DISSERTATION

A KNOWLEDGE-BASED, SPATIAL, MULTI-CRITERIA DECISION ANALYSIS METHODOLOGY FOR POND SITE EVALUATION

Submitted by

Catherine Jane Shrier

Department of Civil Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2004

UMI Number: 3160056

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

COLORADO STATE UNIVERSITY

NOVEMBER 5, 2004

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY CATHERINE J. SHRIER ENTITLED A KNOWLEDGE-BASED, SPATIAL, MULTI-CRITERIA DECISION ANALYSIS METHODOLOGY FOR POND SITE EVALUATION BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DOCTORATE OF PHILOSOPHY.

Committee on Graduate Work

David Freeman

Deanna Durnford

Darrell Fontane
Advisor

Luis Garcia
Co-Advisor

Sandra Woods
Chair

Sandra Woods

ABSTRACT OF DISSERTATION

A KNOWLEDGE-BASED, SPATIAL, MULTI-CRITERIA DECISION ANALYSIS METHODOLOGY FOR POND SITE EVALUATION

The use of knowledge-based systems (KBS) has been increasingly recognized as a way to combine scientific understanding of the processes of the natural world with the heuristic rules developed by managers through observation and experience, even when the processes behind those observations may not be fully understood. KBS combine applied knowledge acquired from local experts and published literature with a model of the human reasoning process or "ontology," presenting the accumulated knowledge in a synthesized manner. KBS can provide greater accountability, transparency, and consistency in these decision-making processes, which can be represented as a series of rules, and can support regional-scale natural resources planning and management.

The use of geographic information systems (GIS) can be an invaluable tool in the evaluation and analysis of natural resources problems, which often involve spatial relationships. Because natural resources problems are frequently complex and multi-faceted, a multi-criteria decision analysis (MCDA) approach may be necessary to address these issues in a synthesized and integrated manner. As demonstrated in this research, the weighted average aggregation algorithm for an MCDA is mathematically similar to the use of certainty factors in a forward-chaining, data-driven KBS. Using a weighted average MCDA as the "reasoning" or "inference" engine within a KBS provides an increased level of flexibility in a rule-based system.

This research integrates a weighted average MCDA within a forward-chaining KBS to enable a natural resources management evaluation and comparison of potential pond development sites based primarily on local knowledge that has been captured in knowledge and rule bases. The KBS has been programmed in an Excel database with links to an ArcView GIS spatial database and spatial analysis tools in a prototype model called the Waterfowl and Augmentation Pond Site Assessment Model. The prototype model application was for the evaluation of potential pond sites to be developed for waterfowl habitat and managed groundwater recharge for streamflow augmentation under Colorado's *prior appropriation* water law.

Catherine Jane Shrier
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523
Fall 2004

ACKNOLWEDGMENTS

This research could not have been completed without the tireless support and perseverance of my advisor, Darrell Fontane, who also provided much of the guidance on the decision analysis and knowledge acquisition methodologies used in this research. Dr. Fontane's willingness to instruct students on these methodologies and to consider innovative applications related to water resources planning and management, as well as his commitment to ensuring that his students complete their graduate programs with worthy research, are just a few of the attributes that make him an asset to Colorado State University.

My initial exposure to the issues of the Lower South Platte River Basin, where I completed my research, came about through a proposal effort I worked on as a graduate research assistant with Deanna Durnford when I first arrived at Colorado State University. Dr. Durnford, who also served on my advisory committee, provided constant support, friendship, and insights into Colorado water and academia which has been invaluable.

Another constant friend and supporter throughout my graduate studies and dissertation research has been Robert Ward, Director of the Colorado Water Resources Research Institute (CWRRI). Funding from the Colorado Water Resources Research

Institute (CWRRI), provided through a grant from the U.S. Geological Survey with approval from the CWRRI Advisory Committee, is also gratefully acknowledged, as is the moral support, advice, and use of office space when my funding expired that was provided by Dr. Ward.

Greatly appreciated is the support of Jon Altenhofen, Northern Colorado Water Conservancy District, and Jay Stafford, Colorado Division of Wildlife, in the development of the research concept and funding for this project. The partial funding for this project by the Colorado Division of Wildlife Species Conservation Trust Fund, through a grant to the South Platte Lower River Group, is gratefully acknowledged. Mr. Altenhofen also continuously worked with me at several stages throughout the research to develop my prototype application as a realistic representation of the recharge site evaluation decision process.

Luis Garcia, who served as my co-advisor, is the Director of the Integrated Decision Support (IDS) Group at Colorado State University, where much of the initial research was conducted. Dr. Garcia served as Principal Investigator for the contract which funded the initial research, and permitted me to develop the original habitat-related spatial library and knowledge bases as a biological module to his South Platte Mapping and Analysis Program, and also permitted me use of IDS office space and facilities. The assistance, friendship, support, and amazing programming capabilities of Dave Patterson, IDS Assistant Director, who provided programming support for the links between the Excel and ArcView portions of the prototype application and the graphical user interface, are gratefully acknowledged.

The support and guidance of my original outside committee member, Kurt Fausch, from the Fishery and Wildlife Biology Department, and my final outside committee member, David Freeman, from the Sociology Department, are also greatly appreciated. Dr. Fausch's willingness to continue to support my research as my focus shifted "from fish to fowl" is appreciated, as is Dr. Freeman's willingness to step in and join the committee at the eleventh hour when Dr. Fausch left for sabbatical.

This research was developed based on knowledge from local experts within the water resources and waterfowl habitat communities in Colorado; completion of this work would not have been possible without the cooperation and support of several individuals who shared their knowledge and experience with me. The continued support of the members of the South Platte Lower River Group, South Platte Wetlands Focus Area Committee, South Platte Integrated Management Program Workgroup, and various staff with the Colorado Division of Wildlife was critical to the successful completion of this work. Local experts who contributed to the development of the knowledge base for recharge pond development included Mr. Altenhofen; Larry Frame, Julesburg Irrigation District; Allen Coyne, Town of Julesburg; Jack Odor, Groundwater Appropriators of the South Platte; Dick Stenzel and Jim Hall, Colorado Division of Water Resources; Bob Schott, Lower South Platte Water Conservancy District; Steve Treadway and Louis Rinaldo, South Platte Lower River Group, among others. Les Dalby from the Colorado Division of Water Resources was also very helpful in providing recharge pond site location data for this research. Several of the geographic information system (GIS) coverages and analytical tools for water conjunctive management were originally developed as part of the South Platte Mapping and Analysis Program (SPMAP), at the

Colorado State University Integrated Decision Support Group under Dr. Garcia's direction.

Local experts who contributed to the development of the knowledge base and spatial databases for waterfowl habitat included Shane Briggs, Jay Stafford, Jim Gammonly, Don Schrupp, Jon Kindler, Dawn Brownne, Colorado Division of Wildlife; Mike Shannon and Greg Kernohan, Ducks Unlimited; Bob Timberman, Bill Noonan, and David Hamilton, U.S. Fish and Wildlife Service; Rick Sandquist, South Platte Wetlands Focus Area Committee; Matt Reddy, Rocky Mountain Bird Observatory; and Denise Culver, Colorado Natural Heritage Program, among others.

Also gratefully acknowledged is the support and advice from others who completed their graduate research on knowledge-based systems for natural resources management, including Dr. Steven Mackinson, who completed his Ph.D. at the University of British Columbia, and Dr. Richard Sojda, who completed his Ph.D. at Colorado State University.

The support of my colleagues at Golder Associates Inc. during the final months of the completion of my degree is also appreciated, particularly from Mike Jacobs and Dave O'Sadnick. I also want to thank Bob and Marney Komives for their friendship and hospitality.

I would very much like to thank my family for their continuous support and numerous reviews of my dissertation, particularly my mother and father. Last but not least, I would like to thank my uncle, Stefan Shrier, one of the pioneers in artificial intelligence, for his review of my dissertation in its various iterations, and his insights into the field.

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

LIST OF ACRONYMS

ARA	Augmentation/Recharge Accounting
CAT	Cost Assessment Tool
CDOW	Colorado Division of Wildlife
CSU	Colorado State University
CWCB	Colorado Water Conservancy Board
CWRRI	Colorado Water Resources Research Institute
DSS	Decision Support System
DU	Ducks Unlimited
EQIP	Environmental Quality Incentives Program
GASP	Groundwater Appropriators of the South Platte
GIS	Geographic Information System
GUI	Graphical User Interface
IDS	Integrated Decision Support
IMP	Integrated Management Plan
KB	Knowledge Base
KBS	Knowledge-Based System
LSPWCD	Lower South Platte Water Conservancy District
MCDA	Multi-Criteria Decision Analysis
NAWMP	North American Waterfowl Management Plan
NCWCD	Northern Colorado Water Conservancy District
NEPA	National Environmental Policy Act
NRCS	Natural Resources Conservation Service
PFW	Partners for Fish and Wildlife
PGIS	Participatory Geographic Information Systems
RPAT	Recharge Potential Assessment Tool
SDF	Stream Depletion Factor
SDSS	Spatial Decision Support System
SEO	State Engineer's Office
SPDSS	South Platte Decision Support System
SPGIS	South Platte Geographic Information System
SPLRG	South Platte Lower River Group
SPMAP	South Platte Mapping and Analysis Program
SWA	State Wildlife Area
USACE	U.S. Army Corps of Engineers
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey
UTM	Universal Transverse Mercator
WAPSAM	Waterfowl and Augmentation Pond Site Assessment Model
WHAT	Waterfowl Habitat Assessment Tool
WHIP	Wildlife Habitat Improvement Program
WRP	Wetlands Reserve Program

CHAPTER I.

INTRODUCTION

I.A. Introduction

The use of knowledge-based systems (KBS) (also called "expert systems") has been increasingly recognized as a way to combine our scientific understanding of the processes of the natural world with the heuristic rules developed by managers through observation and experience, even when the processes behind those observations may not be fully understood (e.g. Clark and Richards 2002, Sojda et al. 2002, Pedroli et al. 2002, Mackinson 2001, Jensen et al. 2000, Shaw et al. 2000, Neis et al. 1999, Mackinson and Nottestad 1998, Lilburne et al. 1998, Chowdhury and Canter 1998). Addressing problems of natural resources management purely through scientific methods can be difficult due to the reductionist nature of scientific research. Reducing the scope of scientific inquiry to a narrow focus makes issues easier to study and understand, but also makes it difficult for that research to be compiled and synthesized in a way that can be applied to complex "real world" problems (Schmoldt and Rauscher 1996).

While all computer programs are based on some amount of knowledge about the problem to be addressed by that program, a KBS is defined as a system in which the knowledge is extracted and organized into a separate entity, typically called a knowledge base (KB) (Schmoldt and Rauscher 1996). A KBS is typically developed to capture and implement an approach to solving a particular type of problem. The knowledge base includes both general information about the subject matter related to the problem (shown in Figure I-1 as the *domain knowledge base)* and information on how that information is processed to derive further understanding of the problem leading to a solution, which can be represented in *rules* (shown in Figure I-1 as the *rule knowledge base*).

KBS also provide a means of combining applied knowledge acquired from local experts and published literature with a model of the human reasoning process or "ontology" (Schmoldt and Rauscher 1996) and providing the accumulated knowledge in a synthesized manner (Mackinson and Newlands 1998). In the development of KBS used for natural resources management, inclusion of knowledge of, and full participation by, local managers and practitioners (e.g. farmers, fishermen) has the added benefit of greater acceptance of management policies and practices that result from the findings of those knowledge-based systems (Mackinson and Nottestad 1998).

For the purposes of this research, a KBS is recognized as containing three main components: a *knowledge base*; an *"inference" engine* or *reasoning engine* which is designed to replicate the human reasoning process used to solve a particular problem; and a *user interface*. Figure I-1 illustrates the components of the KBS developed as part of this research.

By capturing and implementing the knowledge and decision-making process used by local experts within an automated system, a KBS can provide greater accountability, greater transparency, and greater consistency in these decision-making processes (Schmoldt and Rauscher 1996, Ignizio 1991). In addition, developing a KBS that can perform some of the basic data acquisition and processing otherwise performed by experts in their decision-making process frees those experts to focus on more complex aspects of problems that may not be as readily addressed in a KBS, and can reduce the overall time, effort, and expense required to perform those steps. The availability of site evaluation data and tools that can be used throughout a given region can also support regional-scale natural resources planning and management, as opposed to a more site-by-site, piecemeal approach.

Geographic information systems (GIS) can be an invaluable tool in the evaluation and analysis of natural resources problems. The data required to perform evaluative tasks is likely to come in several forms, including both spatial data (e.g. GIS map coverages) and tabular data (e.g. numerical, symbolic, relational, and temporal data). In order for GIS to be used most effectively to support the evaluative tasks normally performed by experts, the spatial data must be tied to the appropriate tabular data, and the GIS coverages must be available with the appropriate level of accuracy and resolution to support the evaluation. If the types, precision and accuracy of data needed to support site assessments can be identified through knowledge acquisition, then GIS coverages can be developed as needed in a cost effective manner, with coverages tailored to suit the uses to which they will be applied.

Because natural resources problems also are frequently complex and multi-faceted, a multi-criteria decision analysis (MCDA) approach may be necessary to address these issues in a synthesized and integrated manner. Using a weighted average MCDA as the “reasoning” or “inference” engine within a KBS also provides high levels of flexibility in a rule-based system. The weighted average aggregation algorithm for an

MCDA is mathematically similar to the use of certainty factors in a forward-chaining, data-driven KBS. Use of an MCDA can increase the versatility of a rule-based system, and support the integration of potentially conflicting rules.

This research integrates a weighted average MCDA within a forward-chaining KBS to enable a natural resources management evaluation and comparison of potential pond sites based primarily on local knowledge that has been captured in knowledge and rule bases. To maximize the use of available data sources and minimize user input requirements, this KBS has also been linked to a spatial data library which has been developed to provide the appropriate site attribute data and basic spatial analyses to support the MCDA in the KBS. The prototype model application was for the evaluation of potential pond sites to be developed for waterfowl habitat and managed groundwater recharge for streamflow augmentation under Colorado's *prior appropriation* water law. The KBS has been programmed in an Excel database with links to an ArcView GIS spatial database and spatial analysis tools in a prototype model called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM).

I.B. Case Study for Prototype Application

Seasonally flooded wetland ponds have been recognized to perform multiple beneficial functions, including groundwater recharge, groundwater discharge to augment streamflows, and habitat for a diverse array of wildlife species, including waterfowl (e.g. Adamus et al. 1991). In the lower South Platte River Basin of Colorado, managed groundwater recharge ponds have been developed for conjunctive management of stream-aquifer systems for streamflow augmentation during low-flow periods to off-set depletions caused by well withdrawals from alluvial aquifers, in accordance with Colorado water law. Several habitat partnership programs have begun working with landowners and water user organizations in this region to include managed groundwater recharge ponds in wetland restoration efforts, and to design the ponds to provide seasonal wetland habitat, primarily for waterfowl.

By selecting appropriate pond locations and appropriately designing and operating the recharge ponds, well users can mitigate the stream depletion impacts of their pumping on more senior water rights under a *prior appropriation* legal doctrine. Pond locations can also be selected and evaluated for their potential to benefit waterfowl at the site, and for the development of regional wetland complexes. The cost of the pond site development is also tied to the pond's location due to such factors as the proximity and gradient to water sources and the pond site's soil profile, which impacts recharge rates and excavation costs.

The selection and evaluation of pond sites in this region for streamflow augmentation benefits, pond development costs, and waterfowl habitat benefits has historically been conducted by local experts. Scientific studies and non-refereed publications are available on some portions of pond site selection for recharge potential (e.g. Bouwer 2002) or waterfowl benefits (e.g. Cross and Vohs 1988, Ringelman 1991). There has been, however, no formal, systematic approach to the selection of pond sites for streamflow augmentation, nor for selection of pond sites for waterfowl habitat benefits in this region. There has also been no pond site evaluation method to support coordination between the water managers and the wildlife managers in the selection of pond sites to provide multiple and mutual benefits.

I.C. Research Objective

The objective of this research was to develop a methodology and prototype application that combines the use of knowledge-based systems (KBS), geographic information systems (GIS), and multi-criteria decision analysis (MCDA) in a flexible and transparent system. The prototype application was developed to provide an automated and integrated site assessment evaluation process for the evaluation of recharge pond sites for streamflow augmentation, pond development costs, and waterfowl habitat restoration benefits, drawing upon the experience and understanding of local water and wildlife managers.

I.D. Research Approach

The methodology was developed as a nine-step process and applied in this research for each of the knowledge domains (i.e. physical site characteristics of pond sites for streamflow augmentation; pond development costs; and physical site characteristics of pond sites for waterfowl habitat benefits). The nine steps used for KBS development in this research are:

1. Pre-Development Analysis of the Suitability of a KBS for the Target Problem
2. Knowledge Acquisition
3. Knowledge Translation and Ontology Analysis
4. Data Source Evaluation
5. Domain Knowledge Base and Rule Knowledge Base Development

6. Development of User Interface and Links with Other Input Sources
7. MCDA Development
8. Integration of MCDA into KBS as a Reasoning Engine
9. System Evaluation

The first four steps (steps 1-4) all involve the understanding and acquisition of the domain knowledge and reasoning process to be modeled by the KBS. The next four steps (steps 5-8) involve the structural development of the KBS prototype. System evaluation (step 9) is typically performed in an iterative process throughout the KBS development.

This methodology was used for the development of an Excel-based prototype model called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM) that:

- is linked to GIS coverages for data acquisition and spatial analysis, so that the only required user input is the selection of the site location to be evaluated;
- provides complete explanations to the user of the multiple criteria and subcriteria analysis results and the rules and raw data behind the results of those analyses as applied to the specific alternatives being analyzed; and
- includes adaptable rule/criterion parameters that can be easily changed by the user for rapid updates to the model outputs to reflect new understanding of site assessment criteria by the user, or to reflect new situations (e.g. assessment for different waterfowl species or changes in cost estimation parameters).

WAPSAM was developed as a prototype containing all of the decision parameters cited by the local parameters for which spatial data could support an automated evaluation process if such spatial data were available. WAPSAM was developed in a modular approach consisting of separate components, i.e. physical attributes of pond sites to be developed for streamflow augmentation credits; pond development costs; and physical attributes of pond sites to be developed for waterfowl habitat benefits. These components are referred to as the Recharge Pond Assessment Tool (RPAT), Cost Assessment Tool (CAT), and Waterfowl Habitat Assessment Tool (WHAT), respectively.

The target region for a demonstration application of the methodology is the Lower South Platte River of Colorado, specifically an area within Sedgwick County. The demonstration application is designed to maximize the ability to evaluate potential recharge sites using 1) available knowledge from both local experts and published literature sources and 2) available databases and GIS tools assembled and updated to provide data necessary for site evaluation in an appropriate format, with minimal input requirements from KBS users.

At the time of prototype development, not all of the databases to support automated site evaluation were available. For system evaluation purposes, testing of real sites was performed only on a reduced version of the streamflow augmentation component of the prototype (i.e. RPAT) for those evaluation subcriteria for which databases were available at the time of testing, so that real data could be used for actual pond sites. The criteria included in the system evaluation were selected following an evaluation of databases, from which attribute values are acquired, and of the acquired knowledge on the decision-making process, from which site attributes measurement methods and threshold values are derived. The evaluation of available databases and knowledge was also used to identify the need for future research to support a more comprehensive evaluation of sites. The complete prototype was designed so that new rules could be added and rule parameters and threshold values could be changed as new databases becomes available or as new understanding of the decision making process is gained through future research.

I.E. Dissertation Outline

Chapter I of this dissertation provides the introduction to the research, research objective and rationale, summary of significant contributions of the research, and dissertation outline.

Chapter II of this dissertation provides a summary of prior research on KBS, GIS, and MCDA, particularly as applied to water resources management; on managed groundwater recharge ponds for streamflow augmentation; and on waterfowl habitat and wetlands restoration; and related uses of KBS, GIS, and/or MCDA.

Chapter III of this dissertation presents the execution of the first four steps in the methodology (i.e. the pre-development analysis of the potential applicability of a KBS; knowledge acquisition techniques, including approaches to knowledge elicitation, knowledge translation and ontology analysis; and evaluation of potential sources of data inputs) as applied to the development of the prototype application.

Chapter IV of this dissertation presents the execution of steps 5-8 of the KBS-development methodology (i.e. Domain Knowledge Base and Rule Knowledge Base

Development; Development of User Interface and Links with Other Input Sources; MCDA Development; and Integration of MCDA into KBS as Reasoning Engine) as applied to the development of the prototype application.

Chapter V presents the complete prototype developed through this research for the comprehensive assessment of potential pond sites, called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM), for all of the criteria identified by local experts that could be incorporated into a prototype KBS based on inputs from spatial databases. WAPSAM is presented using hypothetical data and assumed MCDA threshold values in those cases where real data was not available at the time of prototype development. This comprehensive KBS includes a component to consider physical site attributes for recharge pond sites for streamflow augmentation (RPAT); a component to calculate and rank sites based upon estimated pond site development costs, including water source access and delivery costs (CAT); and a component to evaluate potential for waterfowl habitat benefits to be generated at the site (WHAT). Chapter V also summarizes the KBS testing approach (step 9: system evaluation) as applied in the testing of a subset of the RPAT criteria in IPSAM for which databases to provide criterion input data and knowledge to support development of MCDA threshold values are currently available for actual pond sites using real site data.

Chapter VI summarizes significant findings, conclusions, and possible future work related to this research.

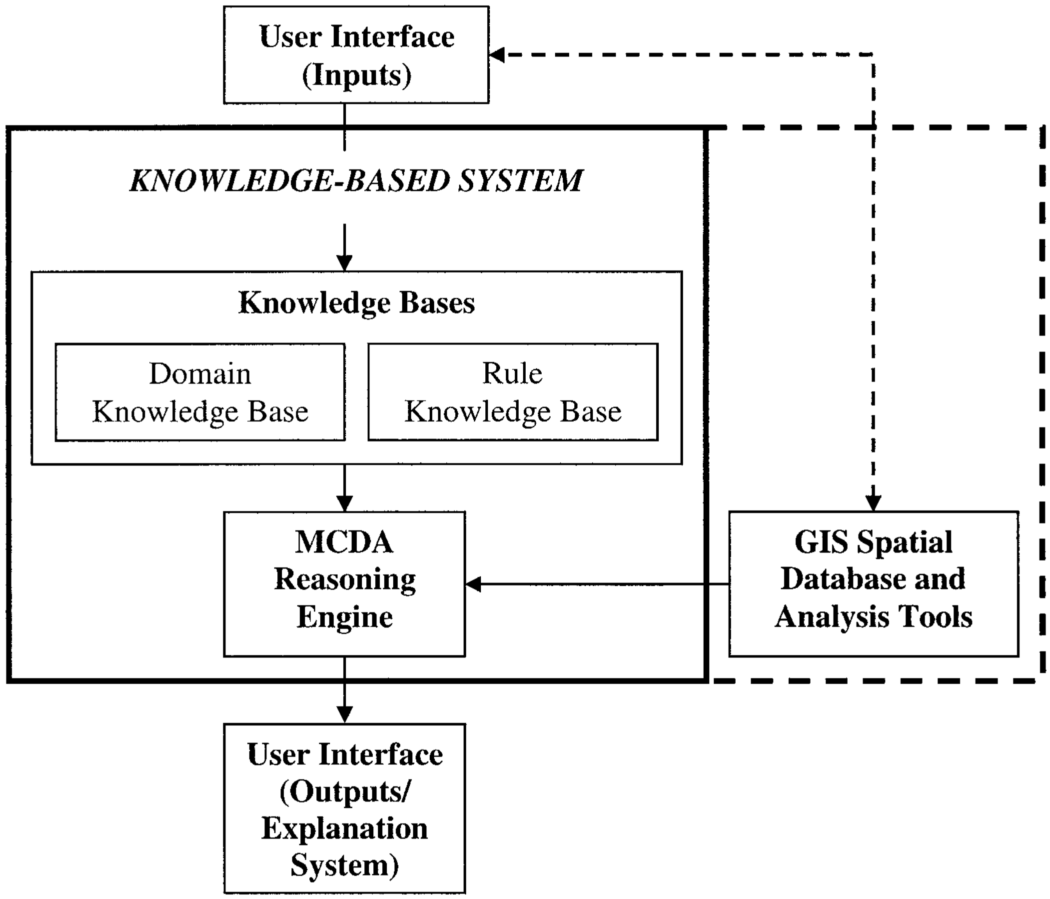
I.F. Significant Contributions of this Research

Specific contributions to be made by this research include the following:

1. Combination of KBS and MCDA methodologies to provide flexibility and adaptability for a rule-based system.
2. Design and development of the KBS in a format that is transparent, is easily identifiable by users and experts, and in a commonly-available Excel-based software package that mimics the functions of more expensive and less commonly used software packages, and which supports rapid and adjustable rule development.
3. Design and development of the KBS to be easily and rapidly adaptable by users so that the threshold values and radius of the area of spatial analysis can be changed to reflect changing site scenarios, user preferences and management priorities, or improved understanding of the decision process.
4. Capture of the decision process of pond site selection for each of the domains of physical site characteristics for groundwater recharge for streamflow augmentation; pond development costs; and waterfowl habitat benefits.
5. Organization of the information on that decision process into domain and rule knowledge bases, including the acquisition and organization of both tabular and spatial databases to support the decision process, in a transparent format that can be incorporated into an automated knowledge-based system.
6. Design and development of a model to link spatial databases in an ArcView/GIS format with site assessment rules for each component criterion and subcriterion programmed into an Excel-based format; linkage of criterion and subcriterion

analyses for each component (i.e. physical site characteristics for recharge for streamflow augmentation; pond development costs; and waterfowl habitat benefits) with MCDAs for each component; and linkage of the MCDAs for each component with an overall site assessment MCDA, with explanations of each component evaluation result and raw data provided in a transparent format, and with the ability to save the results for individual sites to enable comparison of multiple sites or the development of regional analyses.

Figure I-1. Knowledge-Based System Schematic



CHAPTER II.

PRIOR RESEARCH

II.A. Introduction to Prior Research

The research conducted for this dissertation touches upon a range of issues related to assessment techniques and decision support systems, including spatial decision support systems for groundwater recharge, water management in areas with conjunctive use of water resources and waterfowl habitat, as well as the application of knowledge-based systems (KBS) and multi-criteria decision analysis (MCDA) for water and other natural resources management. Prior research on KBS, geographic information systems (GIS), and MCDA, particularly as applied to water resources management, is summarized below, along with a discussion of prior research related to managed groundwater recharge ponds for streamflow augmentation. A summary of prior research on waterfowl habitat and wetlands restoration and site selection, including systems that use KBS, GIS, and MCDA for these applications, is also provided below.

II.B Knowledge Based Systems (KBS) and Water Resources Applications

Knowledge-based systems, also referred to as "expert" systems, are a form of "Artificial Intelligence," which describes methods for computerized simulation of human reasoning, as initially explored at a conference at Dartmouth College in 1956 (Durkin 1997). One way in which knowledge bases and knowledge-based systems differ from other forms of data management and analysis is that KBS include both facts and heuristics, or "rules of thumb" that are used by knowledgeable persons or "experts" in their practice within the domain, although these rules may never have been scientifically proven. Another distinguishing characteristic of KBS from other computer programs that use heuristic programming is the extraction of the program's knowledge into a separate entity, typically called the knowledge base (Schmoldt and Rauscher 1996).

Among the early uses of KBS were applications in natural resources management, particularly for the management of water resources, forest resources, and agricultural resources. One of the first applications of a KBS "shell" program (i.e. a program that can be used to develop KBS regardless of the knowledge subject matter or "domain"), as noted by Schmoldt and Rauscher (1996), was Davis and Nanninga's geographic expert system for resource management called GEOMYCIN (Davis and Nanninga 1985). An early example of a KBS application to wildlife management was a KBS to identify forest stand prescriptions for deer (Buech et al. 1990). Another knowledge-based information management system, called the Environmental Management Decision Support (EMDS), was developed by the USDA Forest Service Pacific Northwest Research Station to provide decision support for watershed analysis, particularly for use with the management of salmon (Reynolds 2001, Reynolds et al. 1999, Reynolds et al. 1996). Local, non-scientific knowledge was an important component in the development of another KBS to predict the distribution and structure of herring shoals (Mackinson 2001, Mackinson 2000, Mackinson and Newlands 1998, Mackinson and Nottestad 1998).

As the use of KBS for water resources and other natural resources management increased, refereed journals dedicated to the discussion of this subject matter began to appear, including *AI Applications*, which was established in 1987 and described itself as "a scientific, peer-reviewed journal devoted to the application of expert systems to natural resources, agriculture, and environmental science." In 1998, this journal was incorporated into *Computers and Electronics in Agriculture (COMPAG),* which continues to publish numerous manuscripts on KBS related to natural resources and ecosystem management. Schmoldt and Rauscher extensively discuss the value of KBS as a tool for natural resource management in their 1996 book entitled Building Knowledge-Based Systems for Natural Resource Management.

The use of KBS has been particularly well suited to natural resources management systems that use an adaptive management approach. Adaptive management, which has been used since the late 1970s for natural resources management, includes the following aspects: 1) management applications that are made in an experimental manner so that the outcome of the management applications can be used iteratively to reduce the uncertainty of the system; 2) monitoring prior to, during, and after the management application that is sufficient to detect impacts and provide feedback; and 3) future management applications that are refined based upon the findings of the monitoring activities as well as feedback from managers and other interested parties (Dovers and Lindenmayer 1997). Adaptive management approaches are often used for species restoration activities, where management actions may be needed to recover declining species before thorough scientific studies can be completed, so that reliance upon heuristics becomes necessary. Water resources management activities are frequently undertaken in conjunction with species restoration activities. Moreover, heuristics are frequently used to develop not only heuristic models to identify management techniques to be applied, but also the approach to evaluation of management outcomes. KBS can be designed so that rules can be added or updated over time, such as when new knowledge becomes available during an adaptive management process. Recent examples of the use of KBS for adaptive management of species and habitat restoration efforts include those described in Norton and Steinemann (2001), Thom (2000), and Kay et al. (1999). Broader analyses of the role adaptive management plays in the integration of species and ecosystem restoration efforts with water resources planning using heuristics and knowledge-based systems are discussed in Prato (2003), Johnson et al. (2002), Jacobs (2002) and Clark and Richards (2002).

