before processing. Set this by typing or copying/pasting, or by right-clicking the desired layer in the list of Map Layers and selecting Make Mask.
- Workspace – the location (a folder or geodatabase) where all Coincidence, Binary and temporary output layers will be stored. Set this by typing or copying/pasting, or by Browsing to the desired folder or geodatabase.
- Cell Size – the raster spatial resolution (in map units) for creation of new Coincidence and Binary output layers.
- Automatically Rebuild Coincidence Charts – when selected, Coincidence Charts are automatically rebuilt when a new Coincidence Layer is made the topmost layer or when the visible extents change, but only if the topmost Coincidence Layer is visible within the current map extents.

Metadata

Metadata provides descriptive, textual information about a layer. The Abstract is a summary description of the layer. MCDAS allows the Abstract to be edited and saved using the Save command button. Edits can be discarded before they are saved using the Revert command button. An Abstract describing the input layers and cutoff parameters will be automatically generated and saved for each new Coincidence and Binary output layer.

Map Document Management

MCDAS uses the ESRI .mxd file format to save the current map layers and visible extent in a map document. The left end of the Toolbar includes the Map Document commands shown in Figure 9.

Figure 9 - Map Document Commands

- New (blank paper icon) – create a new, empty map document.
- Open (folder opening icon) – open an existing map document.

- Save (single diskette icon) – save/overwrite the active map document using its existing name and location.
- Save As (multiple diskettes icon) – save the active map document using a new name or location.
- Add Data (plus sign over layer icon) – add an existing raster or vector layer to the active map document.
- Create New Group Layer (asterisk over layers icon) – create a new group layer within the active map document, and display it in the Map Layers (table of contents).

MCDAS will prompt the user to save the current map document when the application is closed, a new map document is created, or an existing map document is opened, but only if the current map document has changed since it was opened.

Other Tools and Commands

The right end of the Toolbar includes the tools and commands shown in Figure 10.

Figure 10 - Other Tools and Commands

- Measure tool (ruler icon) – click to measure the distance along one or more line segments.
- Identify tool (i icon) – see the underlying attributes for a specific location of the topmost layer.
- Identify MCE Cell Details tool (i over calculator icon) – see the MCE value details for a specific location of the topmost layer.
- View/Edit Environment Settings command (pencil and paper icon) – view and edit Environment Settings.
- View Documentation command (question mark icon) – view this document.

Naming Conventions

The following layer naming conventions have been used in the District15 Land Management map document, and are generally recommended:

- If the group or layer contains the organization abbreviation in brackets it is original data as received from that organization; otherwise it is derived data.
- Group Layers for MCE Output Layers, Normalized01 Layers, Coincidence Output Layers, Binary Layers, Potential Criteria Layer and References groups will be recreated as necessary by MCDAS. Users are encouraged to organize their layers under these groups, and to create additional group layers below these as required.
- All other group layers are optional.
- Use an underscore (_) to indicate the results of an intersection operation (logical AND), as in Coincidence Output Layer names like "Harv_Tour".
- Use a "u" to indicate the results of a union operation (logical OR), as in creating a new Binary Layer like "VQ11_PVuMHR7" from multiple Coincidence Input Layers.

Note that ESRI supports a maximum of 13 characters for new raster layer names, so use consistent abbreviations!

Release Notes

The following issues and wish list items were addressed in version 1.0.1, February 2010:

- MCE Input Layers are cleared when a different Map Document is opened or a new Map Document created.

- The Make Extent and Make Mask right-click menu items in the Map Layers Right-click Menu now work correctly with shapefiles.
- MCE Details cell colour determination no longer assumes the minimum value is 0 (but still assumes the palette stretch is set to "none").
- Error message boxes simplified by excluding messages from successful geoprocessing runs and only showing error message.
- Added color ramp Yellow to Dark Red and made it the default for new MCE Outputs.
- Documented the applicability of MCDAS' MCE capability to only spatially continuous problems.
- Now installs a sample geodatabase to C:\MCDASData\SampleMCDAS.gdb and map file to C:\MCDASData\SampleMCDAS.mxd, and configures application to use these by default.

The following issues and wish list items were addressed in version 1.0.2, March 2010:

- Now supports input and output layers (shapefiles and grid rasters) not contained in a geodatabase.
- Displays correct colours for coincidence charts when a subset of the coincidence output chart is visible.