Knowledge acquisition methods can be used to develop knowledge bases that provide information on individual sites, information on their proximity to other landscape features, and a method to evaluate that information as needed for regional water resources planning and management, e.g. for management of a stream-aquifer system that uses recharge ponds for stream augmentation. Local expertise can be drawn upon to develop knowledge bases necessary to support an evaluative system. Discussion on the value of the use of knowledge-based systems, particularly those in which local expertise has been incorporated into decision support systems for natural resources management, is available in several publications including Clark and Richards (2002), Sojda et al. (2002), Pedroli et al. (2002), Mackinson (2001), Mackinson (2000), Jensen et al. (2000), Shaw et al. (2000), Neis et al. (1999), Mackinson and Nottestad (1998), Mackinson and Newlands (1998), Lilburne et al. (1998), and Chowdhury and Canter (1998). More information on knowledge acquisition approaches is provided in the next section.

II.B.1. Knowledge Acquisition Methods for Knowledge-Based Systems

Knowledge acquisition has been described as "the process of collecting, organizing, and formalizing the information, concepts, and strategies that pertain to some subject area of interest" (Schmoldt and Rauscher 1996, page 142). Sources of knowledge include human "experts," or knowledgeable persons, as well as published documents (e.g. articles, books, pamphlets) and computer databases (Schmoldt and Rauscher 1996, Laufmann et al. 1990). Schmoldt and Rauscher (1996) characterize the extremes of knowledge capture and problem solving tools as ranging from books, pamphlets, and other "natural language" systems, which have "high generality, but low problem-solving power," to quantitative models, which have "high problem-solving power, but are not generally applicable to situations outside of their explicit models." Knowledge acquisition includes the capture of knowledge from knowledgeable persons (experts) and from published "natural language" sources and the conversion of that knowledge into a format that can be programmed into a "problem-solving" tool, or a tool that can support problem solving and evaluating, mimicking the reasoning process used by human experts.

In referring to the sources of knowledge for a KBS, Laufmann et al. (1990) use the term knowledge source (KS) to describe all possible sources of knowledge, while they use the term "experts" to refer specifically to human sources. The human sources of knowledge are also referred to by various authors (e.g. Ignizio 1991) as the "domain expert," because they are a source of knowledge on the domain in which the problem represented by the KBS is to be solved. The person (or persons) conducting the knowledge acquisition and KBS development is called the "knowledge engineer" (e.g.

Schmoldt and Rauscher 1996, Ignizio 1991). For this research, the author served as the knowledge engineer.

Knowledge elicitation is a term used with respect to the actual process by which the knowledge to be evaluated, compiled, and converted for use within a KBS is acquired. The knowledge engineer can select from several specific knowledge elicitation techniques, or combinations thereof. These techniques include *interviews, questionnaires, observed problem solving, and machine learning:*

- *Interviews:* One of the most commonly used methods for acquiring knowledge, particularly from human experts, is through *interviews.* Interviews may be *unstructured,* with no set question format, topic, or length, and extensive use of *free association dialogue* to identify major issues related to the domain and problem(s) to be addressed in the KBS. Unstructured interviews may be used as an "ice-breaker" and as a means of developing a quick "prototype" during a KBS feasibility study. There are also several methods of *structured* interview approaches, as described in some detail in Schmoldt and Rauscher (1996), such as spreading activation theory (Anderson 1983), physiological scaling techniques (Cooke and McDonald 1987), anthropological methods (Brokenshaw et al. 1980), *modus ponens* sorting (Schweickert et al. 1987), and analytic hierarchy process (Saaty 1980). Several authors have also recommended an approach in interviews for knowledge engineering that is not fully "unstructured" but also flexibly structured (e.g. Mackinson 2001, Hart 1989). Although a knowledge engineer may have prepared questions and subject matter to include in an interview, Mackinson (2003, personal communication) recommends allowing some "free range" discussion during the interviews to allow for acquisition of knowledge the knowledge engineer may not have considered prior to the interview, and further recommends that the knowledge engineer approach the interview with an "open mind." Hart (1989) recommends adaptability in the format and directness of questions depending upon the context of the discussion.

Interviews and other forms of "qualitative research," the results of which are often incorporated into quantitative models, have been used extensively within several fields, including social sciences, behavioral and health sciences, psychology, economics and marketing, as well as in engineering (Flick 2002). The interview methods described by Mackinson (2001) and Hart (1989) fit the definition of a "semi-structured interview" used in qualitative research literature (e.g. Flick 2002, Willig 2001). Willig described the semi-structured interview as one in which the interviewer drives the interview to address a specific research question, following an interview agenda or guide, while encouraging the participant to speak freely and openly. In the case of an interview for a KBS, addressing a research question would entail ensuring that any necessary heuristic rules are identified by the experts, along with any methods for measuring the applicability of those rules, e.g. threshold values. Willig (2001) notes that semi-structured interviews combine the features of the formal interview (e.g. with fixed roles of the "interviewer" and "interviewee") with features of an informal conversation, including use of open-ended questions and an emphasis on narrative and experience.

- *Questionnaires* can be used in cases where the experts are hard to meet with, where there are several experts to be contacted, or where specific, detailed knowledge on a specific sub-domain is sought (e.g. Schmoldt 1987).
- *Observed problem solving* is an approach in which the knowledge engineer watches as the domain expert performs the problem-solving tasks to be represented in the KBS, either in an artificial situation or "on the job." This technique may be used when the experts are reluctant or unable to articulate their decision-making process. Observed problem solving can also supplement other knowledge elicitation methods, recognizing that experts may become self-conscious during interviewing and describe an unrealistic decision-making process, or may overlook details that the expert takes for granted. The domain expert may be asked to explain the decisions they make during the process, or the knowledge engineer may infer the strategies that are employed. Regardless of the method primarily used for knowledge acquisition, Ignizio (1991) recommends site visits, where applicable to the problem to be represented in the KBS, as a means by which the knowledge engineer can "view the problem in its physical context" (page 113). Particularly where natural resources management problems are concerned, the author would also recommend that the

knowledge engineer get to know the intended users and individuals impacted by the problem-solving decisions to be supported by the KBS under development, in order to gain a better understanding of the potential ramifications, uses, and possible misinterpretation of the results produced and decisions supported by the KBS.

- *Machine learning* is used in cases where the knowledge is to be extracted primarily from documentation of problem-solving examples, rather than from domain experts. Methods of *machine learning,* including machine induction (e.g. Michalski et al. 1986), neural networks (Hebb 1949), or genetic algorithms (Goldberg 1989), may be used to identify patterns between decision factors and solutions, as discussed in further detail in Schmoldt and Rauscher (1996).

Knowledge elicitation techniques involving interviews and other interactions with experts provide an opportunity for building mutual respect and trust with the experts, and for gaining an improved understanding of the knowledge domain, terminology, and "world view" of the experts. Initial meetings with interview subjects may also involve a presentation or other explanation by the knowledge engineers regarding the objectives of developing the KBS, including the fact that a KBS is not intended to replace an expert, but to provide computerized support for some of the more basic tasks so that the expert can be available for more interesting and challenging work (Ignizio 1991). Schmoldt and Rauscher (1996) stress the importance of keeping the expert(s) included in the progress of the project to provide "a sense of ownership" and maintain interest in the project.

If multiple experts are interviewed and the level of expertise is uncertain, knowledge acquisition interviews may also include use of methods to test the interview subject's knowledge, honesty, and trustworthiness. In cases in which such testing is to be used, Ignizio (1991), among others, recommends that the interview subjects not be told that they are being tested. Techniques to test the knowledge and credibility of interviewees, as described by Mackinson and Newlands (1998) and Johannes (1978), include 1) asking questions to which the answer is well-known, and 2) asking questions that "sound plausible" but that the interviewee is unlikely to be able to answer. A correct answer to the first type of question establishes that the interview subject has some basic level of domain knowledge. An answer of "I don't know" in the case of the second type of test question indicates that the interview subject is willing to admit to areas where they lack knowledge. These testing methods may be less applicable, however, in cases where an expert or experts have been designated by the client or where the interview subject's level of expertise has been well established prior to the interview.

Several authors have addressed the use of a single expert versus the use of multiple experts in the development of a knowledge base (e.g. Schmoldt and Rauscher 1996, Ignizio 1991, Surko 1989). In some cases, the expert or experts may be designated by the client (Ignizio 1991). In other cases, particularly where local input is sought such as for natural resources management concerns, multiple experts can be identified through word-of-mouth, in which interview subjects are asked to identify other experts on the subject matter (Mackinson 2001). Surko (1989) notes that use of multiple experts creates the possibility of disagreement between experts, but recommends that the knowledge engineer determine which knowledge to incorporate into the system. Mackinson (2000) attempts to treat all knowledge sources as equally valid through the use of a fuzzy rule base. Ignizio (1991) recommends an approach in which a "key expert" is designated, from whom the initial knowledge is acquired and initial rule base derived, and further recommends that the initial rule base, or a "prototype" KBS using that rule base, be presented to other experts to critique or for initial testing. The comments received from the other experts are then compiled and presented back to the key expert. An additional scenario was suggested by Ignizio (1991) involving the use of multiple experts in which different experts provide knowledge on different sub-domains that are pertinent to the overall knowledge represented within the KBS. Within this scenario, the knowledge engineer can create separate knowledge bases for each sub-domain, and combine these knowledge bases within a single KBS package.

Mackinson has written extensively (e.g. Mackinson 2001, Mackinson 2000, Mackinson and Nottestad 1998, Mackinson and Newlands 1998) on the integration of "local knowledge" from natural resource users and managers, for whom practical, applied knowledge regarding the management of those resources is a "prerequisite for their profession," and who are very knowledgeable about the resources they are using or managing "because their livelihood depends upon it" (Mackinson and Nottestad 1998, page 482). Mackinson integrated both local and "scientific" knowledge (from published studies, data, and interviews with scientists and engineers) into a fuzzy logic expert system to "provide quantitative and qualitative predictions on the structure, dynamics and mesoscale distribution of shoals of migratory adult herring during different life stages of their annual life cycle" (Mackinson 2001, page 533) As with the target problem for the research described in this work, Mackinson's KBS targeted a problem for which "large gaps still exist in our basic scientific knowledge" (Mackinson 2001, page 533).

Mackinson and Newlands (1998) stress the importance of the incorporation of knowledge by local resource users and managers (which, in the case of their target problem, included fisherman and fishery managers) in the development of decision support models within their field (i.e. for fisheries science). They support the assertions by social scientists (e.g. Strauss 1997, Pinkerton and Weinstein 1995, Johannes 1978) that the "accumulated knowledge" of fishermen and fishery managers needs to be incorporated into modeling efforts within fishery science. Numerous similar discussions of the importance of the integration of input by resource users, managers, and other "stakeholders" have appeared throughout the field of natural resources management, including the areas of forest management (e.g. Laukkanen et al. 2002, Schmoldt and Peterson 2000, Johnson 1999); marine and coastal area management (e.g. Klaus et al. 2003); mining (e.g. Bhattacharya 2000); wildlife (e.g. Layden et al. 2003); grazing and rangeland management (e.g. Brogden and Greenberg 2003); and farming and food production (e.g. Johnson et al. 2003, Kam et al. 2002).

Mackinson and Nottestad (1998) have noted that the integration of local knowledge into the development of models to support natural resources management decision can be extremely beneficial in terms of the level of acceptability of scientific findings and recommendations that come out of such models. They state that the involvement of resource users who are impacted by management decisions in the development of the models "provides a sense of worth and pride" and may be "instrumental in fostering greater responsibility ... to the resource" (Mackinson and

Nottestad 1998, page 488). In addition, the mutual respect fostered through the knowledge acquisition process and involvement by local resource users in model development enables continued dialogue and information sharing that is essential to local involvement in resource management. Mackinson and Nottstad (1998) cite numerous successful examples of local co-management of fisheries, as described in Jentoft and Kristoffersen (1989), Kew and Griggs (1991), Gillis and Ellis (1995), Stephenson (1997), and Pinkerton and Weinstein (1995).

While efforts to acquire public input as a part of natural resources management efforts have increased, local knowledge has typically been viewed as anecdotal, and has been used primarily to provide cultural and historical context to decision support models (Mackinson and Newlands 1998). Integrating knowledge from non-scientific sources into decision support models has remained a challenge. As several authors have noted (e.g. Mackinson 2001, Saila 1996), local knowledge does not fit well into mathematical representation. Instead of traditional numerical modeling, Mackinson (2000) recommends the use of a fuzzy logic (Zadeh 1965, 1973) KBS to combine scientific information with local knowledge. In his KBS application, Mackinson integrated "practical data" or "applied knowledge" from fishers, First Nations peoples, and fishery managers with "hard data" or "scientific knowledge" from fishery managers, scientists, field studies, and published data.

Mackinson conducted a total of 30 formal interviews, with 8 fishery scientists, 7 fisher managers, 9 fishers, and 6 First Nations people, all with experience as herring fishers. Selection of interviewees was deliberately non random, with an attempt made to interview fishers who had the most and broadest experience, and who held the respect of other fishers in the community. Thus, interviewees were selected progressively using "word of mouth" recommendations by other fishers. Fishery scientists and managers were selected on the basis of their experience with herring. The interviews averaged 2 hours but ranged from 1 to 4 hours in length.

Using methods recommended by Hart (1989), Mackinson asked each interviewee "the same type of questions" but the specific interviews were "free-range or adaptive in the sense that the format and directness with which the questions were presented depended upon the context of the discussion" (Mackinson 2001, page 535). Mackinson noted that "allowing discussion to continue openly in this manner provided insight into many aspects that would have been overlooked by a questionnaire offering only a fixed set of responses." This method was particularly helpful in the interviews with subjects who did not have scientific training, e.g. fishers. The expertise and credibility of the interviewees were tested using the techniques recommended by Johannes (1978), as previously described.

The objective of Mackinson's KBS was to provide a decision support tool that provides quantitative and qualitative predictions on the structure, dynamics and mesoscale distribution of shoals of migratory adult herring during different stages of their annual life cycle, using input on biotic and abiotic conditions. In his interviews, however, Mackinson typically began by asking the interviewee to "talk [him] through a fishing year" and interjected specific questions related to the shoal attributes and descriptors as appropriate to the conversation (Mackinson 2003, personal communication). Interview subjects were also asked to provide explanations for their observations, which the fishery managers and scientists attempted to do, but the fishers were typically unable or reluctant to offer interpretations of their observations. Once the interview input was collected, scientific literature searches and field studies could be used to "test" and quantify the knowledge gained through the interviews (Mackinson 2003, personal communication). Mackinson stated that "an attempt to elicit a rank order of factors they considered important in determining the observed shoal structure, distribution, and behaviors was unsuccessful," and that the "weight of evidence" method was used instead (Mackinson 2001, page 535). Where interview subjects used terms to describe shoals that were different from those used in scientific literature, Mackinson would translate the fishers' terminology to the scientific terms. The shoal descriptors used by the interview subjects, however, with one exception, matched the descriptors used in published literature, although the interview subjects provided extensive functional knowledge and values associated with these descriptors that was not present in the published literature. Several of the techniques used by Mackinson for knowledge acquisition and knowledge base development were applied to the development of the demonstration application for this research.

II.B.2. Structural Development Methods for Knowledge-Based Systems

Knowledge-based systems are generally recognized as consisting of three main components: a *user interface*, a *knowledge base*, and an *inference engine* or *reasoning engine* (e.g. Mackinson and Newlands 1998, Schmoldt and Rauscher 1996). Some authors (e.g. Shortliffe 1976) identify other KBS components for specific implementations, such as a *working memory* and an *explanation system.* Working memory can be viewed as a reasoning engine component in which data or intermediate conclusions are stored temporarily while the KBS continues to operate. Explanation systems provide transparency to KBS, identifying the rules and data used by the system to reach the conclusion. They generally produce user reports or can be invoked by the user as an option. Explanation systems can be viewed as a part of the user interface. Thus, there remain three main components within a KBS (i.e. the user interface, knowledge base(s) and reasoning engine), as shown in Figure I-1. This section (Section IV.B) describes the structural alternatives to the development of each of these KBS components.

The *user interface* is the means by which the end user provides inputs into the system and by which the system provides outputs to the user. One of the goals of this research was to minimize the need for data inputs by the user and maximize the use of spatial databases as a source of data inputs. Thus, as shown in Figure I-1, the spatial database serves as an additional source of inputs between the end user and the KBS. The development of the spatial database was guided by the identification of needs and format requirements for data to support site evaluations by local experts for potential pond locations for stream augmentation and waterfowl habitat.

The development of the user interface is guided by the determination of who the intended "users" of the KBS are. Schmoldt and Rauscher define the users of a KBS as "the people that have a need for advice or knowledge to perform well in a specialized field" (Schmoldt and Rauscher 1996). Determining both who the users are and how they are likely to use the KBS are important steps in the planning of a KBS application. Other critical planning steps in the development of a KBS include identification of both the sources and the characteristics of the data and knowledge. Data inputs to be provided by the users should include only those inputs that the intended KBS users can be expected to have, or the KBS is not usable. Other data sources, such as computerized databases, would need to be made available to the KBS or developed as part of the KBS.

As noted above, the user interface includes both the inputs and outputs. The explanation outputs may include both *descriptive* explanations, also called *justifications*, and *reason-giving explanations,* also called *warrants* (Kline and Dolins, 1985). Descriptive explanations provide a trace of the rules and knowledge used to reach intermediate and final conclusions, while reason-giving explanations provide more in-depth discussion of the data inputs and rationale used to reach those conclusions, reflecting a deeper understanding of the knowledge domain (Schmoldt and Rauscher 1996, Kline and Dolins 1985). Explanations may vary in the level of detail provided, and may also provide discussion of the levels of uncertainty associated with the various rules and final conclusions. An understanding of who the users are and how they may intend to use the KBS also guides the development of the explanation system.

The second component of a KBS is the *knowledge base.* While all decision support systems are based upon some sort of knowledge about the problem domain for which the system was developed, a KBS is distinguished from other systems in that the knowledge in the program is extracted into a separate entity (Schmoldt and Rauscher 1996). As shown in Figure I-1, this component can be divided into the *domain knowledge base* and the *rule knowledge base* (Vlahavas et al. 1999), representing the two kinds of knowledge (facts and rules)(Ignizio 1991).

The *reasoning engine* provides the rules and knowledge which govern the inference and control mechanisms by which a solution is developed. While the term "inference engine" may also be used for this component, the term "reasoning engine" is more inclusive, since both inference and control mechanisms are included in this component, and is reflective of the fact that this component represents the human reasoning process by which an expert or knowledgeable person would derive a solution for a given circumstance with a given set of facts and rules. The term "fired" is used to describe the use of a rule. The reasoning engine determines which rules are "fired," under what conditions, and in what order.

The term *inference* refers to the process by which a conclusion (either intermediate or final) is drawn using a set of rules for a specific set of facts and given situation (Ignizio 1991). The most commonly used inference procedure used is *modus ponens* in which, given that the premise p is known to be true, and that the rule *if p then q* is also known to be true, then the conclusion q is inferred to be true. For this research, *modus ponens* is used. Intermediate and final conclusions are drawn based upon data related to the selected site, as provided by the user or spatial database. This input data forms the rule premises for the initial rules.

The term *control* refers to the overall strategy of moving through the entire rule set in search of a solution. Control mechanisms or *search strategies* are typically applied either by beginning with a consideration of the factual data or causes to establish the conclusions ("data-driven, forward-chaining, antecedent reasoning") or by beginning with the conclusions or goals to identify causes ("goal-driven, backward-chaining, consequent reasoning"). For a *forward-chaining* search, all of the rules are fired and data required for rule premises are either provided at the outset or requested from the user as needed. In a *backward-chaining* search, a possible goal or final conclusion is selected, and the premises and subgoals required to reach that goal are sought and tested. Rules associated with a particular goal are only fired until the goal being tested is found to be "not true." Hybrid searches can also be used, such as when a search is begun using forward-chaining until the set of possible outcomes or final conclusions has been narrowed down to a manageable number of possibilities, at which point, backward-chaining is employed to find the correct outcome.

II.B.3. Use of Prototyping for KBS Development

As noted by Schmoldt and Rauscher (1996), the development of "prototypic implementations" or "proof-of-concept" systems are often an essential part of the KBS development process, in that they can be used to demonstrate and test feasibility of the use of a KBS as a method for problem-solving within a particular domain, and for securing the resources to support further system development. There is extensive literature available on various types of and approaches to "prototyping" as an evolutionary software development method (e.g. Schmoldt and Rauscher 1996, Bischofberger and Pomberger 1992, Budde et al. 1991, Budde et al. 1984, Floyd 1984).

The use of the term "prototyping" is typical in software engineering, and refers to a systematic approach to the development of a program or system. While the term "prototyping" is not found in the dictionary, it is very different from the concept of a "prototype" in manufacturing, which is defined in the Mirriam-Webster Online Dictionary (www.m-w.com) as "a first full-scale and usually functional form of a new type or design of a construction (as an airplane)." (Mirriam-Webster Online Dictionary 2004). Bischofberger and Pomberger (1992), however, present two alternative definitions of "prototype" from their review of literature on prototypes and prototyping in the software development field. One definition of "prototype," provided by Boar (1984), is "an easily modifiable and extensible working model of a proposed system, not necessarily representative of a complete system, which provides later users of the application with a physical representation of key parts of the system before implementation" (page 19 in Bischofberger and Pomberger 1992). A definition of "system prototype," provided by Connell (1989), is "a dynamic visual model providing a communication tool for customer and developer that is far more effective than either narrative prose or static visual models for portraying functionality" (page 19 in Bischofberger and Pomberger 1992). Budde et al. (1991, pages 7-8) distinguish between the use of the term "prototype" in software engineering and in other engineering disciplines, noting that "A software prototype is not the first specimen of a large series of products, as is the case with mass production in the automobile industry, for example: reproduction of a software product is not an engineering problem. The nature of a software prototype is different from that of, say, a wind tunnel or an architectural model: it actually demonstrates in practical use features of the target system. And not merely a simulation of it." Budde et al. (1991) also note, however, that software prototypes are used in a manner similar to prototypes in other engineering disciplines, such as, for example, to provide a basis for discussion, an aid to decision-making, and a means for experimentation.

The development of initial proof-of-concept systems is an essential component of KBS development, and there are several approaches to the development of these initial systems. The development of a "cursory test version" without extensive time and knowledge source availability can not only demonstrate that further expenditures are warranted, but also generates the interest in and understanding of the KBS process necessary to support participation by the experts and dedication of their time and input into KBS development. In addition, as previously quoted from Buchanan et al.'s 1983 publication entitled Constructing an Expert System, "knowledge acquisition and system-building interact inseparably." (page 127 in Hayes-Roth et al. 1983) Thus, the development of a "prototype" provides an essential means by which the knowledge engineer can provide "feedback" to the experts, demonstrating how the KBS is (or is not) successfully capturing the expert's domain knowledge and reasoning process, and, in turn, providing a tool that the knowledge engineer can use to acquire additional knowledge and refine the KBS in an iterative fashion. The use of a "prototype" is also an important means of testing various aspects of the KBS, including the domain knowledge, reasoning process, and user interface, in order to ensure that the framework and approach that is taken to KBS development is appropriate to the problem at hand.

Schmoldt and Rauscher (1996) dedicate an entire chapter section (pages 206-213) to the discussion of different approaches to prototype development in knowledge-based systems development and associated considerations. *Plenary prototypes* is a term they use to refer to the development of the entire application at one time, which they state as being possible typically "when the application covers a very narrow, carefully-defined problem and ... involves little complexity." (Schmoldt and Rauscher 1996, page 207). Even when working towards the development of a "plenary prototype," this approach often involves numerous revisions of a "first-pass prototype." Walters and Nielsen (1988) recommend the development of a broad but shallow version of the system, which can later be fleshed out as further knowledge is acquired and further components are developed.

Schmoldt and Rauscher (1996) also present to two other methods of prototyping, which they refer to as "vertical prototypes" and "horizontal prototypes," and note that these methods are often useful "as applications become larger and more complex" so that prototyping an entire system at once is difficult. (Schmoldt and Rauscher 1996, page 208) Both of these methods have been used to some extent in the applications of this methodology. *Horizontal prototyping* is a method in which a skeleton is developed of the entire KBS indicating all of the components to be included. One of the positive attributes of KBS is that new rules can be added to the system as new knowledge and resources become available so that additional component development can be completed. *Vertical prototyping* is a method that can be used or large, complex applications in which various subcomponents of the larger problem are independent … and may then be combined into a final product later." (Schmoldt and Rauscher 1996, page 209).

II.B.4. System Evaluation Methods for Knowledge-Based Systems

The final step in KBS development is system evaluation. Approaches to, and potential concerns with, the evaluation and testing of KBS through various verification and validation methods have received extensive attention in the literature (e.g. Schmoldt and Rauscher 1996, Lee and O'Keefe 1994, Ignizio 1991, O'Leary et al. 1990, O'Keefe et al. 1987, Buchanan et al. 1983). As noted by Lee and O'Keefe (1994), because expert knowledge may be incomplete and imprecise, it may be difficult to identify whether the KBS is performing incorrectly. The imprecise and rapidly changing nature of the KBS development environment creates problems for specification-based verification approaches (Lee and O'Keefe 1994). Lee and O'Keefe quote Hollnagel (1989) as stating that "the paradox in applying [KBS] is that we want them to do perfectly things we don't really understand" (Lee and O'Keefe 1994 p. 643). O'Keefe et al. (1987) similarly state that "it's unfair to expect [KBS] to perform at levels close to known results when human experts cannot perform at these levels" (p. 83).

As noted by Schmoldt and Rauscher (1996), the problems of testing KBS are compounded in the natural resources fields, where there may be a shortage of "experts" on the target problem and gaps in scientific knowledge may exist, although it may be possible to draw upon the empirical experience of specialists working directly with the targeted natural resources problems in the field, as was done for this demonstration application. There may also be a lack of agreement on the solutions to natural resources problems, or possibly even lack of agreement as to whether there are any "correct answers" to these problems at all. That agreement which does exist on solutions to natural resources problems may also vary between disciplines and geographic regions.

Many authors (e.g. Lee and O'Keefe 1994) discuss the testing process for KBS and other decision support systems as including *verification* and *validation*. O'Keefe et al. (1987) describe the distinction between the two by stating that verification is "building the system right" while validation is "building the right system" (p. 83). As noted by O'Keefe et al. (1987), however, a survey of validation literature by Balci and Sargent (1984) found that there are not standard definitions for these terms and that the term *validation* is often used interchangeably with the term *evaluation*.

O'Leary et al. (1990) suggest that the term *validation* should be used within knowledge engineering to describe the process by which an expert system is determined to represent accurately an expert's knowledge of a particular problem domain, with a focus on the relationship between the KBS and the expert. Under this definition, validation would include both O'Leary et al.'s definition of *verification*, which would include a review of the formulated problem to ensure that the actual problem is included in its entirety and has been structured to enable a credible solution to be derived, and *substantiation,* which would include a check on the accuracy of the computer model and associated data. O'Leary et al. (1990) derive their definition of *verification* from a publication by Balci and Nance (1985) and their definition for *substantiation* from a publication by Balci and Sargent (1981).

Using O'Leary et al.'s definition, *verification* would include simple checks for programming errors as well as reviews of possible errors in rule construction, including checks on *consistency* and *completeness.* Ignizio (1991) identifies several checks for rule consistency, including the identification of redundant, conflicting, subsumed, unnecessary, or circular rules. Ignizio (1991) also identifies tests for rule completeness in KBS, including unreferenced attribute values, illegal attribute values, unachievable intermediate conclusions, unachievable final conclusions or goals, and unachievable premises.

O'Leary et al. (1990) distinguish *validation* from *evaluation*, which they describe as the process by which the KBS can solve real-world problems within the problem domain, focusing on the relationship between the expert system and the real world. Schmoldt and Rauscher (1996, p. 304) also stress the importance of separating the two possible goals for KBS system evaluation between testing the claim that the KBS "captures expertise" and testing the claim that the KBS provides "credible solutions to real-world problems." They further recognize that the latter type of KBS would require the evaluator "to consider the competence of the expert ... in addition to the program's successful portrayal of that competence" (Schmoldt and Rauscher 1996, p. 304-305).

II.C. Geographic Information Systems (GIS) and Water Resources Applications

Water and other forms of natural resources management have benefited greatly from the use of GIS as a decision support tool because many management decisions that must be made related to natural resources are spatially-based. The spatial components of natural resources can be seen in two ways. On the one hand, characteristics of natural resources at individual sites are tied to the site's location. For example, the vegetation that can grow at an individual site is related to the soils at that site. On the other hand, natural resources management often involves decisions regarding individual sites within the context of a watershed, regional, or other larger scale, in which individual sites are evaluated according to their proximity to one another, or to other features. GIS provides an excellent means by which resources can be evaluated on a regional basis, answering such questions as how closely located resources are to one another or how many sites are located within a given area. Spatially-dependent parameters linked to the site location may include not only physical characteristics but also economic/financial considerations and legal/institutional considerations related to land ownership, funding opportunities, and water rights administration. The use of GIS for analysis of spatially dependent situations, and particularly for land use and water resources management, has been discussed extensively in refereed literature (e.g. Mahoud et al. 2002, Shim et al. 2002, Geertman 2000, Cedfeldt et al. 2000, Haupt et al. 1998, Garcia and Armbruster 1997).

GIS has been defined as "a decision support system involving the integration of spatially referenced data in a problem solving environment" (Cowen 1988, page 1551). Geographical data is a subset of spatial data, referring to data related to a place or location in relation to the Earth's surface. Worrall (1991) estimates that 80% of data used by managers and decision makers are related geographically. Initially viewed as a tool for the creation of easy-to-use maps and spatial analysis tools, GIS has been increasingly recognized as being essential to decision support for spatially-related problems. Grimshaw (1994) defines GIS as a system containing a set of procedures to facilitate data input, storage, manipulation, analysis, and output for both spatial data and associated attribute data to support decision-making activities. GIS typically supports spatial decision support systems (SDSS), which developed as a DSS methodology along with advancements in GIS technology (Nyerges et al. 2002, Armstrong 1993, Densham 1991).

The use of GIS in environmental and water resources decision support systems has increased rapidly since the early 1990s. One literature review contrasted a 1988 conference proceedings on "Computerized Decision Support Systems for Water Managers," which included no reference to GIS in the subject index, and a 1991 conference proceedings on "Decision Support Systems in Hydrology and Water Resources Management," in which more than half the papers discuss GIS as part of the research methodology (Fedra 1993). Refereed literature on GIS applications and their benefits have frequently appeared in journals dedicated to natural resources management such as *Environmental Management* (e.g. Stoms et al. 2002) and *Ecological Modelling* (e.g. Garcia and Armbruster 1997).

Foote and Lynch (1996) recognized that the extent to which GIS is useful for decision-making tasks is tied to the manner in which data are entered, stored, and analyzed by the decision makers. For natural resources management, considerations regarding database and coverage development for GIS include whether the system is intended for use at a site-specific, watershed, regional, state or multi-state scale, and whether the level of detail required is for initial screening and general planning, or for more intensive site analysis (Foote and Lynch 1996).

Several authors have cited the use of GIS as a tool to support conflict resolution and consensus building efforts, particularly in natural resources management (e.g. Geertman 2002, Nyerges et al. 2002, Malczewski 1999, Malczewski 1996). Conflicts are common in natural resources management activities, where decisions can impact a range of interested parties, including municipal, agricultural, recreational, and environmental interests. Several methods of participatory GIS (PGIS), a term coined by Harris (1995), have been used, often in conjunction with MCDA, to enable diverse interests to reach consensus on the management and use of natural resources (e.g. Shim et al. 2002, Jankowski and Stasik 1997, Couclelis and Monmonier 1995, Nyerges 1995, Densham 1991).

II.D. Multi-Criteria Decision Analysis (MCDA) and Water Resources Applications

Because the use of natural resources, and particularly water resources, has such wide reaching impacts on human needs, both for survival and for economic purposes, as well as impacts on other species, some of the earliest and most common uses of MCDA have been for water resources planning and management. Recent research that has applied MCDA to water resources related issues has included evaluation of alternatives for regional water supply planning (Rajabi et al. 1999, Netto et al. 1996, Stewart and Scott 1995); river basin management (Raju et al. 2000, de Azavedo et al. 2000, Raju and Pillai 1999a, Bella et al. 1996); reservoir operations (Flug et al. 2000, Fontane et al. 1997, Ko et al. 1994); groundwater management and monitoring (Kwanyuen and Fontane 1998, Dutta et al. 1998, Elmagnouni and Treichel 1994); water quality and ecosystem impacts (Neder et al. 2002, Patil et al. 2001, Randhir et al. 2000); irrigation planning (Karamouz et al. 2002, Gupta et al. 2000, Raju and Kumar 1999, Raju and Pillai 1999b, Gates et al. 1991, Heyder et al. 1991), and recreational uses of water (Flug et al. 1990).

The use of MCDA has been an integral part of the regulation of water development by federal and state agencies. For example, the U.S. Army Corps of Engineers' (USACE's) approach to the evaluation of potential reservoir projects require that projects serve multiple purposes, with possible purposes including municipal and industrial water supply, agricultural water supply, flood control, recreation, and fisheries. Examples of the USACE's use of MCDA to evaluate alternative water resources projects are discussed in Hillyer (1996). The National Environmental Policy Act (NEPA) Environmental Impact Assessment process also requires consideration of multiple types of environmental impacts, and the extent of each impact. These sorts of multi-faceted natural resources management decisions, with consideration of multiple costs, benefits, or both spurred by regulatory requirements, often benefit from the use of an MCDA to provide a structured approach to analysis for regulatory purposes.

Vlahavas et al. (1999) describe components for an MCDA:

A = *the set of alternatives ($a_1 \ldots a_n$) to be evaluated by this model.*

Exclusionary screening, as described in Goicoechea et al. (1982), is used in the development of this set A to ensure that all alternatives are potentially feasible and that attribute values can be determined for each criterion for each alternative.

T = *the type of evaluation.*

Possible types of evaluation include binary choice (either "best" or "not best"); class (sub-sets of choices with various classifications); sort (rank possible alternatives from best choice to worst choice); and descriptive (produce a formal description of each choice without ranking).

D = *tree of attributes.*

Vlahavas et al. (1999) refer to the definition of the tree of evaluation attributes D as "the most important step of the evaluation process" (p. 189). This is the step in which the attributes to be considered in the criterion evaluations are identified. These attributes can also be placed into a hierarchy, in which certain attributes may be dependent upon the evaluation of other attributes. "Basic" attributes are those which cannot be further subdivided, while "compound" attributes are dependent upon the evaluation of sub-attributes

M = *set of measurement methods.*

For each basic attribute d there must be a method M_d used to assign values to that attribute. Values can be arithmetic or nominal. If measurement of an arithmetic value is not practical or nor possible, knowledge acquisition can be used to associate a value to be used for evaluation based upon other data that is measurable. In the case of a knowledge-based system, rules (e.g. "IF, THEN" rules) that have been created through knowledge acquisition can be used to establish this relationship between alternative attributes and the values by which those alternative attributes will be evaluated. In order to include an alternative, also called an "object," within an MCDA evaluation, there must be a value available for each attribute to be evaluated for each of the criteria included within the MCDA evaluation. Thus, it is possible to create a unique combination of a value for each attribute (or MCDA criterion) with each object (or alternative). These unique combinations are called "object-attribute-value" or "OAV" triplets.

E = *set of measurement scales.*

For each basic attribute d there must be an associated scale e_d. The scale must be at least ordinal so that the preference of any two attribute values can be clearly determined (e.g. excellent > good > fair > poor). A point scale can be developed to support a combined evaluation of criteria, particularly when both qualitative and quantitative attribute measurements are used (e.g. excellent = 4; good = 3, etc.). Even through the attribute may itself be measurable, the value of that attribute as it pertains to the criterion may be less quantitative. For example, a price tag of $50 may be considered "inexpensive" for a house, but "expensive" for an ice cream cone. The Saaty scale is an example of a rating scale that can be used to measure and compare qualitative and quantitative attribute values. The Saaty scale (Saaty 1980) is a five-point scale containing the values 1, 3, 5, 7, 9. Five attributes can be measured and assigned to points on that scale. A five-point scale can be used to provide a mid-point, so that anything above that mid-point (i.e. greater than 5) is "better" and anything below the mid-point (i.e. less than 5) is "worse." Bana e Costa and Changas (2002) note that interval scales are a crucial part of MCDA, providing a quantitative representation of both the order and relative attractiveness of the criteria. The scales are set up with a "high" and "low" anchor representing the most and least preferred option. Examples are scales that rank from 0 to 100, or from 1 to 4 (Bana e Costa and Changas 2002). Mathematically, any numerical scale can be converted to any other numerical scale, e.g. a 1 to 4 scale can be converted to a 0 to 100 scale. If a scale is to be developed through knowledge acquisition methods, however, use of a scale that begins with a positive non-zero value may be preferred in that all criteria can be seen by the participants to be considered, even if a low score is assigned to a criterion. Assigning a criterion rating of "zero" may be seen by the local experts as discarding that criterion from consideration. If a criterion is to be excluded from consideration in the MCDA, the appropriate place for that adjustment would be in the aggregation method (e.g. by setting the weight for a criterion to zero) rather than through the measurement scale.

G = *set of preference structure rules.*

For each attribute and the associated measures, a rule is defined to transform measures to preference structures. Preference structures compare two distinct alternatives (e.g. two potential recharge sites) on the basis of a specific attribute. In the case of the demonstration application for this research, knowledge-based system rules are used to determine the value of the attributes according to preferences of excellent-good-fair-poor. In an MCDA that uses a weighted average aggregation method, the weight determines the relative preference between alternatives on the basis of a specific attribute.

R = *aggregation method.*

The aggregation method is the algorithm used to transform the set of preference relations into a "prescription" or order of the set of alternatives

A (e.g. $a_1 \leq a_2 \leq a_3$). These aggregation methods are often referred to as "ranking methods" (e.g. Nijkamp et al. 1990). An appropriate aggregation method must be selected, with numerous choices available within the MCDA field. Categories of aggregation methods include *out-ranking* methods and *value-based* or "*multiple attribute utility*" methods. Out-ranking methods can be very useful when dealing with qualitative evaluation criteria or attributes that may not be easily measured, although these methods can be conceptually more challenging to grasp. Out-ranking methods are "ordinal" in that the attribute values for criteria are given a preference order, but there is no quantitative measurement for the extent to which one criterion value is preferred over another. In other words, criterion value A may be preferred over criterion value B, but A is not "twice as good" as B. Examples of out-ranking methods include PROMETHEE (Brans et al. 1986) and ELECTRE (Roy 1968). Value-based methods, however, are "cardinal" in that there is a scaled measurement associated with different criterion values. The most commonly used method for MCDA is the weighted-average method, which is a value-based method. This method is generally easy to comprehend because it is used so often, e.g. for calculating grade point averages in schools. The weights in a weighted average are often normalized so that the total of all criterion weights equals one, simplifying the process by which the weighted average is calculated. Compromise programming (Zeleny 1973; Duckstein and Opricovic 1980) and analytical hierarchy process (AHP) (Saaty 1980) are other value-based methods. Compromise programming was originally developed by Zeleny (1973) for use in multiobjective problems, but was later used by Duckstein and Opricovic (1980) for discrete MCDA problems. Compromise Programming provides a unique method for determining the set of measurement scales (*E*) to be used in the weighted average, while AHP provides a unique method for determining the weights. In both Compromise Programming and AHP, once the measurement scales and weights are determined, the aggregation calculation is performed in the same manner as the weighted average method.

In addition to the above components and MCDA development decisions suggested by Vlahavas et al. (1999), a decision also needs to be made regarding whether the MCDA aggregation algorithms is to be operated using a "backward" or "forward" approach. In a "backward" approach, the preferred outcome or goal is selected for testing purposes, and each alternative combination of attribute values is evaluated only to the extent that they are shown to be able to produce the preferred outcome. Once an alternative is found that produces that outcome, the analysis typically stops, whether or not that alternative would produce an "optimum" outcome. In a "forward" approach, all combinations of alternatives are considered feasible and all are evaluated. Several alternative outcomes can be produced within each criterion and evaluated. If weights are assigned to various criterion evaluation outcomes, then the more heavily weighted criteria will have a greater effect on the overall outcome or decision.

II.E. Combined Use of KBS or MCDA with GIS

Because KBS are often valuable in dealing with water resources management and other spatially-based problems, several authors have discussed the combination of KBS with GIS (e.g. Royle et al. 2002, Stoms et al. 2002, Reynolds 2001, Reynolds et al. 1999, McKinney et al. 1995, Fedra 1995). Because water resources and other natural resources management problems often require consideration of multiple criteria for decision making, the combination of GIS or KBS, or both, with MCDA also has appeared in the literature, particularly with regard to natural resources management (Store and Kangas 2001, Malczewski 1999, Thill, ed. 1999, Tkach and Simonovic 1997, Malczewski et al. 1996). No prior research has been found, however, which links the development of an MCDA with a KBS developed through work with "local" experts and with data inputs from GIS coverages reviewed and selected using knowledge-based methods.

II.F. Artificial Recharge Ponds and Streamflow Augmentation

No existing methodology to evaluate the siting of recharge ponds in terms of site characteristics for potential to supply recharge for streamflow augmentation, or for other site benefits such as water rights compliance, economic benefits, or habitat, has been found in the literature. There have been few efforts to develop models and decision support tools to evaluate existing or hypothetical managed groundwater recharge ponds and the impacts of these on streamflow and water rights, including comparisons of models to predict return flows from recharge ponds (Garcia et al. 2001, Fredericks et al. 1998, Hartwell 1987, Kundhardt and Fontane 1995, Sophocleus et al. 1995). Some studies have discussed physical site characteristic and design considerations for recharge ponds (Bouwer 2002, Mushtaq et al. 1994, Warner et al. 1994, Masciopinto et al. 1991), although only one of these (Warner et al. 1994) dealt with recharge ponds for streamflow augmentation.

II.G. Use of GIS, MCDA, or KBS for Evaluation of Potential Habitat or Wetland Restoration Sites

The author has found no existing methodology to evaluate the siting of ponds in terms of site characteristics for potential to provide waterfowl habitat in the Lower South Platte of Colorado, nor to identify the ability of particular sites to meet programmatic goals of habitat restoration programs, such as eligibility for funding or support for a landscape level wetlands restoration strategy under the Colorado Wetlands Program.

There have been numerous efforts, as cited below, to develop methodologies to evaluate potential wetland restoration or habitat sites, and there have been a number of computer-based, and especially GIS-based, decision support systems (DSS) developed to support these efforts. In the area of wetlands, techniques developed for wetland assessment and classification to support wetland restoration activities include the Federal Highway Administration's (FHWA's) Method for Wetland Functional Assessment (Adamus 1983, Adamus and Stockwell 1983), later revised as the U.S. Army Corps of Engineer's (USACE's) Wetland Evaluation Technique or "WET" (Adamus et al. 1991); the U.S. Fish and Wildlife Service (USFWS) wetland classification system (Cowardin et al. 1979); and the USACE's Hydrogeomorphic Method (HGM)(Smith et al. 1995). The manner in which wetlands can be evaluated on the basis of various wetland functions and geographic applications ranges widely among the different evaluation procedures available. Bartoldus (1999) identified and reviewed 40 different procedures for evaluating wetlands, highlighting differences between the various procedures in terms of geographic application, types of categories addressed, data requirements, procedure output (e.g., functional capacity, wetland quality), units of measure (e.g., functional capacity index, performance score), list of states where procedure has been applied, use on mitigation banks, and list of corresponding terminology both emphasize the importance of recognizing that wetlands can have any of a number of recognized functions.

The WET manual provides correlative predictors for each of eleven wetland functions and values, based on an extensive literature review, and defines wetland functions as "physical, chemical, and biological processes or attributes of wetlands that are vital to the integrity of the wetlands system" (Adamus et al. 1991 page 5). Wetlands values are defined as "wetlands attributes that are not necessarily important to the integrity of the wetlands system itself, but are perceived as being valuable to society," such as recreation, aesthetics, or "heritage" (Adamus et al. 1991 page 5). HGM was developed as a method to assess self-sustaining ecosystem functions of wetlands, as opposed to wetland functions that society determines to be "valuable." HGM classifies wetlands into hydrogeomorphic groups first, then identifies the functions that each group is capable of performing. For a given region, "reference wetlands" are identified that represent each hydrogeomorphic group (Cedfeldt et al. 2000). The level to which various wetland evaluation methods can evaluate specific wetland functions also varies according to the level of understanding of each function and the ability to measure each function. Several authors have reviewed the usefulness and applicability of HGM and WET (e.g.

Stevenson and Hauer 2002, Whittecar and Daniels 1999, Brinson and Rheinhardt 1996). As noted by one of the developers of HGM, "The present classification [HGM] stops short of discussing values.... By limiting the analysis to science, issues can be avoided that deal with which value is more important than others (Brinson 1993, p.3)."

Several methods and decision support systems, cited later in this paragraph, have been developed to address wetland site evaluation priorities for specific regions and for specific values or program goals, including regulatory requirements and restoration programs for particular species, as well as more general habitat considerations for the support of "biodiversity." Identification and classification of wetland functions has generally become important in restoration activities to ensure that there is an understanding of the costs of specific wetlands impairments and benefits of specific wetlands restoration or conservation activities. Examples of DSS developed to evaluate wetland functions include the North Carolina Department of Environment and Natural Resources' Geographic Information System for Targeting Wetland Restoration (Haupt et al. 1998); the Automated Assessment Method for Northern Wetlands (Cedfeldt et al. 2000); the National Wetlands Research Center's GIS-based decision support function for coastal wetland permit analysis (Ji and Johnston 1994); a spatial DSS developed for prioritizing of restoration sites in the Mississippi River Alluvial Plain (Llewellyn et al. 1996); a system to prioritize wetland restoration sites for flood attenuation in the Prairie Pothole Region of the United States (McAllister et al. 2000); a DSS using mathematical optimization to support wetland maintenance in the Kesterson Refuge area of California's San Joaquin Valley (Vadas et al. 1995); and a DSS to support sustainable management of perifluvial wetlands of the Po River in Italy, including consideration of biodiversity and tourism goals (Bodini et al. 2000). The main incentives cited for the development of these DSS have been: 1) the USACE permitting requirements under the Clean Water Act and associated state-level permitting requirements associated with wetlands and 2) landscape-level planning of wetland restoration and conservation activity to support biodiversity or protected species recovery efforts. These DSS are typically developed specifically to address regional considerations, and have been tailored to support local wetlands concerns.

To date, there has not been a wetland planning DSS developed in Colorado, although the Colorado Natural Heritage Program (CNHP) wetlands classification and characterization system provides an important tool to support the future development of a wetland planning DSS, where sufficient data is available to provide the inputs needed for this classification system. The CNHP classification system was developed for the Colorado Department of Natural Resources and has been proposed to form the basis for wetlands management, restoration, and protection in Colorado (Carsey et al. 2003), although this system has not yet been incorporated into a formal process to regulate or otherwise guide wetland permitting and restoration activities in Colorado. The CNHP classification system is based on HGM classes as well as the U.S. National Vegetation Classification System (Federal Geographic Data Committee 1997) and the U.S. Fish and Wildlife Service (USFWS) definition of wetlands (Cowardin et al. 1979). Unlike the definition used by the USACE, the USFWS definition recognizes that not all wetlands are "jurisdictional" as recognized under the Clean Water Act permitting process. Under the USFWS definition, wetlands have one or more of three attributes: 1) the land predominantly supports, at least periodically, wetland plants (hydrophytes); 2) the substrate is predominantly undrained hydric soil; and/or 3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year (Cowardin et al. 1979). According to the USACE definition, "jurisdictional" wetlands must have all three recognized wetland attributes, i.e. vegetation, soil, and hydrology (Carsey et al. 2002).

USFWS classifications are used for National Wetlands Inventory maps, which are available in a digitized format for use with GIS-based systems in many parts of the United States, but have not yet been digitized for the Lower South Platte of Colorado. Several GIS-based decision support systems use USFWS wetland classifications and National Wetlands Inventory coverages, often in combination with soils maps to identify hydric soils, to identify USACE jurisdictional wetlands for permitting purposes.

Other evaluative procedures and DSS for selection and ranking of habitat sites for various species have been developed, including the Habitat Evaluation Procedures (HEP), which were developed by the U.S. Fish and Wildlife Service to provide a standard means for habitat planning and evaluation. The basic premise of HEP is that an area will have specific suitability to support specific species, and that the suitabilities can be quantified. In order to use HEP, Habitat Suitability Indices (HSIs) must be developed. Other habitat evaluation models based on HEP and HSI that have been developed by federal agencies to support habitat evaluation and planning activities include the Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation Model (PHABSIM) for stream habitat and Habitat Management Evaluation Tools, to simulate the effect of alternative management actions (Stauffer et al. 1990).

HSIs are developed as the quantified representation of habitat suitability used to support the HEP approach. The U.S. Fish and Wildlife Service provides information on how to develop a HSI, and also has developed software to support HEP and HSI applications. A number of GIS-based DSS (Garcia and Armbruster 1997, Lyon et al. 1987) have been developed in which HSIs have been incorporated into GIS-based systems in order to address the spatial aspects of habitats and spatial relationships between habitat sites and between habitats and other landscape features (e.g. wetlands or manmade disturbances).

A benefit of the approach of developing GIS-based DSS for HSI is that, in cases where habitat suitability is determined by spatial relationships (e.g. a minimum area or distance between features), GIS is highly suitable. A limitation of these GIS-based DSS, however, is that they can be used only for species for which an HSI has been developed. To date, the U.S. Fish and Wildlife Service only has completed and published HSIs for a total of fewer than 175 species. Generally, the development of these indices requires extensive field studies and literature review, and is specific to only a certain species or subspecies, and may need to be modified for a specific region. There is also variation by species on what criteria are used to determine habitat suitability. For example, for a bird species, nesting and brood rearing habitat may be considered limiting factors, although these habitat types would not be applicable for ungulates. Thus, the development of an HSI for a species requires not only collection of the data needed for the assessment, but also determination of the criteria to be used for the assessment.

In order to evaluate habitat preferences in cases where HSIs are not available, or where other local knowledge can improve habitat analyses to support management decisions, some GIS-based DSS have been developed that use knowledge-bases. The Ecosystem Management Decision Support System (EMDS) was developed by the Pacific Northwest Research station of the U.S. Forest Service to provide an application framework for knowledge-based spatial decision support of ecological assessments (Reynolds et al. 1996). As with many "shells", this system is limited in the amount of re-programming that can be performed to tailor the system to the user's needs.

II.H. Waterfowl Habitat Restoration, Wetlands, and Recharge Ponds, and Related Decision Support Systems

The connection between wetlands and waterfowl has long been recognized, and many efforts to protect and restore waterfowl and other wetland-dependent birds has centered around wetland restoration activities. Several refereed publications are available on the use of wetlands by specific waterfowl species (e.g. Krapu et al. 2000 on Mallards). Most literature on wetlands and their importance to waterfowl in general, and on the management of wetlands to support waterfowl, are available only in non-refereed publications. Typically, this literature is published by wildlife agencies and organizations, such as the U.S. Fish and Wildlife's "Wetlands of the United States: Their Extent and Their Value to Waterfowl and Other Wildlife," published in 1956 (Shaw and Fredine 1956), and Waterfowl Management Handbook (Cross and Vohs 1988). Other handbooks have been developed by state agencies, including Ringelman's manual entitled "Evaluating and managing waterfowl habitat: a federal reference on the biological requirements and management of ducks and gees common to Colorado" (Ringelman 1991).

Little refereed literature is available that provides an overview of wetland habitat requirements more generally. As Fredrickson and Reid stated in their publication, "Management for waterfowl in North America is complicated ... because each of over 40 species has unique requirements that are associated with different wetland types. Likewise, the requirements of a single species are best supplied from a variety of wetland types." (Fredrickson and Reid, in Cross and Vohs, 1988, Fish and Wildlife Leaflet 13.2.1. page 1) Important life cycle stages in which waterfowl may be dependent upon wetlands include breeding and brood rearing, as well as feeding to prepare for migration and overwintering. Different dietary requirements, ranging from a protein-rich diet to a carbohydrate-rich diet, can be met by different types of wetlands. Frederickson and Reid (in Cross and Vohs 1988) and Frederickson and Taylor (1982) provide information on the water depths and vegetative requirements for various waterfowl species. Frederickson and Reid (1988) note, "Determining a reasonable balance of the resources required to meet seasonal requirements of all populations of waterfowl using a specific refuge undoubtedly is more challenging than determining the species of plants needed to provide food and cover." (Fredrickson and Reid, in Cross and Vohs, 1988, Fish and Wildlife Leaflet 13.2.1. pages 3-4).

The importance of seasonal wetlands for waterfowl, in which the wetlands are drained from shallow ponds (providing access to insects) to mudflats (providing access to seeds), is also discussed in various publications (e.g. Gammonly and Lauhban 2002, Naugle 2001, Krapu et al. 2000, Cross and Vohs 1988, Frederickson and Taylor 1982). Numerous studies have documented the dependence upon various wetland types by specific waterfowl species. One of the assessment criteria cited the most often in guidebooks, as well as by local experts, was the need for the development and restoration of wetland complexes. Frederickson and Reid, in their chapter of the USFWS Waterfowl Management Handbook (Cross and Vohs 1988), provide an overview of waterfowl use of wetland complexes. The term and criteria for assessing a "wetland complex," however, is not well-defined in either refereed or non-refereed literature, although Ringelman (1991) stresses the importance of providing a "diverse wetland community" and "a wide range of 'microhabitats'" as are available in a wetland complex to support both a diversity of waterfowl species and varying life cycle stages (Ringelman 1991, page 16).

Two KBS (Sojda 2002 and Gammonly and Laubhan 2002) have been identified that address waterfowl habitat and wetlands in the Rocky Mountain region. Sojda (2002) completed dissertation research at Colorado State University on the development of a knowledge-based decision support system for trumpeter swan *(Cygnus buccinator)* management. This KBS was developed to support population recovery efforts and reestablishment of migration paths through the Montana-Idaho-Wyoming region. Sojda's research, also presented in Sojda et al. (2002), was intended to test the feasibility of using a KBS to support integration of flyway management into site-specific decision support for trumpeter swan management. Sojda linked together three separate KBS which he developed on breeding habitat needs for trumpeter swans, management of palustrine wetlands in the Northern Rockies, and the contribution of site-specific management activities towards flyway management for the Rocky Mountain population of trumpeter swans.

Hamilton and Laubhan (1997), through the U.S. Geological Survey Midcontinent Ecological Science Center, developed a KBS, called the Moist-Soil Management Advisor

(MSMA), to support the management and operation of moist-soil complexes, or complexes of constructed seasonal wetlands with plants that are intended to provide habitat primarily for waterfowl. These complexes are typically operated so that they are wet in the spring and fall and dry in the summer, with specific manipulations that may be required to control vegetation or salinity problems. This system requires extensive inputs from the user describing the managed area, plant species, and management goals. Moist-soil complexes are used primarily to provide habitat to support migration, rather than for breeding and brooding. This KBS has been used by the U.S. Fish and Wildlife Service to support management of National Wildlife Refuges, but the use of this KBS to support management of habitat on private lands is unknown. Moist-soil complexes are the type of habitat which local habitat experts are seeking to develop in the Lower South Platte, and this KBS may be usable to support operation of facilities once the location of those facilities have been identified. Unlike the KBS developed in this dissertation, however, MSMA does not support the evaluation of potential sites in a manner used by local experts to determine suitability for development of sites within the Lower South Platte Region, nor does it address programmatic considerations such as landowner eligibility to participate in habitat partnership programs.

Neither of these KBS addresses the aspects of site evaluation for potential waterfowl habitat and habitat partnership program participation that are addressed in this dissertation. There has been no formal delineation published of the criteria considered by habitat partnership programs in the selection and evaluation of potential sites for waterfowl habitat sites and wetlands restoration, nor has there been a knowledge-based system developed to support this evaluation process.

II.I. Artificial Recharge Ponds and Habitat and the Recharge Functions of Wetlands

Recharge has been recognized as a wetland function under the Federal Highway Administration's Method for Wetland Functional Assessment (Adamus and Stockwell, 1983) and U.S. Army Corps of Engineer's Wetland Evaluation Technique (Adamus et al., 1991). Adamus et al. (1991) also note that wetlands can provide low (or base) flow augmentation when recharge in wetlands becomes discharge to streams during dry seasons. Existing wetlands, and particularly prairie potholes, have been studied for their contribution to groundwater recharge (Lissy, 1971, LaBaugh et al., 1987, Wood and Osterkamp, 1984, Mills and Zwarich 1986, Siegel, 1988, Koreny et al. 1999, Winter 1999). In 1991, Adamus et al. noted that "the recharge function of wetlands has been inadequately studied and in some regions has apparently been totally unmeasured by systematic water budget studies" (Adamus et al. 1991, page 9).

Extensive studies have been completed on wetland functions related to water quality improvement, including the removal of specific contaminants (e.g. nutrients including phosphorus and nitrogen, and toxic metals and toxic organic compounds) and aquatic and wildlife habitat, as discussed in detail in Campbell and Ogden (1999). Information on projects where wetlands have been developed to provide water quality improvement benefits and stormwater filtration benefits have been designed to provide additional wildlife habitat benefits is largely anecdotal (e.g. Campbell and Ogden 1999, Artz 1998, Lyle 1985). A contingent valuation study was conducted by a multi-disciplinary team (Loomis et al. 2000) in which five ecosystem services were identified that would be provided with changes in riparian management, including dilution of wastewater and natural purification of water, for which the recharge to the aquifer and augmentation of streamflows are a result, not a primary objective.

While review of relevant literature has revealed a lack of formal research studies on the use of wetlands to provide recharge benefits or the use of recharge facilities to provide wetland or waterfowl habitat benefits, there have been a number of recent projects developed in the Lower South Platte of Colorado in which habitat biologists and water resources engineers have worked together to design multi-purpose facilities. Ducks Unlimited (DU) and the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program (PFW) have both developed wetlands at pond sites that were also intended to serve as recharge ponds. Typically, these habitat partnership programs, along with the Natural Resources Conservation Service's (NRCS's) Wetlands Reserves Program (WRP), develop agreements for conservation easements with private landowners in this region. A landowner who is developing a recharge pond, and is interested in working with a habitat partnership program and designing the recharge pond to provide habitat benefits, will typically contact the habitat partnership program, or may be referred to a habitat partnership program by local water user organizations, to determine whether their site would be suitable for habitat and meet the eligibility requirements of that program. McAllister et al. (2000) refers to this approach as "restoration efforts … driven by opportunity" in which contacts to the restoration programs by landowners determine the selection of wetland restoration sites. While habitat partnership programs have been involved with the development of habitat at managed groundwater recharge sites in Colorado since the mid-1990s, no formal research has been conducted on the effectiveness of the integration of habitat and recharge benefits, nor have site selection methods been developed to maximize benefits for habitat and recharge credit development. No formal criteria for selection and evaluation by habitat partnership programs of potential sites for waterfowl habitat sites and wetlands restoration has been published, nor has a knowledge-based system developed to support this evaluation process been created.

CHAPTER III.