Known Issues

The following are known issues and potential problems with the current version of MCDAS:

- It is highly recommended that you use geodatabases for all input layers and for the workspace, because most MCDAS testing has used geodatabases. If the Workspace is set to a folder (as opposed to a geodatabase), there are some known issues:
    - MCDAS may have trouble reusing output layers names, even if the previous layer with that name has been deleted.
    - MCDAS cannot delete the temporary raster that is created to support coincidence chart creation when zoomed in on a portion of a coincidence output layer. These temporary rasters are named tp*, and can later be manually deleted without causing any problems.
    - The Multi-part Color Ramp "Green to Blue" cannot be applied to MCE output layers upon creation, and will result in an all-black layer. It can be applied after the fact to MCE output layers via the Change Colour feature.
    - Calculation of histograms (in MCE charts or in View Histogram) may be slow, because non-geodatabase rasters do not expose their internal histograms and MCDAS is forced to loop through every cell!
- The output coordinate (spatial reference) system cannot be explicitly set. It is highly recommended to transform/project all input layers to the same spatial reference system. One problem that can occur is applying the cell size environment variable intended for the horizontal unites one coordinate system (such as metres) to an input with different horizontal units (such as degrees), resulting in significantly lower resolution output rasters!
- Chart outputs assume that spatial units are in metres, and use the cell size to calculate areas in hectares (ha). If the spatial units are in degrees, feet or any unit other than metres, the hectare area values will be incorrect.
- Certain features look for Coincidence and MCE Input Layers in their original locations. If the geodatabase location is changed, the MCE Cell Details feature will not work for old MCE Output Layers, and the Run MCE and Run Coincidence features will not work after loading old input lists.
- Coincidence Analysis is limited to 16 binary inputs, due to the use of a bit mask to store unique combinations of inputs as the raster output value.
- MCE Histogram/Distribution chart does not recalculate for visible extents, which is inconsistent with the behaviour of Coincidence charts. MCE uses the raster statistics (not the raw values) to build the histogram, and thus needs to clip the visible extents to a temporary raster and use its statistics. This is similar to the approach taken by the Coincidence charts, which calculate based on the raster attribute table values and thus also clip to a temporary

Coincidence charts, which calculate based on the raster attribute table values and thus also clip to a temporary raster and rebuild the table. The primary concern of this approach is the performance hit, which is obvious with the Coincidence charts on some machines/datasets. Any suggestions appreciated.

- Rounding issues could cause the creation of Normalized01 Layers with values slightly higher than 1 or lower than 0, which will not qualify as Normalized01 Layers (N) when they are subsequently used as input to another MCE run.
- Release builds occasionally crash on exit. This has been difficult to diagnose because it does not occur in debug. Any clues greatly appreciated.
- Occasionally after loading an input list, Run MCE or Run Coincidence will look for the layers in the application's working directory instead of the geodatabase! The workaround is to recreate the input list by clearing it then adding the inputs one at a time from the list of Map Layers. Any thoughts on causes or work-arounds greatly appreciated.
- Successive pan/zoom actions can sometimes cause problems due to time-consuming chart calculations. This could be overcome by running chart calculations in a background thread. Similarly, geoprocessing (Run Coincidence and Run MCE) should be executed in a background thread to avoid the inconsistent responsiveness of the application when geoprocessing is running on the main thread.

Wish List

The following features are high on the priority list for future versions of MCDAS:

- Automate transfer of input layers between Coincidence Analysis and MCE.
- When drilling down on chart bars/slices, highlight corresponding cells in map.
- Change the examples in this documentation to use the sample geodatabase, or provide a quick-start tutorial based on it.
- Perform extra checking regarding environment settings when Coincidence Analysis or MCE is run – do the Environment paths and datasets exist, do the analysis inputs overlap the Extent, etc.
- Describe the ability to perform hierarchical aggregation by doing multiple MCE runs.
- Allow creation of Binary and Normalized01 layers without doing a Coincidence or MCE run.
- The underlying geoprocessing uses the MXD's environment setting (or ArcGIS defaults in its absence) to determine the Spatial Reference System of newly created output layers. Create an MCDAS environment setting to make this explicit.
- Drag and drop Map Layers to Coincidence and MCE Inputs. Technical details from ArcObjects developers on how to accomplish greatly appreciated!
- Allow more than 10,000 rows in View Table.
- Allow column header click sorting in View Table.

Add your idea to the wish list using the contact information below.

Technical Support

Please direct problem reports, questions and comments to Randal Greene, rgreene@feaverslane.com.