RESEARCH METHODOLOGY PART I:

KNOWLEDGE ACQUISITION AND DATA INPUT ANALYSIS

III.A. Introduction

As stated in Chapter I, the objective of this research was to develop a methodology and prototype application that combines the use of knowledge-based systems (KBS), geographic information systems (GIS), and multi-criteria decision analysis (MCDA) in a flexible and transparent system. This system was developed in a nine-step process, outlined in Chapter I. This chapter describes the first four KBS-development steps, which involve the understanding and acquisition of the domain knowledge and reasoning process to be modeled by the KBS. The KBS development steps described in this chapter, as applied to the development of a prototype application for evaluation of recharge pond sites for streamflow augmentation, pond development costs, and waterfowl restoration benefits, are:

1. Pre-Development Analysis of the Suitability of a KBS for the Target Problem
2. Knowledge Acquisition
3. Knowledge Translation and Ontology Analysis
4. Data Source Evaluation

Background information on the use of recharge ponds for streamflow augmentation in the Lower South Platte of Colorado is provided in Appendix A. Background information on waterfowl habitat and wetlands restoration efforts in the

Lower South Platte of Colorado is provided in Appendix B. A more detailed account of the knowledge acquisition processes for evaluation of potential recharge pond sites for streamflow augmentation, pond development costs, and waterfowl habitat, with knowledge acquisition results, are provided in Appendix C.

III.B. Domain Validation of Suitability for KBS

Prior to developing a KBS, some initial pre-development analysis of the problem to be solved is normally conducted to determine whether the use of a KBS is warranted and viable. Some authors have attempted to develop lists of conditions under which the application of a KBS is suitable (e.g. Schmoldt and Rauscher 1996, Ignizio 1991, Laufmann et al. 1990, Casey 1989, Prerau 1985) although, as noted by Schmoldt and Rauscher (1996), any particular problem to be addressed in unlikely to satisfy all of the "conditions" for KBS suitability, and there may be subtle differences between categories of problems that may not become evident in a "succeed/fail" list comparison. Laufmann et al. (1990) suggest a formal, systematic procedure for evaluating potential KBS applications. Many of the pre-development evaluations of potential KBS applications (e.g. Schmoldt and Rauscher 1996, Ignizio 1991, Laufmann et al. 1990) address considerations regarding the potential net benefit of the KBS, the goals of the users, the level of support and expectations of the client, and other considerations of importance primarily to knowledge engineering consultants.

To evaluate the potential suitability of a KBS to evaluate recharge pond sites for streamflow augmentation, pond development costs, and waterfowl habitat restoration benefits, the principal considerations used in this research pertained to the comparative suitability of a KBS over a more quantitative model as a problem-solving or problem-evaluating tool, and the ability of a KBS to provide a means of capturing and presenting the current level of knowledge. Recommendations by several authors (Schmoldt and Rauscher 1996, Ignizio 1991, Laufmann et al. 1990) were considered regarding potential KBS suitability.

The required decision had the following characteristics that indicated that a KBS application would be suitable for evaluation of potential pond sites for streamflow augmentation, pond excavation costs, and for waterfowl habitat benefits:

1. The problem of evaluating pond sites for streamflow augmentation or for waterfowl habitat restoration has been addressed previously by experts in several instances over time, so that a "library of test cases" is available for the evaluation of ponds for these separate purposes (although there are fewer examples of ponds that have been developed for both purposes).
2. With the number of recharge ponds and waterfowl habitat restoration sites increasing in the region (as discussed in Appendices A and B), there is an increasing need for additional applications of the problem-solving approach to be represented in the KBS.
3. The number and availability of experts is limited, so that capture of, and access to, their expertise would be valuable, and there is a need for the experts to spend their time and efforts on other problems.
4. At least one expert exists who has a sufficient level of expertise and experience solving the problem to be represented by the KBS. The expert has considered

multiple cases under varying circumstances and is capable of articulating the important concepts in solving the target problem.

5. There is some agreement among experts regarding approaches to and criteria for problem-solving for this application.

6. The scope of the problem can be compartmentalized and limited, and incremental development of the KBS is possible.

7. The problem is combinatorial, with several considerations put together during the evaluation of a potential site.

8. Extensive scientific studies of the physical characteristics of preferred recharge sites for stream augmentation or for the costs associated with pond development are not available. A few studies of recharge sites have been performed (e.g. Warner et al. 1994, Burns 1984, Burns 1980), but these studies do not provide a systematic approach to the selection or analysis of potential recharge sites. Algorithmic representations of certain portions of managed groundwater recharge, such as the Glover method for determination of Stream Depletion Factors (as described in Glover 1964), are available for some aspects of site evaluation. These algorithms, however, do not provide a complete picture of the various criteria considered by local experts in their evaluation of potential recharge pond sites. While a few prior studies have reviewed some of the physical or legal aspects of recharge ponds for stream augmentation (Garcia et al. 2001, Fredericks et al. 1998, Warner et al. 1994), the selection and evaluation of potential recharge sites for stream augmentation is a complex, ill-structured problem typically addressed by local experts based upon heuristics developed through years of

experience. The cost aspects of pond site development has received little or no attention in published literature.

Habitat restoration and site evaluation processes have been studied but remain complex and not well understood. There are some studies published on some aspects of evaluation of pond sites for waterfowl habitat, particularly for individual species in specific locations and typically limited to habitat needs for a specific life cycle stage (e.g. Krapu et al. 2000, on breeding habitat for mallards in the Prairie Pothole region), as well as numerous non-refereed guidebooks published by experts in this practice (e.g. National Biological Survey 1995, Ringelman 1991, Bridges et al. 1989, Cross and Vohs 1988, Frederickson and Reid 1988, Frederickson and Taylor 1982). However, these published materials are not comprehensive and have not been structured in a manner that is conducive to the development of an automated decision support tool. While parts of the problem can be addressed algorithmically, there are no existing algorithms or other quantitative models explicitly designed to address the comprehensive and ill-structured problem of site evaluation for potential waterfowl habitat pond sites to be represented by the KBS.

II.C. Knowledge Acquisition

Once an initial analysis of the potential applicability of a KBS to address a problem-solving need has been accomplished, development of a knowledge base is normally considered the next step. Background on various methods of knowledge acquisition is provided in the literature review (Chapter 2). Buchanan et al. (1983), however, note that "acquiring knowledge from experts resists linear, one-pass techniques. Instead, knowledge acquisition and system-building interact inseparably" (Buchanan et al., page 127 in Hayes-Roth et al. 1983). Schmoldt and Rauscher (1996) note that "knowledge acquisition occurs throughout the different development stages and does not constitute a stage in and of itself" (page 111). Schmoldt and Rauscher (1996, page 112) further state that it is "very important to acquire additional knowledge and restructure the knowledge based on a more refined understanding of the domain knowledge – whether that knowledge originates from documents, people, or other software." While the knowledge bases can be refined as new knowledge is gained, however, the development of an initial knowledge base is the first step in the development of a KBS. A KBS is defined by the existence of a knowledge base, which is developed through knowledge acquisition (Schmoldt and Rauscher 1996). Buchanan et al. (1983) note that the use of a stand-alone domain knowledge-base provides the advantages of "transparency and flexibility" (page 130 in Hayes-Roth et al. 1983). For the demonstration application in this research, semi-structured interviews were conducted, using methods described by Mackinson (2001) and Flick (2002), as discussed in the literature review (Chapter II).

III.C.1 Knowledge Acquisition for Streamflow Augmentation and Cost Knowledge Bases

A more detailed discussion of the knowledge acquisition process and results for the streamflow augmentation and cost knowledge bases is provided in Appendix C, and is summarized here. Interview subjects for knowledge elicitation were selected with input by members of the South Platte Lower River Group (SPLRG), an organization which includes as participants several of the water users, water managers, water engineers, water accountants, and other individuals involved in the development and management of recharge ponds for stream augmentation in the Lower South Platte. SPLRG, which provided partial funding for this research, identified one individual, Jon Altenhofen, Supervisory Water Resources Engineer with the Northern Colorado Water Conservancy District, as having had the most experience with the selection of pond sites and development of ponds. Mr. Altenhofen also heads the Northern Colorado Water Conservancy District's (NCWCD's) Augmentation Recharge Accounting (ARA) program, a service provided by NCWCD to well owners and water user organizations throughout northeastern Colorado for the accounting of recharge "credits" for stream augmentation plans in accordance with Colorado water law. Mr. Altenhofen was designated by SPLRG as the "key expert" for the purposes of the development of the initial knowledge base. Several other individuals involved in SPLRG, who had experience with the development of augmentation plans and management and development of sites for water user organizations, ditch companies, and municipalities, or who reviewed augmentation plans for the state water resources agency (i.e. the State Engineer's Office or "SEO"), were later asked to review and test the domain and rules knowledge bases and the KBS demonstration model, and to make their own recommendations for additional knowledge, rules, and criterion rankings and weights. The initial knowledge bases and the demonstration model were also presented at SPLRG meetings for review and feedback. This research study used a combination of a single key expert and multiple experts.

Prior to the initial expert interview, and throughout the KBS development process, the author gained mutual trust and respect with local experts through attendance at SPLRG meetings and other meetings related to stream augmentation in the Lower South Platte region and visited recharge pond sites with the site owners or managers. An important benefit of attendance at these meetings was the opportunity to meet and gain the trust of individual water users and managers in the region. Mackinson and Nottestad (1998, page 483) stress the importance of "personal face to face communication" because "body language is crucial and cannot be interpreted by telephone, fax, or email" and because "personal character judgment is fundamental in our evaluations of others' ability." Because the author had met personally with local experts repeatedly prior to the formal knowledge acquisition, however, it was possible to contact some of the local experts through remote means (e.g. by phone or electronic mail), particularly for follow-up questions or review of the knowledge bases and testing of the demonstration model.

The initial interview with the key expert lasted two hours. Mr. Altenhofen was asked to describe the questions he would ask a landowner or representative of a water user organization who had contacted him regarding the development of a recharge pond or augmentation plan. Mr. Altenhofen identified physical site characteristics as well as economic, legal, and personal preferences (e.g. willingness of the landowner to work with particular water user or habitat organizations). The interviewee was also asked to describe any other database reviews or initial field investigations he would conduct to determine the potential suitability of a site for recharge pond development for stream augmentation. Wherever possible, Mr. Altenhofen was asked to provide the rationale behind the questions asked and data sought, and to qualify and quantify the types of responses he would normally expect in his review of a potential pond site. This additional information on the interviewee's evaluation process was very useful for the evaluation and modification of potential data sources and the development of the rule base and MCDA reasoning engine.

Although interviews with local experts was the primary means by which knowledge was elicited, observed problem solving also occurred during recharge pond site visits and through attendance at SPLRG meetings at which the selection and development of recharge facilities was discussed. Scientists, regulatory agency personnel, and published literature were also consulted, as appropriate, to test and quantify specific site attributes recommended for consideration in the rule knowledge base. Figure III-1, adapted from Mackinson and Newlands (1998), illustrates how various sorts of knowledge are integrated into a comprehensive knowledge base.

III.C.2. Knowledge Acquisition for Waterfowl Habitat Knowledge Base

There were multiple local experts available with experience in the evaluation and development of sites for waterfowl habitat in the region, including sites that were also intended for recharge ponds for streamflow augmentation. The development of dual purpose pond sites was relatively new, and the protocol for identifying suitable sites for this dual purpose was less established than the protocol for identifying suitable sites for recharge for stream augmentation alone. However, the interview subjects had had extensive experience with the evaluation and development of sites for waterfowl habitat alone. As noted previously, there were also several published materials on evaluation of wetlands and habitat suitability, although these methodologies were typically applicable to species or geographies other than the target region (the Lower South Platte Basin of Colorado) for this prototype, as discussed further below.

Knowledge was elicited from the local experts using semi-structured interviews. Although the knowledge base was developed on the basis of input from several experts rather than through the use of a single "key" expert, as was done for the streamflow augmentation knowledge base, the approach to the interviews was similar. During knowledge acquisition, the author asked the experts to explain what specific information they sought in asking each question of the landowner, and in consulting local maps, GIS coverages, and databases, and the type and level of resolution of information the expert sought in each answer. The experts were also asked to explain what threshold values they considered in their determination of the extent to which a site attribute supported a finding that the site was preferred for waterfowl habitat and participation in their habitat partnership program, if applicable. This information was used to guide the development and evaluation of potential data sources for a spatial database that could be used to provide inputs on site attribute values, while requiring a minimum of user inputs, and to guide the development of the MCDA for the KBS reasoning engine. Several other habitat biologists from the South Platte Wetlands Focus Area Committee (SPWFAC), Colorado Division of Wildlife (CDOW), and Colorado Natural Heritage Program (CNHP) also participated in reviews of the domain and rule knowledge base and MCDA.

In addition to the availability of local experts, there were several non-refereed guidebooks and leaflets available (e.g. National Biological Survey 1995, Ringelman 1991, Bridges et al. 1989, Cross and Vohs 1988, Frederickson and Reid 1988, Frederickson and Taylor 1982) providing suggestions on physical and biological considerations for waterfowl habitat site selection and development. Some refereed literature was available for specific species in specific locations, and typically limited to habitat needs for a specific life cycle stage (e.g. Krapu et al. 2000, on breeding habitat for mallards in the Prairie Pothole region). As noted by several authors (e.g. Roloff and Kernohan 1999), habitat suitability indices (HSIs) are similarly limited to specific species, location, and life cycle stage. One of the challenges for the development of this KBS was to identify site attributes and value ranges that were suitable for multiple waterfowl species and their various life cycle stages within the target region. As with the recharge pond site evaluations, the development and use of a "screening tool" was identified by the local experts as unsuitable. Some flexibility in the final KBS was required to allow the user to change the criteria ranges, weights, and radius of the geographic area around the site to be evaluated based upon the target species, life cycle, or habitat type.

Many of the considerations identified by local experts pertained to physical features of the site itself or the proximity of the site to other features. Unlike the approach used for recharge pond site evaluation, the local habitat experts were more likely to rely upon their own assessment of the site, and would request less information from the landowners.

It was also apparent that some of the site evaluation criteria used by the local experts were tied to the constraints of the funding programs for which the experts performed their evaluations, or "programmatic" criteria. Programs involved with the development of waterfowl habitat at recharge pond sites included the CDOW Wetlands Program, Ducks Unlimited (DU), the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program (PFW), and several programs run by the U.S. Natural Resources Conservation Service (NRCS), including the NRCS Wetlands Reserves Program (WRP), NRCS Environmental Quality Incentives Program (EQIP), and NRCS Wildlife Habitat Improvement Program (WHIP). Appendix B includes summaries of the major habitat partnership programs in the region and their eligibility requirements. Representatives from all of these programs have begun to coordinate their wetlands restoration activities through the SPWFAC. Site evaluation criteria pertaining to site eligibility for specific programs included whether the site was on private or public land; whether the site was on a CDOW State Wildlife Area; whether the site was on private land that had been used for irrigated agriculture; whether a private landowner was willing to convert that land to a temporary or permanent conservation easement; the size, location, and habitat type at or near the site; and proximity of the site to other habitats or potential disturbances to habitat.

There was some agreement among the experts and published knowledge sources on the physical and biological site attributes to be considered in an evaluation of a potential waterfowl habitat site. By contrast, for the recharge knowledge base, there was little published or otherwise compiled and organized knowledge available on the site attributes considered by experts for recharge. Consequently, development of the recharge knowledge base also involved the use of knowledge acquisition for identification of the site attributes considered by experts in a site evaluation as well as knowledge acquisition for the values associated with those attributes and methods for collectively evaluating those attributes. For the waterfowl habitat assessment, some guidance was available on which site attributes to consider in a waterfowl habitat assessment, although the threshold values for those attributes and methods for evaluating sites comprehensively on the basis of the collective attributes were yet to be determined. As a result, the waterfowl habitat assessment knowledge base development process more closely resembled the approach taken by Mackinson (2001), as discussed in the literature review (Chapter II), both because new knowledge was obtained on the values of those attributes with respect to the local application and species and because that knowledge base could be drawn from a wide range and number of experts and other knowledge sources.

III.D. Knowledge Translation and Knowledge Base Development

Schmoldt and Rauscher (1996) describe the overall knowledge acquisition process as consisting of two sub-tasks: the first subtask is the elicitation of knowledge from human experts, literature, and other sources, and the second subtask is the *knowledge translation* task in which that knowledge is converted into domain knowledge base and rule knowledge base for the KBS. The alternative structures for a KBS, including the role of the domain and rule knowledge bases within the KBS, and the alternative knowledge representation approaches that are used to develop knowledge bases are discussed in greater detail in Chapter IV. This chapter section presents the approach to knowledge translation used for the demonstration application in this research.

In addition to serving as a means of acquiring specific knowledge to be incorporated into the knowledge base, the knowledge acquisition process provides an opportunity for the knowledge engineer to gain insight into the "ontology" or "reasoning" process used by the experts, which guides the selection of knowledge representation and reasoning engine approaches for the KBS. During knowledge acquisition, the knowledge engineer can determine whether and to what extent the solution sought for the problem to be represented by the KBS falls within one of the *pre-enumerated* categories of problem-solving approaches (e.g. diagnosis, classification, and interpretation), or more *constructed* problem solving approaches (e.g. design and planning), or other problem-solving approaches and level of specificity as discussed in Schmoldt and Rauscher (1996) and Kline and Dolins (1985). The understanding of the ontology process and solution types to be represented by the KBS is critical to the determination of the alternative KBS structure to be used, as described in Chapter IV.

For the demonstration application of this research, it became apparent during the initial interviews with the key expert that the expert applied a data driven ontology approach to his evaluation of potential recharge sites for stream augmentation, and that he considered multiple criteria in his site evaluations. By asking a series of questions, and following up with database searches and site visits, the expert would acquire information about the site to assess the level of suitability of the site for recharge for stream augmentation, to identify potential drawbacks or need for additional work to develop a recharge pond at the site, to identify potential funding opportunities for the site, and to identify potential legal or other obstacles, such as whether the landowner was willing to enter into an agreement with a particular ditch company to provide water for the site.

The target problems to be represented in this KBS was determined to be "classification" problems in which an expert would review various data inputs to determine the strengths and weaknesses of a site on the basis of various site characteristics, and the overall site suitability. Although the suitability of sites varied, the key expert for the streamflow augmentation knowledge bases stressed that he very rarely rejected sites altogether, particularly if no other site was available on the landowner's property. Thus, the KBS was developed as a means of characterizing potential sites rather than "screening out" sites, and all sites considered are treated as feasible. For the waterfowl habitat knowledge bases, the experts were more likely to reject sites because the total number and type of sites they could develop was limited by funding and programmatic requirements than because a site was not suitable for habitat.

As described below, the approach of developing a list of questions asked by the experts, and of identifying the types of information sought by the experts in asking these questions, produced acquired knowledge that could be readily converted to rules and criteria for the KBS and MCDA. Identifying an expert's reasons for asking particular questions also supported the review of the potential data sources to be incorporated into the spatial database for the KBS and the type, format, and level of resolution required of electronic data sources to provide an adequate response.

In light of this process by which the key expert normally acquired and evaluated data on potential recharge sites for stream augmentation, the author, who was the knowledge engineer for this project, determined that a rule-based approach, using "IF-THEN" rules, was an appropriate form of knowledge representation. A rule-based approach could be used to represent both the collection of site attribute data (in the "IF" statements) and an expert's use of that data to draw conclusions about that site (in the "THEN" statements). The author also determined that the conclusions drawn by the experts would then be evaluated collectively in an approach that was similar to a MCDA. Thus, a MCDA was developed as the reasoning engine for the KBS, as will be discussed in greater detail in Chapter IV.

During knowledge acquisition, the experts were asked to explain what specific information they sought in asking each question, and the type and level of resolution they sought in each answer. The experts were also asked during the initial interview and subsequent interviews to explain what threshold values or "rules-of-thumb" they used in order to determine the extent to which a site attribute supported a finding that the site was preferred for recharge pond development. This information was used to guide the development and evaluation of potential data sources for spatial databases that could be used to provide inputs on site attribute values, while requiring a minimum of user inputs, and to guide the development of the MCDA for the KBS reasoning engine.

III.D.1. Streamflow Augmentation and Cost Knowledge Base Development

As knowledge was acquired through interviews with the key expert and discussions with other local experts who have been involved with the selection, evaluation, and development of recharge pond sites for stream augmentation, the author began to categorize the types of data sought by the local experts and the purposes for which that data was used in site evaluations. The questions that the key expert would ask landowners who were interested in developing recharge sites for stream augmentation were sorted into three main categories or criteria of site characteristics that are primarily physical or hydrological in nature, namely:

I. Extent to which the aquifer can be recharged at the pond site

II. Extent to which source water can be developed for and delivered to the pond site

III. Extent to which streamflow augmentation credits can be accrued as needed by the recharge at the pond site

In many cases, the information sought by local experts for their site evaluations have both physical/hydrological ramifications and economic/financial ramifications related to the costs to develop, maintain, and operate the recharge site. There are also legal/regulatory considerations, and some personal preference concerns, such as whether a landowner is willing to work with specific water organizations or habitat programs. The question lines were sorted according to the three physical/hydrological categories of site attributes regardless of whether the responses to those questions would be evaluated by the experts primarily for a physical evaluation or for cost, legal, or other considerations.

In the development of the rule base, the data requests by the experts would be the equivalent of the development of object-attribute-value ("OAV") triplets for the rule premise or "IF" portion of a rule, while the use of the question responses for the site evaluation would be the equivalent of the development of the rule conclusion or "THEN" portion of the rule. Further discussion of the use of OAV triplets and IF-THEN rule development is provided in the next chapter (Subsection IV.B.2 KBS Components: Knowledge Bases). The same specific data collected from a single question may be used by the expert to perform multiple aspects of his site evaluation, and the same premise in the rule base may be associated with multiple conclusions. For example, the dimensions of a pond may be considered by an expert to calculate the amount and cost of water needed to use the pond for recharge as well as to determine whether the pond may be suitable for a habitat restoration project, and thus be eligible for a funding partnership with a habitat program.

Table III-1 summarizes all of the questions identified by the key expert for the streamflow augmentation knowledge base as questions he would ask in evaluating a potential recharge pond sites. Table III-2 illustrates the evaluation of the type of knowledge sought in each question, which was one step in the ontology evaluation process, leading to the identification of data sources to provide the required knowledge. That data source evaluation process is discussed later in this chapter (Section III.E). More detailed information on the knowledge acquisition process for the streamflow augmentation and cost knowledge bases, including background on the local experts, and initial knowledge acquisition results from the interviews, including the list of questions normally asked by local experts, sorted by question category, and the types of information sought by the experts and uses of that information by the experts, are provided in Appendix C. Specific considerations related to the potential cost of site development, operation and maintenance are also discussed in Appendix C.

III.D.2. Waterfowl Habitat Knowledge Base Development

As knowledge was acquired through interviews with local experts who have been involved with the selection, evaluation, and development of waterfowl habitat pond sites, and further knowledge acquired through literature review, the author worked with the local experts and a review of published literature to categorize the types of data sought by the local experts and the purposes for which that data was used in site evaluations. The local experts noted that an automated model would most likely be useful to support identification of spatially-based features that could be used both for individual site evaluation and for the development and support of regional planning and wetland complex development. Consequently, several of the site considerations identified by local experts, including those related to program eligibility, were not included.

Like the local experts on recharge, the habitat experts were very reluctant for the KBS to be developed as a "screening tool" because they sought to maximize the involvement of local landowners in their programs. One program representative made the point that their best assessment tool was a site visit. He gave an example in which a site visit was scheduled to view one site on a property. During that site visit, after discussing with the property owner the kinds of sites their program looked for, he and the property owner visited seven other sites, and eventually set up conservation easement agreements with the owner on two of the other sites (Personal communication, Bob Timberman, Habitat Biologist, U.S. Fish and Wildlife Service Partners for Fish and Wildlife Program, April 16, 2002).

At the same time, however, several local habitat experts noted that there were circumstances under which a site might be rejected due to lack of eligibility of the landowner or an overabundance of similar habitat sites developed in the same region. SPWFAC and the individual habitat programs were still in the process of planning their approach to habitat development in the region at the time of knowledge base development, so some of these programmatic and planning considerations were not included in the KBS, although it should be possible to include them in the future.

The selection of characteristics to include within the assessment also depended upon the availability of coverages with sufficient level of detail to support site-scale or reach-scale analyses. Many of the coverages used for this assessment were not already available in SPMAP. While several mapping projects have been completed for habitat-related parameters in the region, as discussed in Appendix B, few are available at a 1:24000 or higher resolution. In several cases, the assessment criteria dealt with the proximity of the site in relationship to other features. To address these criteria, new coverages were either obtained or created on the basis of lists of feature locations, provided to the researchers as UTM coordinates. Data sources included the Colorado Division of Wildlife (CDOW), Colorado Natural Heritage Program (CNHP), Ducks Unlimited (DU), U.S. Fish and Wildlife Service Partners for Fish and Wildlife Program (PFW), and the Natural Resources Conservation Service (NRCS).

The site characteristics identified by local experts during knowledge acquisition for possible inclusion in the WHAT KBS include:

1) **Proximity to wetland complexes and to other water sources.** One of the assessment criteria cited the most often by local experts was the need for the development and restoration of wetland complexes. However, the term and criteria for assessing a "wetland complex" was not well-defined. The definition of "wetland complexes" provided by Ringelman (1991) was used for this research. Ringelman describes a "wetland complex" as "a *diverse wetland community, ranging from ephemeral wet meadows to semi-permanent cattail ponds, is essential to waterfowl breeding success and desirable for migrating and wintering birds. During breeding, habitat requirement of waterfowl differ not only among species, but by sex and reproductive stage. Diversity in the wetland complex promotes a wide range of 'microhabitats,'*

thereby helping to assure that the needed resources are present. Since interspecific territoriality is rare among ducks and geese, diverse wetland will result in a higher density and diversity of waterfowl than that found in monotypic communities ... Wetland complexes are also important to migrating and wintering ducks, because they provide a range of foraging habitats and isolation for paired birds away from concentrations of unpaired individuals. Such complexes also tend to have more numerous 'microhabitats,' which help increase the likelihood of meeting the habitat needs of many species." (Ringleman 1991, pages 16-17)

In order to perform a GIS-based analysis of wetland complexes, it would be necessary to define what the different wetland types or microhabitats are and to classify individual sites according to their wetland type. It would also be useful to determine what combination of wetland types are needed within a complex in order to sustain target species, so that a region or area around a site can be evaluated to determine what wetland types are missing from a wetland complex. The CNHP Wetland Classification System may be useful as a tool to classify individual wetland sites. Insufficient data and expertise were available to classify individual sites within the constraints of this project, although future work may involve classification of specific wetland types in the region to allow for assessment of wetland complexes. WHAT identifies the riparian vegetation type for a selected site, using the CDOW Riparian Vegetation Mapping Project. WHAT also identifies the location and distance to other habitat sites, as well as recharge ponds and other water bodies within a 5-mile radius of the site. Waterfowl are likely to be attracted to clusters of water bodies, whether they are intended as habitat or as water storage or for other purposes. The locations of all recharge facilities in Water Districts 1, 2, and 64 of Division 1 (South Platte) of the Colorado State Engineer's Office (SEO) were obtained from the SEO and converted into a new GIS coverage. The locations for new recharge facilities under development were obtained from NCWCD, and converted into a new GIS coverage. Coverages were obtained or created showing the locations of all State Wildlife Areas, Ducks Unlimited project sites, Partners for Fish and Wildlife project sites, and NRCS WHIP, EQIP, and WRP project sites in the Lower South Platte region. Coverages of ditches and area hydrography were already available from SPMAP.

2) **Proximity of other habitat complexes.** Some programs (e.g. WHIP) also consider the proximity of a prospective site to other conserved habitats. Coverages were obtained or created with locations of all State Wildlife Areas, DU project sites, PFW project sites, and NRCS WHIP, EQIP, and WRP project sites in the Lower South Platte region. There are no federal wildlife refuges in this region, and the only major federal lands are the Pawnee National Grasslands (primarily in the uplands areas).[1] WHAT identifies sites

[1] Other federal land in the region consists mainly of U.S. Bureau of Reclamation land that is leased to private landowners for grazing use.

in each of these categories within a 5-mile radius of a selected site.

3) **Proximity to potential hazards.** Some programs (e.g. WHIP) considered the proximity to features that might be hazardous to wildlife or might disturb wildlife behavior, e.g. roads, houses, and confined animal feed operations. Of these, GIS coverages were available to show the proximity of a selected site to roads. The proximity of the site to other features would be determined on the site visit and through conversations with the landowner.

Other characteristics cited as important for wetland habitat benefits included the ratio of the area to perimeter/shoreline of the wetlands, the depth of the wetlands, and the variety of depths within the pond. The depth is tied to the design of the facility, and is not likely to be determined by an initial GIS-based assessment of the site. The area topography is also a factor in the facility design, but the digital elevation maps available for this region are not at a high enough resolution to show the relatively little variability in elevation in this very flat region. The total area and perimeter of the area ponds could not be determined since most of the pond site data was provided as point data. If these coverages were developed as polygon data showing the outlines of the ponds, then the perimeters and areas could be easily calculated.

The existence at the potential waterfowl habitat site of rare species assemblages ("Element Occurrences") or Potential Conservation Areas (e.g. bald eagle nests), as identified by the Colorado Natural Heritage Program, was also a reason cited by local habitat biologists for rejecting a site for development for waterfowl habitat. Prairie dog colonies, which also can serve as burrowing owl habitat, are also sites at which habitat biologists would avoid development of waterfowl habitat, which would result in disturbance or destruction of habitat for other important species. However, in order to protect the location of these sites from the general public, the spatial databases identifying the location of the sites are generalized to show only that the element occurrence or potential conservation area exists within a 1-square-mile or 10-square mile area. Consequently, potential habitat sites cannot be rejected or accepted for consideration on the basis of available spatial databases. Instead, a "flag" was added to the KBS output reports if GIS data indicated that a site might overlap a protected species habitat or assemblage in order to notify the habitat biologist that further investigation at the potential site would be necessary to determine whether habitat development would disturb these important habitat areas.

At the same time, local experts favored sites that were close to protected habitats, including Potential Conservation Areas, State Wildlife Areas, and habitat partnership program sites, including sites enrolled in NRCS Habitat Programs. Therefore, the KBS needed to identify those sites which were within a given radius of other protected lands, while also flagging sites that might be at the same location as other existing habitat sites.

III.E. Data Source Evaluation Process for KBS Inputs

One important objective in the development of this research methodology was to determine how to create a KBS for which the required user inputs could be minimized by the use of a spatial database containing the correct data at a sufficient level of resolution for both compilation of site data and analysis of that data. As each expert question was identified, the type, quality, and potential electronic sources of data to provide an answer to that question were determined. In some cases, the experts suggested methods by which site attributes could be approximated using available electronic data. Potential data sources were acquired, evaluated, and sometimes modified or combined to create a compiled GIS database for the demonstration application containing both spatial and tabular data to provide site attribute values as needed to fire rules and to perform the MCDA.

As presented in Chapter V, a prototype model called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM) was developed to include evaluation of all of the criteria and subcriteria for evaluation of pond sites for streamflow augmentation, pond development costs, and waterfowl habitat restoration. In many cases, the data sources that would be required to support subcriterion evaluations were not available. To test the ability of a knowledge base developed using the methodology described in this research, a subset of the streamflow augmentation criteria was used in a demonstration application called the Recharge Potential Assessment Tool II (RPAT-II). As described in Chapter V, RPAT-II was used to compare the evaluations of actual recharge sites by the KBS against evaluations by local experts who were provided with identical site data. Evaluation of potential data sources was an important step in the development of an automated tool that could be used to evaluate real site data.

In some cases, data that is used by the local experts to evaluate potential recharge sites can currently only be acquired through visits to the site by the expert or through questioning the landowner. If the level of effort required to gather the data for manual input into the automated system is nearly the same as the level of effort that would be required for the expert to both collect that same data and perform the evaluation of that data, then there would be little or no savings in effort, time, nor money in the development of an automated knowledge-based system designed to evaluate that data. However, if the number of instances which the problem-solving approach used by the experts is increasing beyond the level that can be addressed by the available experts, or if there is a need to consider individual site evaluations collectively, such as for regional planning, then there is an increased motivation to compile, enhance, and create spatial databases that can support automated evaluations. The initial costs associated with database development and maintenance, as necessary, are offset by the savings in time and effort by local experts who would otherwise perform the site evaluations individually, and by the long-term benefits of coordinated regional planning that can be supported by automated evaluations. Additionally, an automated system provides a documentation source that insures reproducibility of results.

In other cases, information that is normally collected by local experts in their selection and evaluation of potential sites may already be available from existing databases and GIS coverages. Water resources and related data are collected in several forms, by several parties, and for several purposes, particularly for regulatory compliance. The mere existence of a database that represents a certain type of data, however, does not guarantee that the database has been developed at a sufficient level of resolution or accuracy, or that the data has been provided in the correct format, for the expert to use to make his or her evaluation. If the data source is not adequate for use by the expert in his or her evaluation, it is also inadequate for use by a KBS replicating that expert's evaluation process.

Each criterion was evaluated to determine whether the attribute values involved spatial analysis or tabular data associated with spatial features, or whether the attribute values could be acquired far more easily through direct discussion with the landowner (in which case, a computerized attempt to determine the information would be superfluous). For example, representations of personal preferences, such as a landowner's willingness to enter into a cooperative agreement with his neighbor or with a ditch company, cannot be easily represented in spatial data. Because the KBS would be designed to acquire attribute values primarily from the KBS data sources and to minimize the need for user inputs, it was important to identify those attribute values that could be determined or approximated through spatial and/or tabular data.

For each criterion, the data sources were also evaluated to determine whether that data source was available for the target region, from which the alternative sites to be evaluated would be selected, and in an appropriate format for use with the demonstration KBS. Often, attribute values that could be determined through links with GIS coverages and associated attribute tables were not available for use with the KBS demonstration application because those coverages had not yet been digitized for the Lower South Platte Basin or the attribute data was not available for digitized maps. Because the KBS demonstration model would be tested using real sites, it was important to develop the demonstration model using real GIS coverages and other databases for the target region, rather than to overlay data from another region of the country for which the appropriate GIS coverages may have been digitized.

Chapter V describes the approach to the system evaluation and testing results for a modified, scaled-back version of the recharge component of the KBS for which actual databases could be used to acquire and assess real site data. Potential data sources for each streamflow augmentation site selection subcriterion identified by the local experts are provided in Table III-3. Potential data sources for each pond development cost site selection subcriterion identified by the local experts are provided in Table III-4. Potential data sources for each waterfowl habitat site selection subcriterion identified by the local experts are provided in Table III-5. If the identified databases were available or could be modified to provide the required data for automated site evaluation, these databases were incorporated into the WAPSAM prototype.

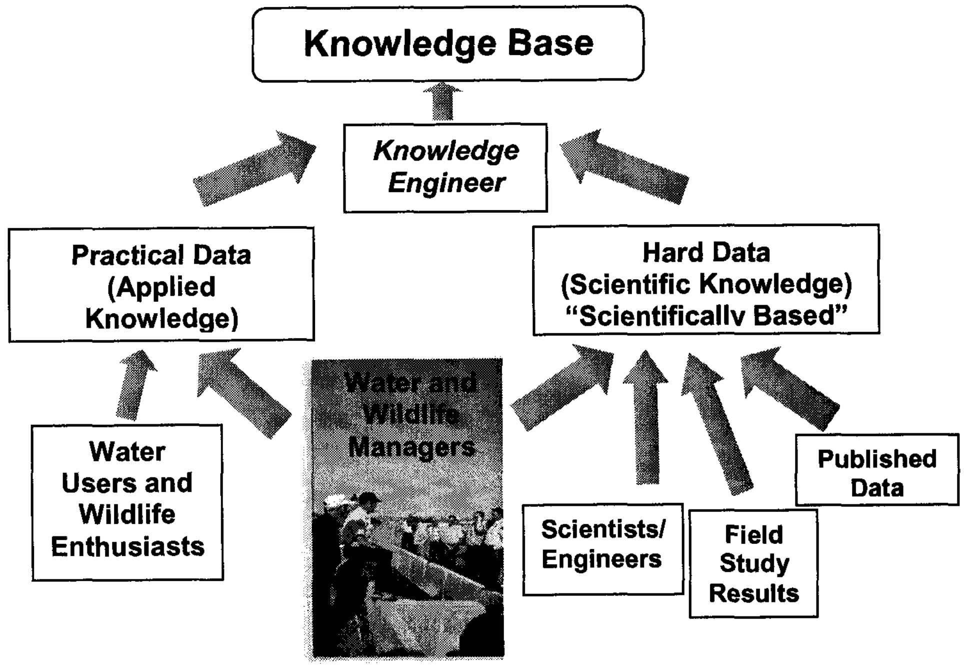


Figure III-1. Knowledge Base Development for Prototype Application

Adapted from Mackinson and Newlands (1998)

Table III-1 Results of Knowledge Acquisition: Physical Site Characteristics for Streamflow Augmentation

Question Lines	Questions Asked by Local Experts
Question Line I. Extent to which the aquifer can be recharged at the pond site	Ques. I.A. Is there an aquifer at the site?
	Ques. I.B. What is the depth to the aquifer water table at the site?
	Ques. I.C. Are there confining layers (tight clay soils through which water cannot seep) at the site, and particularly within the first 3 feet?
	Ques. I.D. What is the depth to bedrock at the site?
	Ques. I.E. What is the surface soil at the site?
Question Line II. Extent to which source water can be developed for and delivered to the pond site	Ques. II.A. Is there a ditch in the vicinity of the recharge site? If a ditch cannot be used to supply water to the pond, is there a well in the vicinity of the recharge site?
	Ques. II.B. Does the owner have a headgate from a ditch that can be used to supply water to the recharge pond? If not, can one be installed?
	Ques. II.C. Is the ditch that will supply the pond uphill or downhill from the recharge pond?
	Ques. II.D. Does the landowner own the land between the ditch and the pond?
	Ques. II.E. If a ditch cannot be used to supply water to the pond, is there a well available?
Question Line III. Extent to which streamflow augmentation credits can be accrued as needed by the recharge at the pond site	Ques. III.A. What is the stream depletion factor (SDF) at the site?
	Ques. III.B. At what time of year is water available for recharge?
	Ques. III.C. Does the landowner own the land between the pond and the river?
	Ques. III.D. Does the source water come from the same stream that is being augmented?
	Ques. III.E. To which river reach are the return flows credited?

Table III-2 Knowledge Sought by Experts for Streamflow Augmentation Pond Site Assessments

Data Category	Knowledge Sought by Local Experts	
I. Aquifer Recharge	I.A.	A suitable aquifer underlies the site.
	I.B.	There is a suitable depth to aquifer (greater than 10 feet preferred).
	I.C.	Confining layers within top three feet below ground surface do not exist or can be excavated.
	I.D.	There is a suitable depth to bedrock (50 to 150 feet preferred).
	I.E.	There are suitable surface soil and seepage rate at the site.
II. Water Source Development and Delivery	II.A.	There is a ditch near the pond site or, if not, a "direct diversion" well within 200 feet of the river can be used to provide source water.
	II.B.	The selected ditch has a headgate or a headgate can be installed (requires ditch company agreement).
	II.C.	The gradient between ditch and pond site determines the method by which water can be delivered to the pond from the ditch (an uphill ditch can "gravity feed" a pond while a downhill ditch would require installation of a pump).
	II.D.	The landowner for the pond site also owns the land between the water source and the pond site (otherwise, an agreement with other landowners is required).
	II.E.	The landowner also owns water rights for the ditch water (otherwise an agreement with ditch company is required).
III. Recharge Credits Production	III.A.	Stream depletion factor or "SDF" value is known.
	III.B.	The timing and availability of the source water is known (the timing of water availability also impacts the pond operation and use of recharge credits).
	III.C.	The landowner for the pond site also owns the land between the pond site and the river (otherwise, an agreement with other landowners may be required to ensure the recharged water is not captured prior to reaching the river).
	III.D.	The water source is from the same stream-aquifer system as the stream to be augmented by the recharge pond return flows.
	III.E.	The recharge pond return flows accrete at a river reach where credits are needed, upstream of more senior surface water diversions.

Table III-3. Prototype Subcriteria and Potential Data Sources for RPAT

Subcriterion	Raw Data Sources and Derivation Tools
Aquifer Existence	USGS Aquifer Coverage
Depth-to-Aquifer	USGS Depth-to-Aquifer Coverage
Aquifer Quality as a function of well density	Well Location Coverage RPAT tool to calculate no. of wells within ½ mile of site
Saturated Thickness	USGS Saturated Thickness Coverage or USGS Depth-to-Bedrock Coverage
Surface Soil/ Recharge Rate	NRCS SSURGO Surface Soil Coverage to determine grain size, grain size converted to recharge rate and associated recharge rate range
Pond-to-Stream Land Ownership	Land Ownership and Streams Coverages
Ditch-to-Pond Land Ownership	Land Ownership Coverage and User-Provided Headgate Location
Water Rights for Ditch	Land Ownership Coverage and User-Provided Water Rights Data
Stream Depletion Factor	GIS SDF coverage
Source Water Timing	User inputs on timing of water availability

USGS = United States Geological Survey
NRCS = Natural Resources Conservation Service
GIS = geographic information systems
SDF = Stream Depletion Factor
SSURGO = Soil Survey Geographic Database
WHAT = Waterfowl Habitat Assessment Tool

Subcriterion	Raw Data Sources and Derivation Tools
Water Source (used to determine which water sources and delivery costs are applicable)	User input on water source. If the water source can be located with a spatial database, the distance and gradient to the water source can be determined using spatial analysis.
Water Source Access Costs	If the source is a ditch, user must provide data on whether a headgate and flume/recorder are needed for the site. If the ditch is downgradient, the user must provide data on whether a liftstation is needed for this site. If the source is a well, the user must provide data on whether a new well must be installed, or whether an existing direct diversion well can be used.
Water Delivery Costs	User must provide data on whether pipes must be installed. The length of pipe and associated costs can be calculated based upon the distance between the water source and the site.
Pond Excavation Costs	User must provide estimated pond area and data on whether excavation of a clay lens is necessary.

Table III-5. Prototype Subcriteria and Potential Data Sources for WHAT

Criterion	Raw Data Sources and Derivation Tools
Proximity to Disturbances from Roads (RD)	Roads Coverage (WHAT calculates distance to disturbances within 2 mile of site)
Proximity to Disturbances from Towns (TD)	Town Coverage (WHAT calculates distance to disturbances within 2 mile of site)
Percent Year-Round Open Water within 2 mile radius	Lakes Coverage (WHAT calculates percent area within 2 mile of site)
Percent Open Water During Breeding (May-June) within 2 mile radius	Point Coverages of recharge ponds and habitat partnership ponds, with attribute tables indicating area and months during which ponds are filled (WHAT calculates percent area within 2 mile of site)
Percent Open Water During Spring Migration (Mar-Apr) within 2 mile radius	
Percent Open Water During Fall Migration (Aug-Nov) within 2 mile radius	
Percent Carbohydrate Food Source within 2 mile radius	Crops Coverage (WHAT calculates percent area within 2 mile of site)
Percent Protein Food Source within 2 mile radius	Shallow Pond Coverage from DU and PFW databases (WHAT calculates percent area within 2 mile of site)
Percent Protected Lands within 2 mile radius	NRCS, CNHP, and CDOW Coverages (WHAT calculates percent area within 2 mile of site)

WHAT = Waterfowl Habitat Assessment Tool
NRCS = Natural Resources Conservation Service
CNHP = Colorado Natural Heritage Program
CDOW = Colorado Division of Wildlife

CHAPTER IV.

KNOWLEDGE-BASED SYSTEM STRUCTURE DEVELOPMENT

IV.A. Introduction

This chapter discusses the approaches to the structural development of a KBS selected for inclusion in this methodology and demonstration application for evaluation of potential pond sites for streamflow augmentation, pond development costs, and waterfowl habitat. Alternative approaches to structural development of a KBS are presented in the literature review (Chapter II). This chapter addresses steps five through eight in the KBS-development process, namely:

5. Domain Knowledge Base and Rule Knowledge Base Development
6. Development of User Interface and Links with Other Input Sources
7. MCDA Development
8. Integration of MCDA into KBS as a Reasoning Engine

IV.B. KBS Structure and Alternative Development Methods

Knowledge-based systems are generally recognized as consisting of three main components: a *user interface*, a *knowledge base*, and an *inference engine* or *reasoning engine* (e.g. Mackinson and Newlands 1998, Schmoldt and Rauscher 1996), as shown in Figure I-1. This section (Section IV.B) describes the structural alternatives to the development of each of these KBS components.

IV.B.1. KBS Structure: User Interface

The user interface is the means by which the end user provides inputs into the system and by which the system provides outputs to the user. One of the goals of this research was to minimize the need for data inputs by the user and maximize the use of spatial databases as a source of data inputs. Thus, as shown in Figure I-1, the spatial database serves as an additional source of inputs between the end user and the KBS. The development of the spatial database was guided by the identification of needs and format requirements for data to support site evaluations by local experts for potential pond locations for stream augmentation and waterfowl habitat.

The input user interface for the model developed in this research, called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM), has been programmed into an ArcView GIS environment. The only input required by the user is the location of the site, which is indicated by the user placing a point on the GIS screen using the "Select Site" button, and any identifying information the user chooses to add, including the Site Name, Site Owner, and Site Owner Contact (phone number or email address). Once the user has inputted the site location and any site identification information, the remaining data inputs for the site evaluation are extracted from the GIS map coverages and attribute tables or are calculated by the KBS through a rule base programmed in an Excel spreadsheet environment. User inputs can also be entered directly into the Excel-based portion of WAPSAM, and the threshold values and radius of the area of evaluation for proximate site features can also be changed in Excel.

The GUI output report provides an overall site evaluation for all of the criteria along with complete explanations, including both descriptive explanations of the raw data used and intermediate conclusions reached and reasoning explanations on why the raw data associated with the site led to each intermediate conclusion and criterion evaluation. WAPSAM also generates a GIS-based map layout of the selected site. The output report shows the weights for each criterion that were used to calculate the overall site evaluation score. More details on the WAPSAM prototype application, including figures illustrating the input user interface and output report, are provided in Chapter V.

IV.B.2. KBS Components: Knowledge Base

The second component of a KBS is the knowledge base. While all decision support systems are based upon some sort of knowledge about the problem domain for which the system was developed, a KBS is distinguished from other systems in that the knowledge in the program is extracted into a separate entity (Schmoldt and Rauscher 1996). As shown in Figure I-1, this component can be divided into the *domain knowledge base* and the *rule knowledge base* (Vlahavas et al. 1999), representing the two kinds of knowledge (facts and rules)(Ignizio 1991). The domain knowledge base is a systematically codified representation of the subject area or domain to which the problems to be addressed by the KBS pertain. In the case of the demonstration application for this research, development of the domain knowledge base includes the identification of input data requirements to be incorporated into the spatial database or requested from the user via the user interface.

The second knowledge base, called the "rule knowledge base," consists of information on how that input data would be evaluated by knowledgeable persons (experts) to produce decisions. There are several knowledge representation methods available in the artificial intelligence field including: rules; frames & scripts; objects; networks; and logic (Bowerman and Glover 1988). Of these methods of knowledge representation, rules are the most widely used, as was demonstrated in a survey of KBS developers, which found that 62% of KBS developers used rules to represent knowledge (Doukidis and Paul 1992).

Rules are typically formatted in an "IF-THEN" format, in which the first portion of the rule contains the *premise* or *condition* and the second portion of the rule contains the *conclusion* or *action* (Ignizio 1991, Schmoldt and Rauscher 1996). These two portions of IF-THEN rules can also be referred to as the *antecedent* and the *consequence.* Rules contain *object-attribute-value triplets* in both the premise and conclusion, although the object may be implicit (consequently, the term *attribute-value pair* is also used). To use an example from the prototype, the rule:

IF stream depletion factor is 79

THEN SDF range is 30-90 days.

contains the following object-attribute-value triplets:

PREMISE:

OBJECT:	pond (implicit)
ATTRIBUTE:	stream depletion factor
VALUE:	number of days (to be tested by rule and categorized as falling within one of a set of ranges)

CONCLUSION:

OBJECT:	pond (implicit)
ATTRIBUTE:	SDF range
VALUE:	30-90 days

This conclusion can also be programmed as follows:

CONCLUSION:

OBJECT:	SDF range
ATTRIBUTE:	30-90 days
VALUE:	true (implicit)

Rules may contain multiple *clauses* connected by operators such as "OR" or "AND." OR operators are used for *disjunctive* clauses where either premise can be true for the conclusion to be true; OR operators can only be used for premise clauses. AND operators are used for *conjunctive* clauses in cases where both premise clauses must be true in order for the conclusion to be true. AND clauses can also be used in the conclusion to indicate that more than one conclusion is true if the premise is true. To use an example from the demonstration application for this research, the following three rules:

1) IF NRCS surface soil type is Haxtun Sandy Loam 0-1 percent slope THEN soil type is sandy loam.

2) IF NRCS soil type is sandy loam

THEN recharge rate is 1-2 feet per day.

3) IF NRCS recharge rate is 1-2 feet per day

THEN soil type is good.

could be joined into a single, conjunctive rule as follows:

IF NRCS surface soil type is Haxtun Sandy Loam 0-1 percent slope

THEN soil type is sandy loam

AND recharge rate is 1-2 feet per day

AND soil type is good

In the first part of this example, the conclusions of the first two rules are considered *intermediate* conclusions, while the conclusion from the third rule is the final conclusion for the criterion of soil type. As will be explained below, for the demonstration application of this research methodology, only the final value assigned to the criterion attribute is considered in the calculation of the overall MCDA weighting and analysis. In the example rules above, the value assigned to a "good" soil type is 3 on a four-point rating scale, so the evaluation score for soil type will be calculated using the value of 3 multiplied by the weight for the criterion "soil type."

Although only the final value assigned to a criterion will be calculated in the weighted average, the intermediate conclusions leading to that final criterion value are also provided in the output explanation of the demonstration application's user interface. Providing these intermediate conclusions illustrate to the user the reasoning process and provide the user with the rationale behind the criterion conclusion that the NRCS surface soil type for the selected pond location is good for recharge. For example, a site output report for a location with the soil type evaluated in the sample rules above would include the statement:

> "For recharge, this soil type is *good* because the grain size is *sandy loam* with an approximate seepage of *1-2 feet/day*."

In a hybrid KBS, algorithms may also be included within the rule knowledge base. The premise/condition for a rule may be determined via calculation using an algorithm, or a rule may direct the KBS to use a particular algorithm. For example, if a certain value is below a particular threshold, then the KBS may be directed to use an algorithm to calculate the input data necessary to use a subsequent rule. In the case of the demonstration application for this research, GIS coverages were available or developed that designated actual values for each of the input attributes, so there was no need for calculation, e.g. of the stream depletion factor (SDF) associated with a selected location. However, if the SDF values were not available in a GIS coverage, but the variables used to calculate the SDF were available from the user or spatial analysis, then the rule would have been programmed to calculate the SDF value from the input data. The SDF value can be calculated using the following equation by Glover (1964):

$$SDF = \frac{\alpha^2 S}{T}$$

for which the required data inputs would be α = perpendicular distance from the well to the stream, S = specific yield of the aquifer, and T = transmissivity (which, in turn, can be calculated as the product of the hydraulic conductivity times the aquifer thickness).

The extent to which rules to determine intermediate conclusions are required within a given rule base depends upon the extent to which the premises for rules can be determined directly through user input or other data sources, or whether other data needs to be pieced together to form intermediate conclusions, which become premises for subsequent rules. The availability of the data required for a particular premise (either from data sources or from the expected user) cannot be assumed to exist when programming a KBS; instead, an evaluation of potential data sources, as was performed in this research, is necessary to ensure that the appropriate data is available.

Identification of the sources and characteristics of both the data and the knowledge of how to evaluate that data are critical steps in the planning and development of a KBS. Characteristics of data include:

- *timing* of data availability;
- *completeness* of data;
- *certainty* in the accuracy and precision (resolution) of the data;
- *form* of the types of relationships represented by the data; and
- level of *ambiguity* or agreement on the meaning of the data items.

Characteristics of knowledge include:

- *currency* of the knowledge and whether that knowledge is up-to-date;
- *completeness* of the knowledge for a particular domain;
- *certainty* of the knowledge;
- *functionality* or whether the knowledge can be used for the purposes programmed; and
- *commonality* or agreement on the validity of the knowledge among the experts or other "knowledgeable people."

As noted by Schmoldt and Rauscher (1996), knowledge is dynamic and changes continually as we learn more about the world. Data availability is also dynamic, with new data sources continually being developed. The development of a KBS can, itself, be a tool in the identification of needs for new knowledge and data, leading to new data availability. Where the data or knowledge is uncertain, the reasoning engine can include certainty factors, as will be discussed in the following section, to account for the level of certainty in the data or knowledge. Some KBS programs, such as the US Forest Service's Ecosystem Management Decision Support (EMDS) system, also include factors to account for the influence of missing information in landscape evaluations (Reynolds 1999). Further discussion of the methods by which uncertainty can be represented in a KBS are discussed in the following subsection on the KBS reasoning engine (Subsection IV.B.3).

For the prototype model, domain knowledge bases were developed that consisted mainly of a spatial database containing data pertaining to site evaluations (e.g. on soils, wells, ditches, and stream depletion factors for the streamflow augmentation evaluations) for the target region of Sedgwick County, Colorado, to the extent that such spatial databases were available. Tabular databases were also developed as needed (e.g. a database of the grain sizes associated with each soil type). Hypothetical data was used for the prototype in cases where databases were not available. Rule bases were developed and programmed into the Excel-based portion of the KBS. Data extracted from the ArcView-based spatial databases were exported into the Excel-based KBS. As described in the next subsection on the KBS reasoning engine (Subsection IV.C.3) and in Section IV.D. on MCDAs, the reasoning engine for this KBS was developed as a MCDA. The rules in the rule knowledge base have been organized and programmed to support evaluations of each site according to each criterion. For each criterion, a measurement method was developed to convert raw data from the selected site to ranges of values that are associated with a four-point measurement scale (1 to 4). For the site report, each numerical rating on the measurement scale is also associated with a word rating (poor-fair-good-excellent). The "IF-THEN" rules are read from the tables using Excel-based programming as:

IF [*raw data*] has value in [*range*]

THEN site is [*measurement scale value*] for [*criterion*]

Chapter V includes tables which summarize the rule knowledge bases that were developed for WAPSAM. The rule threshold values and the radius of the area to be evaluated for proximate site features for some rules can be changed by the user.

IV.B.3. KBS Components: Reasoning Engine

The reasoning engine developed for the prototype application for this research use a forward-chaining search, which is a data-driven search in which all rules are fired. The objective of WAPSAM is to provide a comprehensive evaluation of user-selected sites on the basis of each of the criteria identified by the experts as significant for the analysis of sites and for which data is or could become available and measurement mechanisms can be developed for an MCDA to support an automated evaluation. The objective is not to eliminate potential sites, but to provide an evaluation of the sites. "Exclusionary screening" is an assumption used in MCDA which removes alternatives for which any criterion is below a feasible value from consideration, so that the MCDA is performed only on feasible alternatives (Goicoechea et al. 1982). For this demonstration, all potential sites are considered "feasible alternatives" and all rules are fired. Thus, it would be a misnomer for any tool produced using this methodology to be referred to as a "screening tool" because all alternatives to be evaluated are considered feasible; no alternatives are "screened out" using this methodology. Instead, this MCDA-based tool provides an evaluation of the extent to which an alternative is preferred, as well as an explanation of the rationale and source data used to produce the overall site evaluation. Further explanation of the components and design alternatives for a MCDA is provided in Section IV.C.

An alternative design for this demonstration application would have been a backward-chaining mechanism, which could have been used for an optimization approach, in which a goal is selected, and rules are fired and criteria evaluated to determine which alternative or alternatives can meet that goal. This approach could be used for a single site, or could be incorporated into a regional analysis, in which all sites that met a certain goal state were identified. A backward-chaining approach is used in cases where it is desirable to determine whether a goal state is met on the basis of the minimum possible amount of data. A backward-chaining approach is used, for example, to diagnose diseases with the minimum amount of data acquired through medical testing, which is preferable because most testing is invasive and expensive. A forward-chaining search is preferred for this demonstration application to replicate the site evaluation process used by local experts, however, because the local experts seek the maximum amount of data possible for a site in order to have a complete understanding of the site characteristics and possible ways to use the site for recharge.

The reasoning engine often includes mechanisms to deal with the uncertainty inherent in the development of a system based upon human knowledge, and the fact that

KBS may be developed using incomplete or approximate knowledge and data. Uncertainty typically occurs within a KBS in two main areas: 1) uncertainty regarding the validity of a rule; and 2) uncertainty regarding the validity of user inputs and other data sources. Section VI.E. below discusses the similarity between one method for determining uncertainty, sometimes referred to as the "MYCIN method" after the KBS for which this method was first applied, and the use of the weighted average method for MCDA, which has been used for this prototype as an approximation of certainty.

IV.C. Multi-Criteria Decision Analysis (MCDA) Prototype Structure

Vlahavas et al. (1999) describes components for an MCDA, as summarized in the literature review (Chapter II). Following Vlahavas et al. (1999), the MCDA components developed for this prototype application are described below, using the components the streamflow augmentation portion of the prototype application as an example.

A = *the set of alternatives ($a_1 \ldots a_n$) to be evaluated by this model.* Exclusionary screening, as described in Goicoechea et al. (1982), is used in the development of this set A to ensure that all alternatives are potentially feasible and that attribute values can be determined for each criterion for each alternative. In the case of the demonstration application for this research, the alternatives are the individual locations considered for development as pond sites.

T = *the type of evaluation.*

In the case of this demonstration application for this research, the MCDA will classifies each alternative as excellent, good, fair, or poor, and produce an associated integer score between 4 (best) and 1 (worst). In addition, a description of each site will be provided with the alternative's rating for each criterion, and the site attributes that lead to each criterion rating.

D = *tree of attributes.*

Vlahavas et al. (1999) refer to the definition of the tree of evaluation attributes D as "the most important step of the evaluation process" (p. 189). This is the step in which the attributes to be considered in the criterion evaluations are identified. These attributes can also be placed into a hierarchy, in which certain attributes may be dependent upon the evaluation of other attributes. "Basic" attributes are those which cannot be further subdivided, while "compound" attributes are dependent upon the evaluation of sub-attributes. To use an example from the demonstration application developed for this research, the surface soil types are evaluated by recharge rate range classifications, i.e. 1-2 feet per day. As shown in Table IV-1, the NRCS Soil Classifications that have been assigned to this recharge rate range (1-2 feet per day) include those with grain sizes identified as sandy loam, gravelly loam, loamy fine sand, and loamy sand.

In this example, the grain size classifications are subattributes to the recharge rate range classifications.

Table IV-1

WAPSAM Conversion Rules from Soil Type Grain Size to Seepage Range

Grain Size	Seepage Range	Measurement Scale Score	Measurement Scale Class Name
clay loam	< 0.5 feet/day	1	Poor
silt loam	0.5-1 feet/day	2	Fair
Loam	0.5-1 feet/day	2	Fair
sandy loam	1-2 feet/day	3	Good
gravelly loam	1-2 feet/day	3	Good
loamy fine sand	1-2 feet/day	3	Good
loamy sand	1-2 feet/day	3	Good
fine sand	≥ 2 feet/day	4	Excellent

M = *set of measurement methods.*

For each basic attribute d there must be a method M_d used to assign values to that attribute. Values can be arithmetic or nominal. If measurement of an arithmetic value is not practical or nor possible, knowledge acquisition can be used to associate a value to be used for evaluation based upon other data that is measurable. For example, a soil type classification of sandy loam may be associated with a range of recharge rates (e.g. 1-2 feet per day) associated with the evaluation value "good." In the case of a knowledge-based system, rules (e.g. "IF, THEN" rules) that have been created through knowledge acquisition can be used to establish this relationship between alternative attributes and the values by which those alternative attributes will be evaluated. In order to include an alternative, also called an "object," within an MCDA evaluation, there must be a value available for each attribute to be evaluated for each of the criteria included within the MCDA evaluation. Thus, it is possible to create a unique combination of a value for each attribute (or MCDA criterion) with each object (or alternative). These unique combinations are called "object-attribute-value" or "OAV" triplets.

E = *set of measurement scales.*

For each basic attribute d there must be an associated scale e_d. The scale must be at least ordinal so that the preference of any two attribute values can be clearly determined (e.g. excellent > good > fair > poor). A point scale can be developed to support a combined evaluation of criteria, particularly when both qualitative and quantitative attribute measurements are used (e.g. excellent = 4; good = 3, etc.). In the demonstration application for this research, a 1 to 4 point scale was used during knowledge acquisition, equivalent to school grades of A (excellent), B (good), C (fair), and D (poor). Although the experts were reluctant to show any sites as failing, there is an implicit F (failure) value, which makes this a five-point scale in which a C (fair) score can be seen as the "average."

If this scale were to be converted to a -1 to +1 scale, as would be required to treat these scaled values as certainty factors, a measurement scaled score of C (fair), or 2, would be the equivalent of a certainty value of 0, which indicates that the site characteristic is "neutral" and has neither a positive nor a negative impact in the evaluation of the site for recharge. An example of the scale used for the MCDA, along with a conversion scale for a certainty factor evaluation, is shown in Table IV-2.

Table IV-2 MCDA Point Scale for Methodology Demonstration Application

Grade	Description	Measurement Scale Score	Certainty Factor Point Value
A	Excellent	4	1
B	Good	3	0.5
C	Fair	2	0
D	Poor	1	-0.5
F	Failure	0	-1

G = *set of preference structure rules.*

In the case of the demonstration application for this research, knowledge-based system rules are used to determine the value of the attributes according to preferences of excellent-good-fair-poor. In an MCDA that uses a weighted average aggregation method, the weight determines the relative preference between alternatives on the basis of a specific attribute.

R = *aggregation method.*

The aggregation method is the algorithm used to transform the set of preference relations into a "prescription" or order of the set of alternatives A (e.g. $a_1 \leq a_2 \leq a_3$). In the case of the demonstration application for this research, a weighted average aggregation method was used both because a) the knowledge acquisition indicated that there was a lack of justification for a more complex method; b) the local experts interviewed as part of the knowledge acquisition process were willing and able to identify criteria and criterion values in a manner consistent with a weighted average method; and c) the weighted average MCDA method was suitable for use as a reasoning engine for forward-chaining search using certainty factors because of the mathematical similarities between these two methods, as is further explained in Appendix E. For the system evaluation described in Chapter 5, weights are assigned to three criteria (Stream Depletion, Soil Type, and Well Density). Each criterion weight is normalized to a value between 0 and 1, as shown in Table IV-3.

Table IV-3 Weights for MCDA Weighted Average Example

Criterion	Original Weight	Normalized Weight
Stream Depletion	3	0.500
Soil Type	2	0.333
Well Density	1	0.167

IV.C.1 MCDA Weighted Average Demonstration

In the development of an MCDA, the components can be organized and illustrated through the use of a decision table, as shown in Table IV-4, which illustrates an MCDA using three criteria (i = 1 to 3) for each of three alternatives (j = 1 to 3). This table shows the scaled values ($e_{i,j}$) associated with the appropriate attribute for each criterion attribute for that alternative ($_j$), as evaluated using the appropriate measurement method for that criterion (m_i). Each criterion (c_i) is also assigned a weight (w_i), which is multiplied by the scaled value ($e_{i,j}$). The aggregation method for this MCDA is a weighted average method, in which the average of the products of the weights times the scaled values for each criterion provides the overall evaluation score (ES_j) for the alternative (a_j).

The general equation to calculate an overall Evaluation Score (ES) for alternative j using the weighted average method for any i criteria would be expressed as:

$$ES_j = \sum_{i=1}^{m} (W_i * e_{i,j})$$

where W_i is the normalized weight for the criterion ranking $e_{i,j}$.

Table IV-4 MCDA Decision Table: Variable Example

Criteria (i)	Weights w(i)	Alternative 1 (a_1)	Alternative 2 (a_2)	Alternative 3 (a_3)
c_1	W_1	$e_{1,1} = (m_1(d_1))$	$e_{1,2} = (m_1(d_2))$	$e_{1,3} = (m_1(d_3))$
c_2	W_2	$e_{2,1} = (m_2(d_1))$	$e_{2,2} = (m_2(d_2))$	$e_{2,3} = (m_2(d_3))$
c_3	W_3	$e_{3,1} = (m_3(d_1))$	$e_{3,2} = (m_3(d_2))$	$e_{3,3} = (m_3(d_3))$
ES		$(\Sigma(w_i{*}e_{i,1}))/(\Sigma(w_i))$ for i = 1 to 3	$(\Sigma(w_i{*}e_{i,2}))/(\Sigma(w_i))$ for i = 1 to 3	$(\Sigma(w_i{*}e_{i,3}))/(\Sigma(w_i))$ for i = 1 to 3

If the criterion weights (w_i) have not been normalized to add up to one, then it is necessary to divide the sum of the products of the weights and ratings for each alternative ($\Sigma(w_i{*}e_{i,j})$) by the sum of the weights ($\Sigma(w_i)$), as shown in Table IV-4. Using a four-point scale (1-4) for the values and using examples of criteria to evaluate alternative potential recharge sites from the demonstration application developed in this research, with normalized weights, Table IV-4, which uses variables, can be rewritten as shown in Table IV-5, using numbers.

Table IV-5 MCDA Decision Table: Numerical Example

Criteria	Weights	Site 1 (a_1)	Site 2 (a_2)	Site 3 (a_3)
Stream Depletion	0.500	4	1	4
Soil Type	0.333	2	3	2
Well Density	0.167	2	4	1
Evaluation Score		3.0	2.17	2.83

The weighted averages for each of the alternatives can then be evaluated to determine the order in which the alternatives are ranked or preferred according to these criteria. On the basis of the rules, weights, and criteria included in this MCDA for the three sites in this example, the preference order for the sites would be:

$$a_1 > a_3 > a_2$$

In order to reach the point illustrated in Table IV-4 and Table IV-5, in which an alternative (a_j) is evaluated on the basis of a criterion attribute (d_i) to produce a scaled value ($e_{i,j}$), which is then multiplied by the criterion weight (w_i), it is necessary to first convert the original site attribute data into the scaled value for that criterion, using the appropriate measurement scale, as is shown in the equation:

$$e_{i,j} = (m_i(d_j))$$

To use an example from Table IV-5, the attribute values for criterion 2 (Soils), alternative 1 (Site 1) produce the following evaluation scaled value:

$$e_{i,j} = 2$$

The original attribute data pertaining to Criterion 2 for Alternative 1 in this example is:

Soil Classification = AsB = Ascalon Sandy Loam, 0 to 3 percent slopes

Grain Size = Sandy Loam

This soil classification is then evaluated through two measurement scales: the first, derived from literature review and interviews with expert soil scientists, converts the grain size classification (GS) to an estimated recharge range (RR); the second, derived from interviews with local expert water engineers with experience in recharge pond development, converts the estimated RR to a measurement value (m_i) that can be converted to an evaluation scale value ($e_{i,j}$), as shown below:

Sandy Loam = Recharge Range (1-2 feet/day)

Recharge Range (1-2 feet/day) = m_j (Good)

m_i (Good) = $e_{i,j}$ (3)

The extent to which compound attributes and measurement scales are needed to develop an evaluation scale value that can be used in a criterion evaluation depends largely upon the availability and format of the original attribute available from either the user or other data sources (e.g. digitized databases). For this example, if a spatial database were available that identified locations by recharge rate or recharge ranges, it would be possible to convert those recharge ranges directly to a measurement value and evaluation scale value. However, in this case, the attribute value data that is available is the NRCS soil classification. Thus, additional steps in which the NRCS soil classification is converted to grain size, which is converted to a recharge rate range, which, in turn, is converted to a measurement value and then to an evaluation scale value, are necessary to reach the point at which the criterion can be evaluated using the available site attribute data.

The weighted average MCDA method can be used in cases when a) all alternatives to be evaluated are potentially feasible; and b) there is an attribute value for each alternative to be evaluated and for each criterion to be considered. The first of these two conditions is met by the *exclusionary screening assumption* commonly used for a MCDA (Goicoechea et al. 1982). To meet the second condition, the potential data sources are evaluated to ensure that all attribute values are available for all criteria included within the MCDA, or that data can be provided via user inputs. The set of alternatives that can be considered would be limited both by feasibility (to meet the first condition) and by availability of data (to meet the second condition).

IV.D. Structural Integration of a Multi-Criteria Decision Analysis as a Reasoning Engine within a KBS

The decision schematic shown in Figure IV-1 illustrates the structure of a subset of the Recharge Potential Assessment Tool (RPAT) portion of the KBS, which was used for system evaluation, as discussed in Chapter V. As shown in this schematic, the reasoning engine has been developed as an MCDA. The data input and other calculations performed to determine the conclusion of each rule (or criterion) are shown in Figure IV-1. The rules for each conclusion lead leading to scaled values for each criterion, and an overall evaluation is produced that aggregates the data inputs and rule outcomes from all of the criteria and subcriteria. This overall evaluation is produced using a weighted average MCDA aggregation method.

Decision schematics are often shown as decision "trees" with separate possible final conclusions as the "leaves" of the tree. In this case, however, the intermediate conclusions for each of the rules associated with a site characteristic criterion are assigned a rating score or value (e_i for all "i" site characteristic criteria) and the rating scores are then combined using the MCDA reasoning engine to develop a single overall site evaluation on the basis of all of the site characteristic criteria, as shown in Figure IV-1. For the system evaluation discussed in Chapter V, the site evaluation is based upon only three site characteristic criteria, namely soil type (ST), well density (WD), and stream depletion factor (SD). These are site characteristic criteria for which attribute values could be determined using real site data.

Because there must be an attribute value for each criterion in order for the MCDA to be performed on an alternative, the development of the MCDA is dependent upon the development of the knowledge base (through which the evaluation criteria were identified) and the development of the library of potential data sources (through which the sources of input data to determine attribute values were identified). In addition, the GIS data must be evaluated to determine whether the input data can be evaluated directly or converted into a measurable, meaningful value, as determined through further knowledge acquisition, to produce attribute values for each criterion. Finally, weights must be determined for each evaluated criterion in order to develop an overall evaluation for each alternative site.

Figure IV-2 illustrates the steps necessary to support the evaluation of each individual subcriterion evaluation. As shown, the evaluation for each subcriterion can be treated as a separate module, so that new subcriterion evaluations (or rules) can be added as the understanding of the decision-making process improves.

IV.D.1.Prototyping Approach to KBS MCDA Development

As noted by Schmoldt and Rauscher (1996), the development of "prototypic implementations" or "proof-of-concept" systems are often an essential part of the KBS development process, in that they can be used to demonstrate and test feasibility of the use of a KBS as a method for problem-solving within a particular domain, and for securing the resources to support further system development. There is extensive literature available on various types of and approaches to "prototyping" as an evolutionary software development method (e.g. Schmoldt and Rauscher 1996, Bischofberger and Pomberger 1992, Budde et al. 1991, Budde et al. 1984, Floyd 1984).

The use of the term "prototyping" is typical in software engineering, and refers to a systematic approach to the development of a program or system. While the term "prototyping" is not found in the dictionary, it is very different from the concept of a "prototype" in manufacturing, which is defined in the Mirriam-Webster Online Dictionary (www.m-w.com) as "a first full-scale and usually functional form of a new type or design of a construction (as an airplane)." (Mirriam-Webster Online Dictionary 2004). Bischofberger and Pomberger (1992), however, present two alternative definitions of "prototype" from their review of literature on prototypes and prototyping in the software development field. One definition of "prototype," provided by Boar (1984), is "an easily modifiable and extensible working model of a proposed system, not necessarily representative of a complete system, which provides later users of the application with a physical representation of key parts of the system before implementation" (page 19 in Bischofberger and Pomberger 1992). A definition of "system prototype," provided by Connell (1989), is "a dynamic visual model providing a communication tool for customer and developer that is far more effective than either narrative prose or static visual models for portraying functionality" (page 19 in Bischofberger and Pomberger 1992). Budde et al. (1991, pages 7-8) distinguish between the use of the term "prototype" in software engineering and in other engineering disciplines, noting that "A software prototype is not the first specimen of a large series of products, as is the case with mass production in the automobile industry, for example:

reproduction of a software product is not an engineering problem. The nature of a software prototype is different from that of, say, a wind tunnel or an architectural model: it actually demonstrates in practical use features of the target system. And not merely a simulation of it." Budde et al. (1991) also note, however, that software prototypes are used in a manner similar to prototypes in other engineering disciplines, such as, for example, to provide a basis for discussion, an aid to decision-making, and a means for experimentation.

The development of initial proof-of-concept systems is an essential component of KBS development, and there are several approaches to the development of these initial systems. The development of a "cursory test version" without extensive time and knowledge source availability can not only demonstrate that further expenditures are warranted, but also generates the interest in and understanding of the KBS process necessary to support participation by the experts and dedication of their time and input into KBS development. In addition, as previously quoted from Buchanan et al.'s 1983 publication entitled Constructing an Expert System, "knowledge acquisition and system-building interact inseparably." (page 127 in Hayes-Roth et al. 1983) Thus, the development of a "prototype" provides an essential means by which the knowledge engineer can provide "feedback" to the experts, demonstrating how the KBS is (or is not) successfully capturing the expert's domain knowledge and reasoning process, and, in turn, providing a tool that the knowledge engineer can use to acquire additional knowledge and refine the KBS in an iterative fashion. The use of a "prototype" is also an important means of testing various aspects of the KBS, including the domain knowledge, reasoning process, and user interface, in order to ensure that the framework and approach that is taken to KBS development is appropriate to the problem at hand.

Schmoldt and Rauscher (1996) dedicate an entire chapter section (pages 206-213) to the discussion of different approaches to prototype development in knowledge-based systems development and associated considerations. *Plenary prototypes* is a term they use to refer to the development of the entire application at one time, which they state as being possible typically "when the application covers a very narrow, carefully-defined problem and … involves little complexity." (Schmoldt and Rauscher 1996, page 207). Even when working towards the development of a "plenary prototype," this approach often involves numerous revisions of a "first-pass prototype." Walters and Nielsen (1988) recommend the development of a broad but shallow version of the system, which can later be fleshed out as further knowledge is acquired and further components are developed.

Schmoldt and Rauscher (1996) also present to two other methods of prototyping, which they refer to as "vertical prototypes" and "horizontal prototypes," and note that these methods are often useful "as applications become larger and more complex" so that prototyping an entire system at once is difficult. (Schmoldt and Rauscher 1996, page 208) Both of these methods have been used to some extent in the applications of this methodology. *Horizontal prototyping* is a method in which a skeleton is developed of the entire KBS indicating all of the components to be included. In the case of the demonstration application for evaluation of potential recharge pond sites, this skeleton would include all of the criteria considered by local experts during site evaluation. Because of current lack of available knowledge, input data, or other resources, *horizontal* *prototyping* would involve the complete development of only a few of the components. Looking at the subset of the recharge component of the prototype application that was used to test this methodology, KBS components were only developed for the three criteria for which both database availability and current knowledge were available to support the development of both a spatial database to provide input data and threshold values to support MCDA development (Figure IV-1). One of the positive attributes of KBS is that new rules can be added to the system as new knowledge and resources become available so that additional component development can be completed.

Vertical prototyping is a method that can be used or large, complex applications in which various subcomponents of the larger problem are independent … and may then be combined into a final product later." (Schmoldt and Rauscher 1996, page 209). In the case of the demonstration application for evaluation of potential recharge sites, the system, called the Recharge Potential Assessment Tool, or "RPAT," was developed in two stages. RPAT-I includes knowledge bases and user interfaces but no reasoning engine, so that output reports were provided with data on the user-selected sites derived from the spatial databases, but no analysis of the site. RPAT-I was then used with local experts to guide the development of the MCDA measurement scales, and to determine for which components MCDA measurement scales could be developed with the current level of knowledge, leading to the development of RPAT-II.

Figure IV-2, which shows a component of the decision schematic from Figure IV-1, shows that each component requires the development of input data sources (domain knowledge bases) and rule knowledge bases in order to complete the that component. Development of each component is completed in a vertical fashion. As sufficient data, knowledge, and resources become available, additional criterion components to the KBS can be developed in a horizontal fashion. Thus, the individual components (or criteria for the MCDA KBS) are developed *vertically*, adding first the domain knowledge bases/spatial databases, then the rules for the MCDA, while the overall system can be developed *horizontally*, adding new criteria/components as the appropriate databases and knowledge for rule bases are developed or acquired.

IV.D.2 Mathematical Similarity Between Certainty Factors and MCDA for Use as a Reasoning Engine within a KBS

A MCDA can be programmed to serve as the reasoning engine of a KBS, in part, because of the mathematical similarities between the weighted average aggregation algorithm and the MYCIN method for determining certainty in a forward-chaining KBS. As noted earlier, the MYCIN method uses certainty factors, which accumulate the level of belief and disbelief in a hypothesis with the creation of new evidence from additional rules until a final conclusion is reached (Shortliffe and Buchanan 1975).

In the MYCIN method, each hypothesis or rule is treated as having two distinct values, one for the belief that that hypothesis is true, and one for the belief that the hypothesis is false (the "disbelief" value). Both the *measurement of belief (MB)* and the *measurement of disbelief (MD)* are values between 0 and 1. The MB and MD can be altered separately from one another, i.e. a change in one value does not cause a change in the other. In a rule-based system, the conclusions for individual rules have MB and MD values, and intermediate and final conclusions have MB and MD values. Premises also have individual MB and MD values, and a rule with multiple premise clauses can have multiple MB and MD values, which can be combined to produce an overall MB and MD value for that rule.

The overall *certainty factor (cf)* for a rule is calculated as the difference between that rule's MB and the MD:

$$cf = (MB-MD)$$

representing the total evidence for and against a particular hypothesis.

Certainty factors range between -1 and 1, with -1 representing total disbelief, 1 representing total belief in the hypothesis. A certainty factor of 0 would represent either a lack of evidence or equally contradicting evidence for and against the hypothesis. In a rule-based system, the hypothesis being tested is the conclusion of the rule. As noted earlier, uncertainty is introduced into KBS in two areas: 1) uncertainty regarding the validity of the inputs, represented in the *rule premises*; and 2) uncertainty regarding the rules, represented in the *rule conclusions*. An individual rule may contain multiple premises, connected by *and*, *or*, or *not*. Certainty theory is not used with rules that have multiple conclusions. For a rule with multiple premises (P_1 and P_2), the certainty represented by the total premise, or *rule input (RI)*, is determined as follows:

$$RI(P_1 \text{ and } P_2) = \min(cf(P_1), cf(P_2))$$

$$RI(P_1 \text{ or } P_2) = \max(cf(P_1), cf(P_2))$$

$$RI(\text{not } P_1) = -1 * cf(P_1)$$

The overall certainty factor for a rule is calculated as the certainty factor for the rule input (RI) multiplied by the certainty factor for the rule (R):

$$cf = RI * R$$

For example, if $RI = 0.5$ and $R = 0.8$, then $cf = (0.5*0.8) = 0.4$.

The *certainty factor union method* is used to determine the *combined certainty factor (C(cf))* for multiple rules:

$C(cf_{1,2}) = \quad cf_1 + cf_2 - (cf_1 * cf_2)$

For example, if $cf_1 = 0.3$ and $cf_2 = 0.9$, then $C(cf_{1,2}) = 0.3 + 0.9 - (0.3*0.9) = 0.93$

This equation is derived from the equation for the probability of the occurrence of two mutually exclusive events. As each additional rule is added, the certainty factor for that new rule is combined with the combined certainty factors for all preceding rules, as follows:

$$C(cf_{1,2,3}) = C(cf_{1,2}) + (cf_3) - [C(cf_{1,2})* (cf_3)]$$

or for any n rules:

$$C(cf_{1-n}) = C(cf_{1,2,\ldots,n-1}) + (cf_n) - [C(cf_{1,2,\ldots n-1})* (cf_n)]$$

The overall conclusion produced by the certainty factor union method, representing a single final estimate of truth or belief in the decision made through the reasoning process programmed into the KBS, is the sum of all of certainty factors of all of the rules fired to reach that overall conclusion, minus the product terms from the certainty factors of all of the rules considered. The MYCIN method is mathematically similar to the use of the weighted average method for a MCDA, as was used as the reasoning engine for the KBS in the demonstration application for this research. As an increasing number of rules are fired, and increasing amount of evidence towards or against the overall conclusion is accumulated, the final term in the combined certainty factor equation becomes increasingly small, so that the single final estimate of truth approaches the sum of the certainty factors for each rule, which is the equivalent of the normalized weighted average calculated in the MCDA.

Using the example from the prototype application, the overall site evaluation score ES is calculated as the sum of the normalized weighted criterion values for each of the criteria considered in this evaluation:

$$ES = w_{ST}*e(ST) + w_{WD}*e(WD) + w_{SD}*e(SD)$$

The weighted criterion value for each criterion is calculated as the weight for that criterion (w_i for criterion i) times the scaled value associated with that criterion ($e_{i,j}$ for criterion i and alternative j). The weight is representative of the level to which that criterion (soil type, well density, or stream depletion factor) impacts the overall preference of the alternative site for development for managed ground water recharge for stream augmentation, as determined by the local experts on the basis of their understanding of site suitability for pond development. The weights are associated with the criteria, and are independent of the data associated with a particular alternative site. The weights of the criteria represent the extent to which that criterion (or rule) contributes to the overall certainty that the alternative is suitable for recharge. Thus, while certainty factors are normally calculated as being between -1 and 1, the rule certainty factor (i.e. the certainty of the rule contributing to the overall suitability score of the site) is shown as all positive values between zero and one. The normalized rule weights, which are equivalent to the rule certainty values (R_i), are as shown in Table IV-6.

Table IV-6 Weights for MCDA Weighted Average Example

Criterion	Original Weight	Normalized Weight
SD	3	0.500
ST	2	0.333
WD	1	0.167

The scaled value for each criterion is associated with the data for that alterative site. For example, a scaled value of "good", or a grade of "B", for the criterion "stream depletion factor" in this demonstration application, is assigned to sites with data inputs (as determined using the spatial database) of stream depletion factors between 90 and 150 days. When determining the suitability of a potential site for managed ground water recharge for stream augmentation, the local experts have identified this range of SDF values as providing sites that generally are considered "good" when evaluated on the basis of the stream depletion factor alone. This scaled value was assigned to the numerical value "3" on the measurement scale for the MCDA calculations. In order to calculate the certainty factor for a site suitability based upon this single rule/criterion, the measurement scale is converted to a scale from -1 to 1, in which an average score (grade = C; description = fair; scaled value = 2) is treated as a 0 value in terms of its application to the certainty of the suitability of the alternative site.

Table IV-7 shows the conversion of the MCDA measurement scale point values ($e_{i,j}$) to Rule Input certainty factor (RI_i) point values for this example.

Table IV-7 MCDA Point Scale for Methodology Demonstration Application

Grade	Description	Measurement Scale Score	Certainty Factor Point Value
A	Excellent	4	1
B	Good	3	0.5
C	Fair	2	0
D	Poor	1	-0.5
F	Failure	0	-1

Table IV-8 shows the entire decision table for this example using variables for three alternatives and three weighted criteria.

Table IV-8 MCDA Decision Table: Variable Example (2)

Criteria (i)	**Weights w(i)**	**Alternative 1 (a_1)**	**Alternative 2 (a_2)**	**Alternative 3 (a_3)**
c_1	w_1	$e_{1,1} = (m_1(d_1))$	$e_{1,2} = (m_1(d_2))$	$e_{1,3} = (m_1(d_3))$
c_2	w_2	$e_{2,1} = (m_2(d_1))$	$e_{2,2} = (m_2(d_2))$	$e_{2,3} = (m_2(d_3))$
c_3	w_3	$e_{3,1} = (m_3(d_1))$	$e_{3,2} = (m_3(d_2))$	$e_{3,3} = (m_3(d_3))$
ES		$(\Sigma(w_i{*}e_{i,1}))/(\Sigma(w_i))$ for i = 1 to 3	$(\Sigma(w_i{*}e_{i,2}))/(\Sigma(w_i))$ for i = 1 to 3	$(\Sigma(w_i{*}e_{i,3}))/(\Sigma(w_i))$ for i = 1 to 3

Using the example from this demonstration application, the scaled values ($e_{i,j}$) can be seen as a level of confidence or certainty on the suitability of a site for managed ground water recharge for stream augmentation on the basis of the data inputs for the rule (RI_i). The weight of the criterion (w_i) can be seen as a level of confidence or certainty in the suitability of a site for managed ground water recharge for stream augmentation on the basis of that criterion's importance (i.e. that rule's importance) with respect to the overall conclusion (R_i). Thus, overall weighted value for a criterion, which is the product of the weight for that criterion times the scaling value associated with the data inputs for that alternative, is mathematically similar to the calculation of a certainty factor for a rule, which is calculated as the product of the certainty for the rule inputs times the certainty for the rule:

$cf_{i,j} = RI_j * R_i \simeq w_i * e_{i,j}$ = (criterion/rule importance)*(level of certainty/rating)

Table IV-9 MCDA Decision Table: Numerical Example with cf Scale

Criteria	Weights	Site 1 (a_1)	Site 2 (a_2)	Site 3 (a_3)
SD	0.500	1	-0.5	1
ST	0.333	0	0.5	0
WD	0.167	0	1	-0.5
ES		0.500	0.083	0.416

Table IV-10 Numerical Example with cf Scale and Combined cf Calculations

Criteria	Weights	Site 1 (a_1)	Site 2 (a_2)	Site 3 (a_3)
SD	0.500	1	-0.5	1
ST	0.333	0	0.5	0
WD	0.167	0	1	-0.5
C(cf)		0.500	0.132	0.458

Table IV-9, showing the MCDA calculations for three alternative sites using normalized weights, can now be shown using certainty factors for the site characteristic values for each of the criteria, as shown in Table IV-10.

The preference order for the sites in this numerical example would be:

$$a_1 > a_3 > a_2$$

Looking at the example for Site 3 (a_3), we can see the impact of each criterion on the overall evaluation score for that site:

(1) Rule one for this alternative has a rule input cf of 1 (from the alternative site's SDF value) and a rule cf of 0.500 (from the weight for the SD criterion), resulting in an overall evaluation score of 0.500 on the basis of the first rule alone;

(2) Rule two for this alternative has a rule input cf of 0 and a rule cf of 0.333, so there is no overall effect from the addition of the rule input from the inclusion of this rule with this rule input. In other words, the soil type for this site does not make this site more suitable for recharge for stream augmentation, but also does not make this site less suitable for recharge for stream augmentation. The impact of this rule on the site evaluation score is neutral.

(3) Rule three for this alternative has a rule input cf of -0.5 and a rule cf of 0.167. When combined with the positive impact of the rule input for rule one and the neutral impact of the rule input for rule two, the overall evaluation score for this alternative site is lowered from 0.500 to 0.483. In other words, the well density site characteristic has a very low rating, resulting in a negative impact on the overall site evaluation score (or level to which the hypothesis that the site is suitable for recharge for stream augmentation is true). Because the weight of the well density criterion is very low, however, the negative impact from the well density slightly lowers, but does not completely offset, the positive impact from the stream depletion factor for this site, because the stream depletion factor has both a higher rule input value (or scaled attribute value) and a higher rule certainty (or weight).

Table IV-10 shows the MCDA normalized weighted average calculations using scales that would be appropriate for use with a certainty factor evaluation, but does not include the actual certainty factor calculations. As stated previously, the overall certainty factor evaluation for a given alternative is a combined evaluation of each of the rules included in the KBS:

$C(cf_{1-n}) = C(cf_{1,2,\ldots,n-1}) + (cf_n) - [C(cf_{1,2,\ldots n-1})^* (cf_n)]$ for all n rules

Thus, the evaluation score for Site 3 (a_3) based upon the first criterion (SD) only would be:

$cf_1 = R_1 * RI_1 = (0.500)*(1) = 0.500$

Using the *certainty factor union method,* the *combined certainty factor (C(cf))* for the first two rules in this example would be:

$$
\begin{aligned}
C(cf_{1,2}) &= cf_1 + cf_2 - (cf_1 * cf_2) \\
&= 0.500 + (0)(0.333) - (0.500)(0)(0.333) \\
&= 0.500
\end{aligned}
$$

Again, the rule input is neutral for Site 3 (a_3), so the impact of the certainty factor from rule 2 (cf_2) on the combined certainty factor for rules 1 and 2 ($C(cf_{1,2})$) is likewise neutral.

The certainty factor for the third and final rule in this three rule system is combined with the combined certainty factors for the preceding two rules, as follows:

$$
\begin{aligned}
C(cf_{1,2,3}) &= C(cf_{1,2}) + (cf_3) - [C(cf_{1,2})^* (cf_3)] \\
&= 0.500 + (-0.500)(0.167) - [(0.500)(-0.500)(0.167)] \\
&= 0.500 - 0.083 + 0.0416 \\
&= 0.4583
\end{aligned}
$$

Thus, with three rules, the overall evaluation score for this site based upon certainty factors (0.4583) is approaching the overall evaluation score for this site based upon a normalized weighted average (0.4166). As additional rules/criteria are added, this number should continue to converge. As shown in Table IV-10, the preference order of the alternatives is the same when the certainty factor method is used as when the MCDA normalized weighted average method was used.

As further rules are added, the overall evaluation score for each alternative using the certainty factor method will continue to approach the overall evaluation score for that alternative using the weighted average method. Thus, the use of a MCDA normalized weighted average is a suitable method by which site evaluations for a KBS can be performed.

Figure. IV-1.

Decision Schematic for Demonstration Application of KBS for Evaluation of Potential Recharge Sites

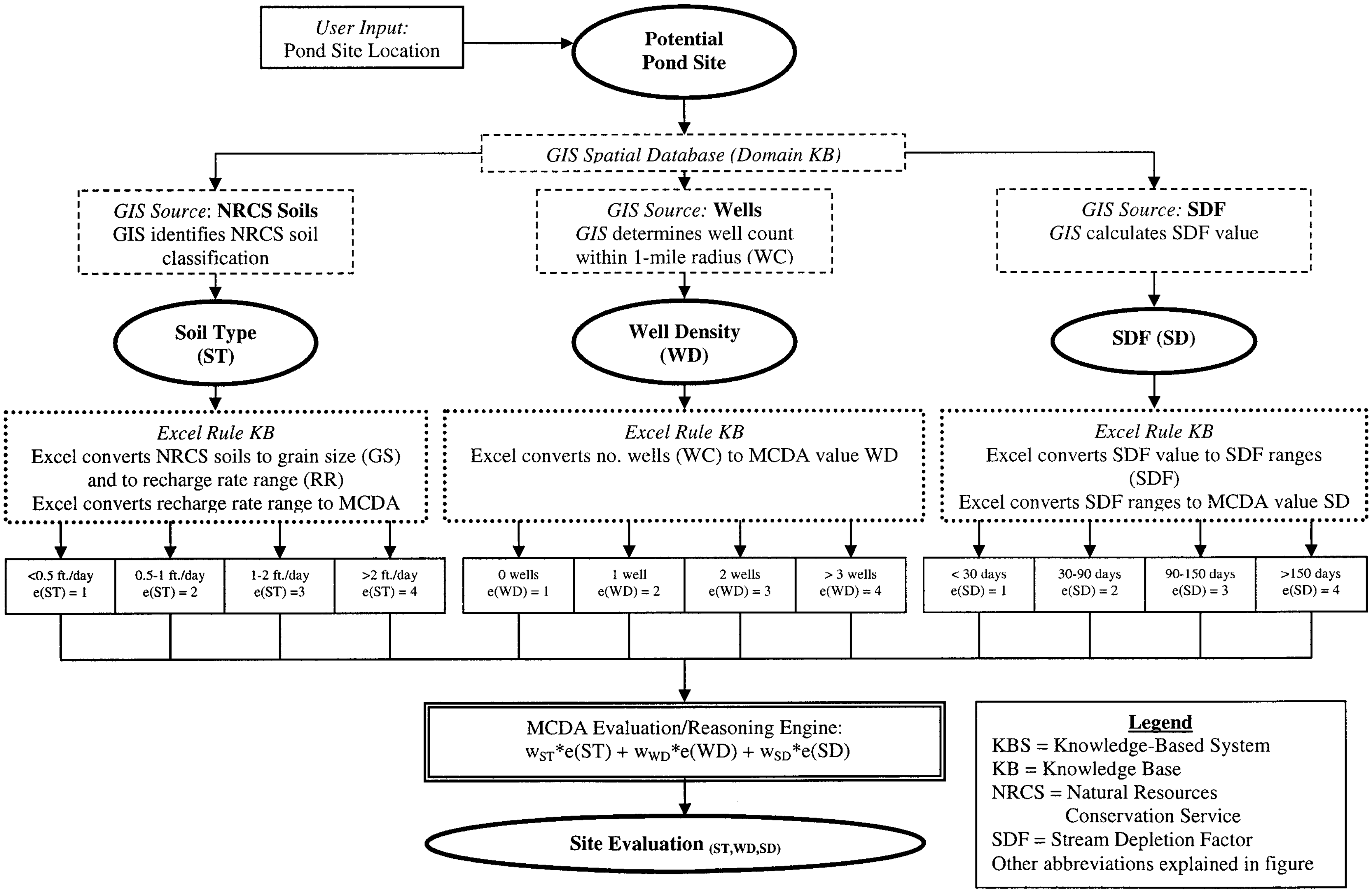
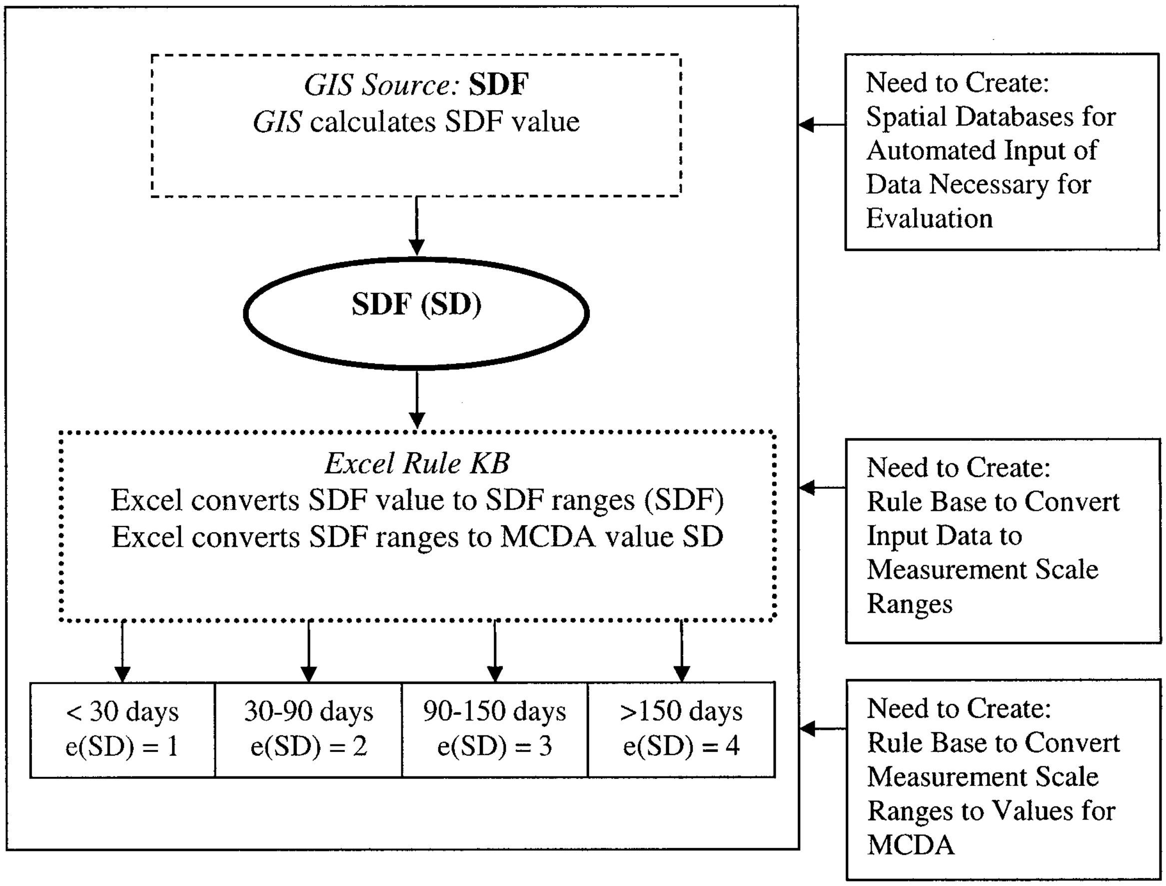

User Input:
Pond Site Location
Potential Pond Site
GIS Spatial Database (Domain KB)
GIS Source: NRCS Soils
GIS identifies NRCS soil classification
GIS Source: Wells
GIS determines well count within 1-mile radius (WC)
GIS Source: SDF
GIS calculates SDF value
Soil Type (ST)
Well Density (WD)
SDF (SD)
Excel Rule KB
Excel converts NRCS soils to grain size (GS) and to recharge rate range (RR)
Excel converts recharge rate range to MCDA
Excel Rule KB
Excel converts no. wells (WC) to MCDA value WD
Excel Rule KB
Excel converts SDF value to SDF ranges (SDF)
Excel converts SDF ranges to MCDA value SD
<0.5 ft./day e(ST) = 1
0.5-1 ft./day e(ST) = 2
1-2 ft./day e(ST) =3
>2 ft./day e(ST) = 4
0 wells e(WD) = 1
1 well e(WD) = 2
2 wells e(WD) = 3
> 3 wells e(WD) = 4
< 30 days e(SD) = 1
30-90 days e(SD) = 2
90-150 days e(SD) = 3
>150 days e(SD) = 4
MCDA Evaluation/Reasoning Engine:
w_ST*e(ST) + w_WD*e(WD) + w_SD*e(SD)
Site Evaluation (ST,WD,SD)
Legend
KBS = Knowledge-Based System
KB = Knowledge Base
NRCS = Natural Resources Conservation Service
SDF = Stream Depletion Factor
Other abbreviations explained in figure

Figure IV-2. Sample Decision Schematic for a KBS Component/Criterion



CHAPTER V

WATERFOWL AND AUGMENTATION POND SITE ASSESSMENT MODEL (WAPSAM) PROTOTYPE AND SYSTEM EVALUATION

V.A. Introduction

Using the knowledge acquisition, MCDA, and KBS development processes described in Chapters III and IV, a prototype application was developed to capture the parts of the process used to make site assessment decisions of water managers and habitat managers on the evaluation of recharge pond sites for streamflow augmentation, development costs, and waterfowl habitat restoration benefits. This prototype application is called the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM).

WAPSAM was developed modularly, with separate modules for the site evaluations on the basis of recharge potential, cost estimates, and waterfowl habitat benefits. The WAPSAM prototype was developed horizontally to include all of the site evaluation criteria identified during the knowledge acquisition process. Not all of the spatial databases were available at the time of prototype development to support the use of WAPSAM for automated site evaluations that include all of these criteria. Further research would be required to develop those additional spatial databases, as well as to confirm or correct the threshold values used to determine the criterion and subcriterion rankings. Vertical prototyping was also used to develop a modified version of the recharge component of WAPSAM, called "RPAT-II", for which complete subcriterion evaluations could be completed for three subcriteria using real site data. The WAPSAM prototype, presented in this chapter, demonstrates how a KBS with MCDA and spatial databases could be used to capture and replicate portions of this site evaluation process.

Throughout the prototype development, the model components, rules, and threshold values were presented to and reviewed by local experts, with feedback used to refine the system. A more formal system evaluation procedure was also developed and used for a modified version of the recharge potential (RPAT) module using three subcriteria for which all of the subcriteria analysis could be performed using existing spatial databases. This testing process and results are summarized in this chapter.

V.B. Overview of Prototype

WAPSAM has three modular components. The instructions for use of WAPSAM, as provided in the program, are shown in Figure V-1. The recharge component is called the Recharge Potential Assessment Tool (RPAT); the cost component is called the Cost Assessment Tool (CAT); and the waterfowl habitat component is called the Waterfowl Habitat Assessment Tool (WHAT). For each of the three components, there is a separate worksheet for the rule base, which assigns threshold values to each subcriterion ranking, and a criterion evaluation output report. Figures are provided showing the rule bases for RPAT (Figure V-2), CAT (Figure V-3), and WHAT (V-4). Potential data sources for evaluation of each of the subcriteria are shown in Tables V-1, V-2, and V-3 for RPAT, CAT, and WHAT, respectively. Figures are also provided showing the output reports for RPAT (Figure V-5), CAT (Figure V-6), and WHAT (Figure V-7).

Each rule includes an assignment of raw or evaluated data values to one of four rankings for that subcriterion value. Generally, the subcriterion values are assigned a ranking of poor (1), fair (2), good, (3), or excellent (4). WAPSAM users can change the threshold values separating each of these rankings (shown as yellow cell blocks in Figures V-2 through V-4), and the results shown in the output reports are automatically updated. For those subcriteria involving spatial analysis within an area of a specified radius, the user can change the radius, save the changes to the Excel portion of WAPSAM, and re-evaluate the site in ArcView on the basis of the new radius value.

Each of the three components is programmed in Excel software, with links to ArcView GIS spatial databases. Using Avenue programming, the Excel-based portion of WAPSAM can both export information from Excel to ArcView (such as the radius of the area around a selected point to be evaluated in ArcView) and import information from ArcView to Excel (such as the results of the spatial analysis performed in ArcView).

WAPSAM users can begin site evaluation by opening ArcView GIS (ERSI 1996a), adding the Habitat Potential Assessment extension and coverage directories, and selecting a site. The user has the option of manually inputting the site name, site contact name and phone number in the dialog box, shown in Figure V-8. WAPSAM then produces results in both ArcView, with a map coverage showing the selected site and nearby features considered during the evaluation (e.g. water sources, protected lands) highlighted and labeled, evaluated using 3-D Analyst (ERSI 1997) as shown in Figure V-8. Using Avenue programming (ERSI 1996b), the raw data for the evaluated site from the spatial databases are exported to both the output reports and the "Inputs&Weights" worksheet in Excel (Microsoft 1995), shown in Figure V-9. Prior to performing a site evaluation, the user can also change the weights associated with each of the subcriteria through the "Inputs&Weights" worksheet. As an alternative to inputting site data from the ArcView GIS coverages, WAPSAM users can enter raw data inputs for a site directly into the Excel-based program through the "Inputs&Weights" worksheet, or can input raw data from one of five sample sites provided in the WAPSAM on the "Sample Site Data" worksheet (Figure V-10).

Once a site evaluation has been performed, the results are summarized in the "Summary Output" worksheet (Figure V-11), which shows the criterion scores and weights for the three major criteria (recharge, cost, and waterfowl habitat), and the overall site evaluation score. In addition, the summary output highlights the site evaluation results in red if there may be Prairie Dog habitat, a Potential Conservation Area (PCA), or an Element Occurrence (EO) as determined by the Colorado Division of Wildlife (CDOW) and Colorado Natural Heritage Program (CNHP). These are ecologically significant features which could be negatively impacted in a pond for streamflow augmentation of waterfowl habitat were built over them. The spatial databases for these ecologically significant features, however, only show large areas in which these features may occur, but do not indicate the exact location of these features (e.g. bald eagle nests) in order to prevent human disturbance of the features. A red "flag" in the WHAT output report and the summary output report notify WAPSAM users that pond development may disturb these ecological features. An on-site investigation would be advisable to determine whether pond construction would actually disturb the site of these ecological features at or near the selected pond location.

The summary output for a site evaluation can be saved (see Figure V-11), and up to five site evaluations can be compared in the "Stored Results" worksheet, shown in Figure V-12.

V.C. System Evaluation

The final step in KBS development is system evaluation. There has been extensive literature on methods for evaluation of KBS, as discussed in the literature review (Chapter II). Throughout the development of the prototype application, there have been continuous presentations to local experts on the rules, spatial database sources, and other aspects of the KBS, and feedback from local experts has been incorporated into the prototype. The prototype has also been designed to provide maximum flexibility in that users can change the threshold values of the rules, change the radius of the area of evaluation for the spatial analysis, and can add new rules and new databases as data availability and understanding of the site evaluation process are improved.

A formal evaluation of this KBS was conducted using real sites for a modified version of the RPAT component of the KBS for which sufficient data was available to conduct the recharge pond site evaluations, and for which local experts were available to test the site evaluation results. This modified version of the RPAT component of WAPSAM is called "RPAT-II".

The prototype KBS developed for this research was intended as a means of "capturing expertise," as described in Schmoldt and Rauscher (1996. p. 304), in a transparent system to identify the process by which local experts selected potential recharge sites, and the various criteria and threshold values used by local experts in their site evaluations. The development of this KBS was intended, in part, to create a better understanding of this site evaluation process and the needs for additional databases and future research in areas where knowledge is lacking and processes are poorly understood.

Testing of the competence of the local experts through independent, empirical evaluations of the quality of recharge sites for stream augmentation or waterfowl habitat was not a goal of this research, and no field investigations or other site evaluations beyond those performed in the development of the prototype were used to determine whether the experts were "correct" in their approach to site evaluations.

Throughout the KBS-development process, there was continuous feedback from the local experts, including formal presentations and requests for feedback from both the water managers and the waterfowl habitat managers, as discussed below. In addition, there was a formal system evaluation performed using RPAT-II module of WAPSAM for which all of the GIS coverages were available that would be needed for a full-scale site evaluation to be performed on the basis of potential streamflow augmentation benefits. A "scenario analysis" approach was taken for this system evaluation.

Without an objective, well-understood and widely agreed upon standard of what constitutes a superior recharge site for stream augmentation, the extent to which this demonstration application "solves real-world problems" is limited. By using real-world sites, however, it is possible to assess whether the demonstration application produces realistic results (i.e. results that resemble the results produced by real experts) within the system's constraints, and to assess in what areas future work is needed. Sites can also be selected using a stratified testing approach, to include representatives of the different identifiable result types, including a few more obscure or complex cases, as recommended by O'Keefe et al. (1987). Rather than using statistical analyses with the small number of case studies and expert responses available, the results of site evaluations from KBS and the various testers can be evaluated individually using a *scenario analysis* approach. Scenario analyses are often used as an evaluation procedure for MCDA, KBS, and other decision support systems to determine how well the system is capable of simulating the decision maker's responses (e.g. Gomez-Limon et al. 2002, Chao et al. 1999). The KBS evaluation process developed for the demonstration application in this research is described in this chapter, including discussion of the test results and analysis, following a description of the system validation processes (i.e. verification and substantiation), using O'Leary et al.'s definitions for these terms (O'Leary et al. 1990). O'Leary et al. (1990) distinguish *validation* from *evaluation*, which they describe as the process by which the KBS can solve real-world problems within the problem domain, focusing on the relationship between the expert system and the real world.

V.C.1. System Validation

The system validation steps taken for this research include both O'Leary et al.'s (1990) definition of *verification*, which would include a review of the formulated problem to ensure that the actual problem is included in its entirety and has been structured to enable a credible solution to be derived, and *substantiation,* which would include a check on the accuracy of the computer model and associated data.

Specific steps taken towards validation of the demonstration application, including the following verification and substantiation steps:

- knowledge base review (verification)
- rule composition and reasoning engine review (verification)

- computer programming review (substantiation)
- database review (substantiation)

Knowledge Base Review

This verification step involves review of the domain and rule knowledge bases by local experts to ensure that these knowledge bases reflect the criteria used by the experts in their site evaluation approach. The use of close coordination with local experts on the development of this KBS, as recommended by several authors (e.g. Mackinson 2000, Schmoldt and Rauscher 1996), provided continuous opportunities for informal review of the knowledge base and input by local experts. A formal presentation was also given to local experts at a meeting of the South Platte Lower River Group (SPLRG) on the findings of the knowledge acquisition regarding the comprehensive list of site evaluation criteria as well as the final list of criteria included in the demonstration application, along with the data used to support each criterion evaluation. In addition, several individual water users and state water agency personnel were invited to review a draft guidance manual for the demonstration application which summarized the site evaluation criteria.

During the SPLRG presentation, local experts confirmed that the comprehensive list of criteria identified during knowledge acquisition was an accurate portrayal of the considerations for potential recharge sites for stream augmentation. The local experts emphasized the importance of the economic considerations on this list, but acknowledged the limitations of the data available to support economic criteria analyses, and recognized that the physical site characteristic criteria selected for inclusion in the demonstration application could be used to support limited site evaluations.

Rule Composition and Reasoning Engine Review

This verification step involved review of the rule composition and organization of the rules within the reasoning engine to ensure consistency and completeness, using Ignizio's definitions of these terms (Ignizio 1991). The rule base has a simple structure in which the supporting data for each criterion is acquired and assigned to a classification category, with each classification type divided into four categories by threshold values identified by the local experts. The final conclusion of the overall site evaluation is reached by a rule that performs a weighted average aggregation of the scaled values assigned to each individual criterion. The rules were checked for inconsistencies, as recommended by Ignizio (1991), and the rules were found not to be redundant, conflicting, subsumed, unnecessary, nor circular.

There were some completeness issues identified in that there were some gaps in the data, so that no value was available for the evaluation of criteria in some locations within the target region. Under the exclusionary screening assumption, sites for which there was no SDF or soils attribute data available would not be considered. However, the system was programmed so that, if a user were to select a site with missing data, an evaluation would be performed but the missing data and the unevaluated criteria would be identified in the output report, rather than allowing the computerized KBS to "crash" due to missing data. The identification of missing or inaccurate data through the development of this KBS was one of the objectives of this research, so the identification of missing or inaccurate data was not considered a failure of this system. Further details on the data gaps identified during system evaluation are provided in the testing results (Section V.D.)

Because the reasoning engine for this KBS is a MCDA, which produces a single overall site evaluation value based upon the aggregated scaled values of the individual criteria, it is possible for multiple combinations of rules and attribute values to produce non-unique outcomes, which could be seen as a conflict under some KBS systems. However, the production of the same aggregated score from multiple combinations of criteria is not unusual for an MCDA. In addition, the KBS is designed to be very transparent, with full explanations provided in the output report on the data and rules used to reach each intermediate and final conclusion. Thus, even though two sites may have the same overall site evaluation, the user can clearly determine which site characteristic attributes led to that site evaluation results.

Computer Programming Review

This substantiation step involved review for programming errors in both the ArcView/GIS-based and Excel-based portions of the demonstration application. Expert systems shells are available that include built-in validation checks which could perform these code-checking functions, but these shells were found to be too inflexible in terms of the comprehensiveness of the output reports that could be provided to the users.

The ArcView/GIS-based programming was checked to ensure that the correct data was imported into GIS and exported out of GIS to the correct cells and worksheets in the Excel-based MCDA, and to ensure that the correct user inputs were requested and the correct data was exported to the Excel-based MCDA and output report. The Excel-based code was also checked to ensure that the correct cell and worksheet references were used, and to ensure that there were no coding errors in the Excel-based portion of the MCDA and KBS.

Database Review

This substantiation step was integrated into the Data Source Evaluation Process for KBS Inputs, as described in Chapter III. To develop the spatial database as knowledge bases to provided inputs for this KBS, databases were reviewed as they were acquired and modified. The only subcriteria included in RPAT-II were those for which data could be provided from the spatial databases at an adequate level of resolution to support criterion evaluation. Additional review of database inaccuracies or completeness issues occurred during the system evaluation. Errors resulting from incorrect or inadequate data were anticipated when real sites were tested by the KBS and by local experts. Discussion of the findings of incomplete or inaccurate data resulting from the system evaluation is provided in the testing results (Section V.D.)

V.C.2. System Evaluation by Scenario Analysis

The KBS was tested using a scenario analysis in which the KBS-produced site evaluations were compared with those produced by local experts, using actual recharge sites in operation or under development. The same site data provided to both the KBS and the expert participants, and the experts were asked to develop and provide their own scaling and weighting functions for each criterion. The KBS results for each site were then re-evaluated using the scaling and weighting functions provided by the experts. This section describes the system evaluation goals, approach, and anticipated errors. Section V.D. provides the results and discussion of results from the system evaluation.

System Evaluation Goals

The primary goal of the system evaluation was to test the claim that the demonstration application KBS "captures expertise" of the local experts on the evaluation of potential recharge sites for stream augmentation. This expertise is reflected in several aspects of the KBS, including:

a) the inclusion of KBS site evaluation criteria that are used by local experts in their site evaluations;
b) the use of KBS input data that would be used or otherwise found acceptable for use by local experts in their site evaluations;
c) the use of measurement methods and scaling functions which reflect those used by local experts; and
d) the use of criterion weighting functions which reflect those used by local experts.

Within the limitations placed upon the development of this KBS, the creation of credible solutions was also tested through the use of data from real sites in the demonstration testing. For this testing scheme, the KBS and a panel of experts were separately given the same raw site data for real sites within the target region. Bias was controlled through the removal of identifying information about the sites. The results for the KBS and the experts were compared and both sets of results were reviewed by both the panel of experts and by outside experts from the South Platte Lower River Group

(SPLRG). The identities of the sites used were revealed during the evaluation of the test results in order to gain feedback on data or system errors, or site-specific considerations not included in the MCDA. Inconsistencies between the findings of the KBS and the local experts on the basis of database errors or criteria that had been excluded from the MCDA were not considered to be flaws in the development of the demonstration application, but were noted to support future work. KBS are typically designed to support the addition of new rules and new or improved knowledge bases as new knowledge and new understanding of processes develop. Consequently, identification of missing rules or knowledge was a part of the system evaluation. The missing subcriteria for evaluation of physical site characteristics for recharge ponds for streamflow augmentation and for pond development costs were added to the final prototype, as shown in Figures V-2 and V-3, even though the knowledge and data to complete these evaluations was not yet available.

With regard to the scaling and weighting functions used by local experts, it was recognized during testing that these functions would vary depending upon the water uses and priorities of the individual experts. Experts were selected with different types of water uses and priorities, as described below.

The goals of this system evaluation can be summarized as follows:

1) To determine whether and to what extent the KBS reflects the local experts' site evaluation process as it would be applied to selected test sites if that evaluation were based solely upon the criteria included in the MCDA; and

2) To identify areas of disagreement among the local experts, and determine whether the KBS can be adjusted to reflect the differences in water uses and priorities among local experts; and

3) To determine what aspects of the test sites (all of which are actual recharge sites) are not accurately portrayed by the available computerized data or insufficiently or incorrectly addressed by the MCDA, in order to determine what future work would be needed to improve this KBS and ensure an accurate site evaluation.

System Evaluation Approach

A scenario analysis was developed to test the RPAT-II demonstration application, using data from recharge sites that had been developed, rejected for development, or were under development at the time of testing. RPAT-II used three streamflow augmentation pond site evaluation subcriteria (i.e. well density, stream depletion factor, and soil type) for which sufficient data was available for site evaluation and sufficient knowledge was acquired to develop rule knowledge bases, as shown in Table V-1.

To create the pool of possible test sites, the locations of existing recharge pond sites was identified from a SEO database of augmentation plans for Sedgwick County, Colorado. Location data was provided by local experts for additional sites that had been rejected or were under development, and were not yet in the SEO database. RPAT-II has been programmed to require only site location data as the user input, and to extract all data necessary for site evaluations from the spatial database.

There were a total of 33 operational and permitted sites available in the SEO database for Sedgwick County. Five of these sites, however, were representative locations for stream augmentation through ditch seepage, rather than through recharge ponds. In these cases, ditch companies run water through unlined ditches during periods when the water is not being used for irrigation, and the water is allowed to seep into the aquifer for stream augmentation. The ditch companies are assigned recharge credits by reach of ditch, so that a ditch that is 3 reaches long would be assigned three separate permits by the SEO. Because RPAT-II was designed to consider only point data, these ditch recharge permits were not included in the analysis of Sedgwick County recharge sites. Consequently, there was data available from the SEO database for 28 existing recharge pond sites to be used for testing.

In addition to the 28 existing sites from the SEO database (not including the representative sites decreed under ditch seepage augmentation plans), site location information was identified by local experts for 5 rejected sites and 1 site under development, for a total pool of 34 possible test sites. Analyses using the KBS demonstration application (RPAT-II) were performed on all 34 sites (assigned site identification letters "A" through "II"), producing overall site assessments as well as individual criterion assessments and raw criterion data for each site.

To select the test sites for a cross-sectional system validation, O'Keefe et al. (1987) recommend that "test cases should be randomly selected using stratified testing; that is, randomly selected within each identifiable result type" (p. 83). O'Keefe et al. (1987) recognize, however, that the stratified approach is limited in its ability to handle cases producing infrequent results and, therefore, they recommend that "a small number of obscure or complex cases" be included (p. 83). They state that, with a limited number of test cases available, the issue in KBS validation is "not the *number* of test cases, [but] the *coverage* of test cases – that is, how well they reflect the input domain" (O'Keefe et al. 1987, p. 83).

A matrix (shown as Table V-2) was developed showing the site characteristic attributes for all three criterion evaluations (i.e., stream depletion factor in days, soil type by grain size, and number of wells within a ½-mile radius) for all 34 possible test sites. Of the 34 possible test sites for which data was available, 9 sites were selected for evaluation by a panel of local experts, as indicated in the shaded boxed in Table V-2 and listed separately in Table V-3, along with the initial site elevation "grades" for each site using the rule base shown in Table V-1. The 9 test sites, profiled in Appendix D, were selected to support a stratified testing approach, with several sites selected with the more commonly found combinations of site characteristics (e.g. Sites R, W, HH), as well as more complex test sites (e.g. Sites C, F, and II) which had very high attribute values for two out of the three site characteristics considered in the MCDA, but a very low value for the third site attribute. These more complex sites were included to assess the sensitivity of the local experts' site evaluations to cases involving an extreme value for just one of the site attributes.

A questionnaire was developed in which information was provided on site attributes for each of the 9 test sites, with the site identities concealed to prevent bias by the panel of local experts participating in the testing. The participants were asked to provide their analysis of each site on the basis of the site data provided, using letter "grades" in place of the KBS scaled values because of the common usage of this ranking system in American schools and general familiarity with this ranking system among the participants (i.e. A= excellent; B=good; C=fair; D=poor). In Part I of the questionnaire, the experts were asked to provide a whole letter "grade" for each of the three criteria. Using their own weighting scale, participants were asked to assign an overall rating for that test site, with plus and minus grades allowed for the overall site "grade." In Part II of this questionnaire, the testers were asked to specify their own scaling functions for each criterion, including the threshold values for each of the four grades in the scale, and their own set of weights for the three criteria to use in a weighted average calculation of an overall site grade.

Local experts were contacted regarding participation in a questionnaire survey to test the demonstration KBS. The questionnaire was sent to each of the participants separately, and the tests were completed individually. The three local experts who completed the demonstration KBS test questionnaire are profiled below:

- *Tester A* is a manager for a large ditch company, and works mainly with agricultural water users. Tester A is also one of the developers of Site HH, which is currently being developed cooperatively by Tester A's ditch company and a habitat organization. Tester A was not involved in the development of the domain and rule knowledge bases.
- *Tester B* is a water resources engineer for a regional water conservancy district and works with water users throughout the Lower South Platte basin. Tester B also served as the "key expert" for the development of the initial domain and rule knowledge bases.

- *Tester C* is a city manager for a rural municipality, and is responsible for providing water supplies to town residents and businesses. Tester C was directly involved in the development and ongoing management of operational Site D. Tester C was not involved in the development of the domain and rule knowledge bases.

Upon receipt of the completed questionnaires, the expert responses for each test site were compared with that tester's scales and weights for each of the three criteria to determine whether the tester was grading the sites consistently with their own MCDA. For the qualitative analysis, a presentation was given at a SPLRG meeting, which was attended by all three testers, in which the RPAT-II grades and site identities for each site were revealed. The testers, as well as the other local experts in SPLRG who did not participate in the KBS testing, were asked to comment upon the results of each site, and to identify any errors in the raw site data or missing evaluation procedures (e.g. site-specific considerations not included among the three site criteria).

Anticipated Errors

Specific errors anticipated and reviewed during the SPLRG presentation are discussed below. Anticipated errors included database errors (e.g. missing or incorrect data), which were identified during this SPLRG meeting. The testing protocol was designed to determine the nature of the errors in the demonstration application and what steps would be needed to correct those errors if a fully operational model were to be developed. Several anticipated errors were identified prior to performing the system evaluation testing, including the following:

1. **Incorrect databases**: Data incorporated into the domain knowledge base was taken from multiple sources. Those sources, in turn, obtained data from other sources. For example, the recharge pond location coverage was created from databases provided by the State Engineer's Office, which developed their databases from reports provided by water users. There were several opportunities for location data to be mis-reported or keyed incorrectly into the computer database.

2. **Insufficient resolution of data**: An example of insufficient resolution of data is the use of Public Land Survey System (PLSS) coordinates to identify the location of wells or recharge ponds. A site identified by a PLSS coordinate that includes a township, range, section, and quarter-quarter identification (i.e. one quarter of one quarter of a section) will be shown in an ArcView GIS tool as being located in the center of that quarter-quarter region, which covers an area of roughly 40 acres. The site location may, in fact, be located anywhere within that quarter-quarter polygon, possibly resulting in an incorrect surface soil identification or other data assigned to that point.

3. **Incorrect criteria**: An error of incorrect criteria would mean that the criteria identified during knowledge acquisition do not accurately reflect the criteria considered by local experts in their site evaluations.

4. **Insufficient criteria**: An error of insufficient criteria would means that the criteria available within the MCDA are not sufficient to determine the feasibility of developing a recharge pond for stream augmentation at a site. Because there were additional potential criteria identified by the local experts

which could not be included in the MCDA due to lack of available data in an appropriate format, this error was anticipated to occur.

5. **Incorrect measurement scales**: An error of incorrect measurement scales would mean that the values of "excellent, good, fair, and poor" did not use the correct threshold values as those that would be used by the local experts in their evaluation of sites.

6. **Incorrect weights**: An error of incorrect weights would means that the weights did not accurately reflect the extent to which local experts considered each criterion to impact the overall site assessment.

Error types 1 and 2 from this list were considered as part of the database evaluation, which considered the quality of the sources of data inputs as part of the system evaluation testing, discussed in the testing results. Error types 3-6 from this list were considered part of the overall system evaluation, which included consideration of the rule base and reasoning engine developed for this demonstration application. In most cases, corrections for all 6 error types would need to be addressed in future work, separate from the current research, such as corrections to or additions of new databases, additional rules, or additional research for improved understanding of the site evaluation process. All 6 error types were reviewed during the SPLRG presentation and feedback session with local experts.

Analysis of Testing Results

The overall site evaluations for RPAT-II and for each of the three tester's results were charted, ranked, and compared to see whether the ranking orders were consistent, even if the actual grade assigned differed among the testers. In cases where the site rankings or overall grades differed between RPAT-II and the testers' results, the testers' scaling and weighting functions were checked to determine whether the differences in the scaling and weighting functions were consistent with the differences in the overall site scores and ranks. For example, if two testers used similar criterion weights, but the threshold values used by one tester were consistently higher than the threshold values used by the other tester, then the final ranking of sites should remain the same, even though the tester using higher threshold values would likely assign consistently lower grades.

In lieu of a formal sensitivity analysis, the demonstration application was tested with the results re-calculated using the scaling or weighting functions suggested by the testers. In addition, the demonstration application was tested by changing the weights to zero for each criterion individually, with the effect of removing that criterion from consideration for the MCDA.

V.D. Major Findings from System Evaluation

Table V-4 shows the results from the questionnaire responses. Table V-5 shows the scaling and weighting schemes provided by the 3 testers. Figures V-13, V-14, and V-15 compare the scaling functions for soil type, stream depletion function, and well density, respectively, for the three testers and the prototype. Figures V-16 and V-17 illustrate the site grades and rankings from the local expert testing. Table V-6 shows the order of the overall grades for each of the testers and for the prototype. Table V-7 shows the results of the sensitivity analysis with each of the three subcriteria removed from the site evaluations, and Table V-8 shows the results of the site rankings with the sensitivity analysis. Major findings from the system evaluation are summarized below:

1) *KBS Validation/Verification.* KBS verification includes review of the domain and rule knowledge bases. Local experts reviewed the knowledge bases and confirmed that the comprehensive list of criteria identified during knowledge acquisition was an accurate portrayal of the considerations for potential recharge sites for stream augmentation, acknowledged the limitations of the data available to support economic criteria analyses, and recognized that the physical site characteristic criteria selected for inclusion in the demonstration application could be used to support limited site evaluations.

2) *KBS Validation/Substantiation.* KBS substantiation includes review of the computer programming and the databases and review of the structural development of the rules and reasoning engine. The rule composition and organization within the reasoning engine was reviewed to ensure consistency and completeness (Ignizio 1991) and no rules were found to be redundant, conflicting, subsumed, unnecessary, nor circular. There were some completeness issues identified in that there were some gaps in the data, so that no value was available for the evaluation of criteria in some locations within the target region, although these sites would not be considered under the exclusionary screening assumption for an MCDA. Errors in the ArcView and Excel portions of the computer programming code were corrected prior to testing. Review of

the database occurred throughout the KBS development process, and additional database errors were identified during KBS testing, as discussed below.

2) *KBS Testing Goals and Approach.* The demonstration KBS was evaluated with the primary goals of testing the claim that the demonstration application KBS captures the expertise of the local experts on the evaluation of potential recharge sites for stream augmentation. The development of this KBS was intended, in part, to create a better understanding of this site evaluation process and the needs for additional databases and future research in areas where knowledge is lacking and processes are poorly understood. Testing of the competence of the local experts through independent, empirical evaluations of the quality of recharge sites for stream augmentation was not a goal of this research, and no field investigations or other site evaluations beyond those developed for the demonstration application were used to determine whether the experts were "correct" in their approach to site evaluations. Because this KBS was also designed to minimize user inputs by performing evaluations based primarily on inputs from the available spatial databases, the demonstration KBS is recognized as not providing a comprehensive evaluation of the physical, legal, and economic factors considered in site evaluation. By making the site evaluation approach used by local experts transparent through knowledge capture, however, the foundation has been laid for the future development of more scientifically-tested site evaluation approaches.

Within the limitations placed upon the development of this KBS, the creation of credible solutions was also tested through the use of data from real sites in the demonstration KBS testing. For this testing scheme, the KBS and a panel of experts were separately given the same raw site data for real sites within the target region. Bias was controlled through the removal of identifying information about the sites. A scenario analysis was developed to test the RPAT demonstration application, using data from recharge sites that had been developed, rejected for development, or were under development at the time of testing, using Colorado State Engineer's Office (SEO) data for sites from decreed augmentation plans, or data from local experts for undecreed sites. Nine sites were selected for testing using a stratified approach to include both representative sites from the more commonly produced results and more complex or obscure sites to "reflect the input domain" (O'Keefe et al. 1987, p. 83). Three local experts completed evaluations of the nine test sites, and also provided their own scaling and weighting schemes for the evaluations of sites. The three testers included a manager for a large ditch company, a water resources engineer for a regional water conservancy district, and a city manager.

3) *Anticipated Errors.* Anticipated errors included incorrect databases, insufficient resolution of data, incorrect criteria, insufficient criteria, incorrect measurement scales, and incorrect weights.

4) *Database Errors Identified.* For the 6 test sites that were operational and decreed sites, the site locations were determined using the Public Land Survey System (PLSS) designations from the SEO database for decreed pond sites for stream augmentation plans. Four of the six sites had incorrect PLSS designations. These database errors indicate that the database development for recharge sites requires greater quality control if the site locations are to be used for computerized modeling and analysis of specific sites or regional analysis of recharge activities in the target region. As stated earlier, however, these errors do not negate the value of this testing to determine whether

the system can approximate the evaluative approach taken by local experts for sites for which the same raw data is provided.

5) *Tester Responses for Well Density and Soil Type.* The site evaluation results for the demonstration application and the three testers are provided in Table V-4, and the scaling and weighting functions for the demonstration application and three testers are provided in Table V-5. Tester B, who participated in the development of the demonstration application knowledge base and scaling functions, had the most similar scaling functions to that used in the demonstration application, although there were some slight differences in the threshold values used for the SDF values and well density grades, and grades assigned to soil types. The three testers varied very little in their scaling functions for the soil type criterion. For the Well Density criterion (i.e. the number of wells within a ½-mile radius of the pond site, as an indication of aquifer suitability), RPAT, Tester A, and Tester B had nearly identical scaling functions, but Tester C assigned much higher threshold values for each grade in his scaling function.

6) *Tester Responses for Stream Depletion Function (SDF) Values.* While soil type and well density are important criteria for determining the viability of the development of recharge ponds at a site, and the costs to develop the pond sites, SDF values are tied to the options for operations of the recharge ponds. The scaling functions developed by the testers varied the most in the decisions regarding the SDF values, because each of the testers had a different perspective on how the recharge credits developed by selected ponds would be used. Tester A had the only SDF Value Scaling Function for which the longer term values (more than a year) were not given the highest grade. This difference in SDF range preferences was explained during the SPLRG

meeting by the fact that agricultural users (such as Tester A, who works with an irrigation district) prefer to focus their water planning on ensuring sufficient water for the next irrigation season. With a 6-8 month timing on recharge credits, an agricultural water user will be able to fill the pond during the fall and winter (time periods when there is typically lower water demands and higher water availability), and will be able to determine how much recharge credits he or she will have for the following irrigation season. Because the amount of water available from irrigation wells depends upon the amount of recharge credits created during irrigation season, this planning horizon will enable the agricultural water user to estimate how much water he or she will legally be able to use during the irrigation season (assuming drought does not further limit that water availability), and thus decide which crops to plant and how much land to irrigate. Longer term recharge ponds (i.e. ponds with SDF values greater than one year) are also valuable and provide recharge credits to support agricultural users through multi-year droughts, but these ponds are less preferred ("B" grade) for agricultural users than ponds that produce water for the next irrigation season. As a water engineer with a major regional water conservancy district, Tester B preferred longer term recharge ponds over shorter term recharge ponds, to help ensure water supplies over multi-year droughts. However, because Tester B also has been involved in the development of and accounting for augmentation plans for agricultural water users and in accounting for exchanges of recharge credits between water users, he has also been active in encouraging the development of a greater number of recharge ponds throughout the Lower South Platte, with a range of SDF values and operational schemes to meet a variety of recharge credit needs. Tester C, who is a town manager for a municipality in a rural region, set very high threshold values for all four grades on his rating scale for SDF values, explaining that, as a municipal water supplier, his priority was to ensure water supplies for his service area every year, regardless of hydrologic conditions, including during periods of multi-year droughts. While SDF values indicate the time during which a large percentage (28%) of the recharged water reaches the stream, there continues to be recharge credits accruing from a pond for years after the number of days indicated by the SDF value. Thus, longer-term recharge ponds provide the greatest insurance for a municipality that it will be possible to operate wells to supply its service area during droughts.

8) *Tester Responses for Weighting Schemes.* As shown in Table V-5, the testers also varied in the weighting mechanisms they used to determine an overall site evaluation score on the basis of the criterion scores for the three criteria. Tester C, like the demonstration application, assigned equal weight to all three criteria. Tester B assigned a slightly higher weight to soil type, but assigned equal weights to SDF values and well density. Tester B indicated on his questionnaire response, however, that very low SDF values (less than 6 weeks) were less desirable, and reflected that preference in his scaling function for SDF values. Tester A gave highest weight to soil type, followed by SDF value, with the lowest weight assigned to well density.

9) *General Feedback by Local Experts*

The feedback provided by the local experts was very positive. The model was found to have captured some of the considerations used by local experts to evaluate a potential recharge site on the basis of certain physical parameters, i.e. the availability of a suitable aquifer, the ability to recharge the aquifer through the surface soils, and the suitability of the stream depletion factor. One concern raised by the local experts was that the use of PLSS coordinates did not place the recharge sites in the correct location, or the PLSS coordinates were wrong. In at least two cases, the PLSS coordinate from the SEO database was incorrect, so that the site was in the wrong place, and the site data was provided for the wrong location. Another concern raised by the local experts regarding the model was the lack of cost considerations. A cost estimate knowledge base has been developed, but had not been incorporated into RPAT-II because of the required data could not be derived from existing databases and would require extensive user inputs on the anticipated design of the proposed recharge pond. The cost estimate knowledge base has been incorporated into a comprehensive demonstration KBS. The local experts also suggested that potential recharge sites could be identified using high resolution topographic maps, and that sites could be eliminated if coverages showing buildings and other structures were available. These coverages are not currently available for the revised target region (Sedgwick County, CO). However, the State of Colorado is beginning the development of a data-intensive model called the South Platte Decision Support System, and the water users will be able to provide input to the State of Colorado on data needs to support water management in the region.

10) *Comparison of Ranking Orders between RPAT and Testers.* As shown in Table V-6 and Figure V-16, while RPAT typically gave higher grades to each site than the three testers, *the order of the site grades was similar for all testers, with few exceptions.* As shown in Figure V-17 and Table V-6, *the ranking order for the 9 sites was nearly identical for RPAT and the three testers.* RPAT gave generally higher grades than all three testers, probably due to the difference in threshold values for the three criteria. As shown in Table V-6, ranking order was consistent for most sites, with Site D

always ranked first or second in the site rankings; Site W always ranked near the top of the rankings; and Sites C, F, L, and FF always near the bottom of the site rankings. The inconsistencies for Tester B's responses have been addressed earlier in this chapter. Tester C, as shown in Table V-6, has an unusually high ranking for Site II in comparison with his other sites and, in fact, noted on his questionnaire response that this was a "good site." While Site II has a soil type that was recognized by all of the testers as relatively poor (loam), the SDF value (651 days) and well density (12 wells within a ½-mile radius) were among the highest of all 34 sites for which data was available within the target region. Because Tester C had high threshold values for his SDF values and well density scaling functions, this site received a relatively high grade and ranking from Tester C.

11) *Tester B Responses.* Tester B's site rankings were the least consistent with the rankings determined by RPAT and the other testers, with Site F given a particularly low overall grade, and sites R and HH given particularly high overall grades. In the case of Site F, he gave this site an overall grade of "D" despite the fact that, using his own scaling and weighting functions, this site would have received a C+. In his questionnaire response, he noted that this site was too close to the river, with an SDF value of only 21 days, which apparently overrode the weighting functions normally used by this tester. In the case of Site R, the difference in grade given by Tester B can be tied to the site's SDF value of 132 days. Tester B was the only tester (including RPAT) to assign an "A" grade to this site for SDF value. He noted on his questionnaire response that this site could be used for spring recharge, and that, during years when "lots of water" is available, sites with an SDF value greater than 120 days are preferred, but

during drought years, the lower threshold for “A” grade SDF values should be increased to 300 days.

In the case of site HH, Tester B assigned a grade of “A” for the SDF value and “A” for the well density, but assigned a grade of “C” for the soil type (loam). According to his scaling function, the SDF value for this site (115 days) would have been assigned a grade of “B.” Despite the fact that this tester recommended that a higher weight be given to soil type, and included a note in his questionnaire response that “heavy topsoil rules out a site,” he gave this site an overall site grade of “A.” If the tester’s scaling and weighting functions were used for this site, the overall site grade would have been C+. No explanation was given for this inconsistency.

12) *Comparison of Demonstration KBS with Tester Weighting Schemes.* Using the original RPAT scaling and weighting schemes, the criterion and overall site grades were determined for the 25 sites that had not been included in the previous testing, and compared with the results using the weighting schemes recommended by Testers A and B (Tester C used the identical weighting scheme to the RPAT demonstration application, with equal weights given to all three criteria). The overall site grades for the non-test sites using the weighting schemes from Testers A and B were very close to the grades produces by RPAT/Tester C, and the average of the 25 overall site grades were approximately a “B” grade in all cases. The difference between the overall site grade using the RPAT and tester weighting schemes was never greater than roughly 0.33, or one plus-or-minus grade, for Tester A, and never greater than 0.2 for Tester B.

13) *Comparison of Demonstration KBS with Tester Scaling Schemes.* Using the 25 sites that were not included in the original testing, the overall site evaluation

grades were determined using the scaling schemes from RPAT and each of the three testers. The overall site evaluation grades for Tester A were identical to those for RPAT for all but one of the 25 sites. The overall site evaluation grades using Tester B's scaling mechanism matched the RPAT grades in 16 out of the 25 sites and none of the unmatched site grades differed by more than 0.33, or one plus-or-minus grade. The Tester C scaling scheme produced the greatest difference in overall site evaluation grades from those produced using the RPAT scaling scheme, with only two of the 25 sites receiving the same overall site grade and grade differences as much as 1.67, or close to two whole letter grades. Tester C set scaling threshold values that were very different from those used in RPAT or by Testers A and B, and had particularly high threshold values for the SDF values and well densities, resulting in lower overall grades.

14) *Sensitivity Analysis.* Data was available for a total of 34 sites, of which 9 sites were used for the questionnaires for Testers A, B, and C. The remaining 25 sites were used to validate the results from RPAT using the scaling and weighting developed by the three testers. Using the original scaling and weighting mechanisms for RPAT on all 34 sites, sensitivity analysis was performed in which site evaluations were performed with all three criteria included, and then performed again on all 34 sites with each of criteria removed from evaluation one at a time. Table V-7 shows the results of the site analyses for each of the 34 total sites, with the 9 sites used for the questionnaire shown in shaded boxes. Table V-7 also shows the overall site score for each of the 34 sites with one of the criteria removed for each of the three criteria ("No SDF," "No Soil," or "No Well") and the difference in the overall site grade from the original grade. Table V-8 then shows the comparative ranking of each of the 34 sites, and the change in ranking

with each of the criteria removed from consideration one at a time. Sites evaluated with a criterion excluded which changed in ranking by more than 2 positions from the original ranking with all three criteria considered are shown in bold on Table V-8. A more detailed discussion of the sensitivity analysis is provided in Appendix F, along with additional tables and figures illustrating results of the sensitivity analysis.

While only 2 of the 34 sites changed ranking by more than two rank levels when the SDF value criterion was removed from consideration in calculating an overall site grade, 12 of the 34 sites showed ranking changes of more than two rank levels when the well density criterion was removed, and half of all the sites (17 out of 34) showed ranking changes of more than two rank levels when the soil type criterion was removed. As shown in Table V-7, while there was only one site that received an overall site grade of 4.00 (a "perfect" score) when all three grades were considered, 12 sites received this score and first place ranking when only the SDF value and well density were considered (no soil criterion), including 3 of the 5 of the sites that had been rejected by local experts in actual site evaluations (i.e. Sites EE, FF, and II). This suggests that the overall site grade, using the original RPAT scaling and weighting functions, is most sensitive to the soil type criterion grade. This sensitivity would be even more evident with the weighting schemes recommended by Testers A and B, both of whom recommended a higher weight assignment for soil type.

Figure V-1. Comprehensive Pond Site Assessment Model (WAPSAM)

Main Page with Instructions (Excel)

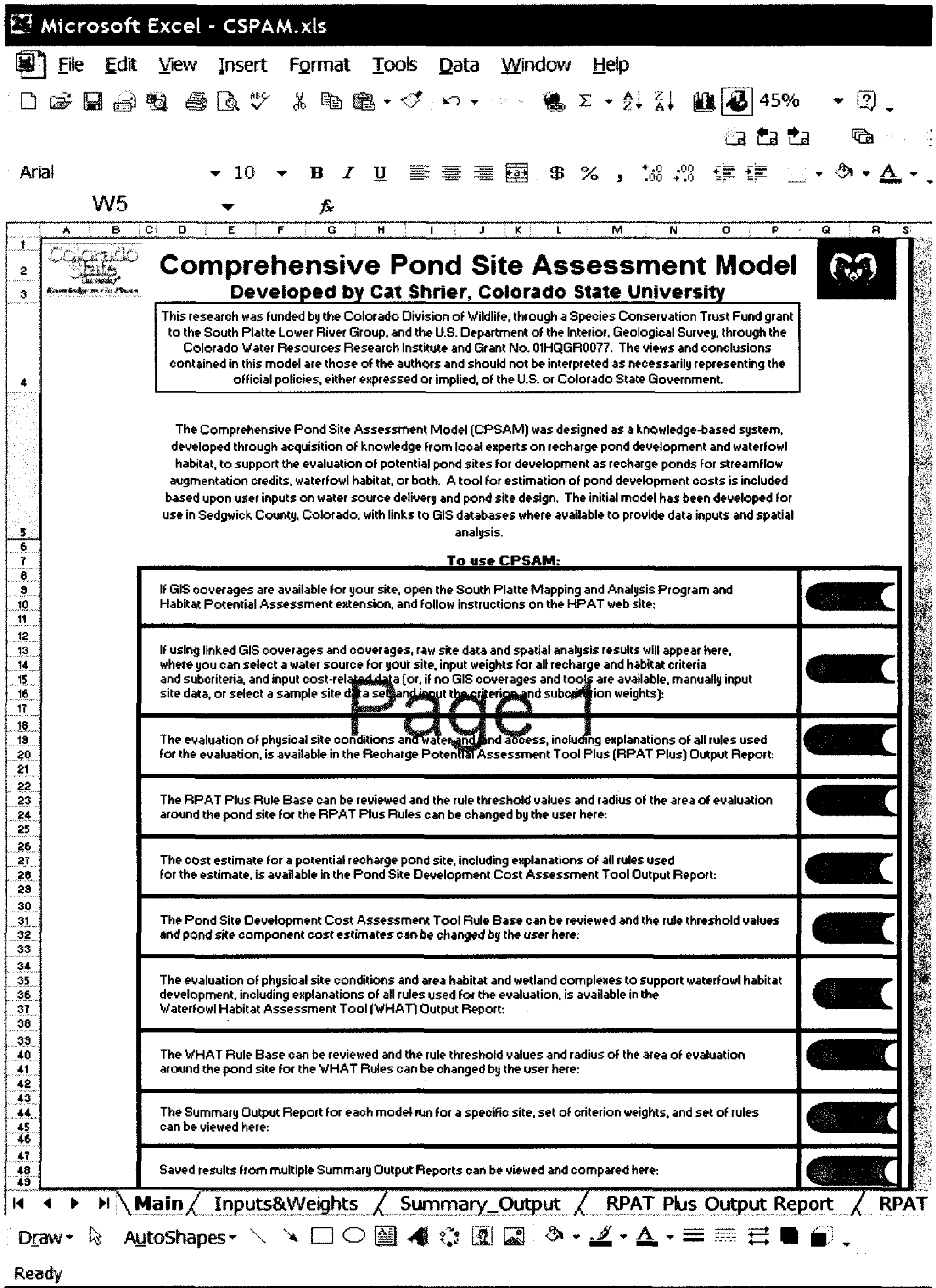
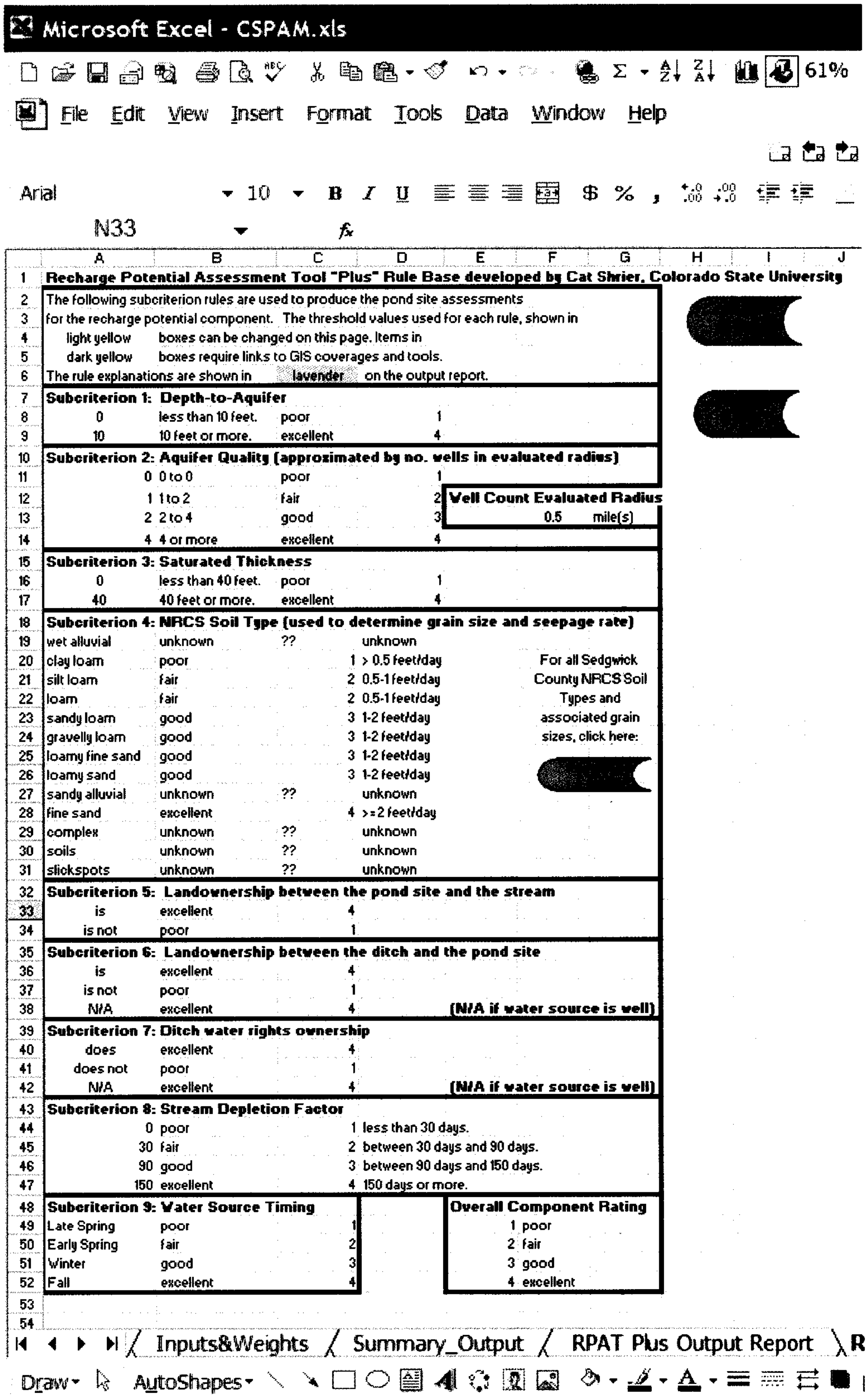


Figure V-2. RPAT Rule Base



	A	B	C	D	E	F	G
1	Recharge Potential Assessment Tool "Plus" Rule Base developed by Cat Shrier, Colorado State University						
2	The following subcriterion rules are used to produce the pond site assessments						
3	for the recharge potential component. The threshold values used for each rule, shown in						
4	light yellow	boxes can be changed on this page. Items in					
5	dark yellow	boxes require links to GIS coverages and tools.					
6	The rule explanations are shown in		lavender	on the output report.			
7	**Subcriterion 1: Depth-to-Aquifer**						
8	0	less than 10 feet.	poor	1			
9	10	10 feet or more.	excellent	4			
10	**Subcriterion 2: Aquifer Quality (approximated by no. wells in evaluated radius)**						
11	0	0 to 0	poor	1			
12	1	1 to 2	fair	2	**Well Count Evaluated Radius**		
13	2	2 to 4	good	3	0.5	mile(s)	
14	4	4 or more	excellent	4			
15	**Subcriterion 3: Saturated Thickness**						
16	0	less than 40 feet.	poor	1			
17	40	40 feet or more.	excellent	4			
18	**Subcriterion 4: NRCS Soil Type (used to determine grain size and seepage rate)**						
19	wet alluvial	unknown	??	unknown			
20	clay loam	poor	1	> 0.5 feet/day		For all Sedgwick	
21	silt loam	fair	2	0.5-1 feet/day		County NRCS Soil	
22	loam	fair	2	0.5-1 feet/day		Types and	
23	sandy loam	good	3	1-2 feet/day		associated grain	
24	gravelly loam	good	3	1-2 feet/day		sizes, click here:	
25	loamy fine sand	good	3	1-2 feet/day			
26	loamy sand	good	3	1-2 feet/day			
27	sandy alluvial	unknown	??	unknown			
28	fine sand	excellent	4	>=2 feet/day			
29	complex	unknown	??	unknown			
30	soils	unknown	??	unknown			
31	slickspots	unknown	??	unknown			
32	**Subcriterion 5: Landownership between the pond site and the stream**						
33	is	excellent	4				
34	is not	poor	1				
35	**Subcriterion 6: Landownership between the ditch and the pond site**						
36	is	excellent	4				
37	is not	poor	1				
38	N/A	excellent	4		**(N/A if water source is well)**		
39	**Subcriterion 7: Ditch water rights ownership**						
40	does	excellent	4				
41	does not	poor	1				
42	N/A	excellent	4		**(N/A if water source is well)**		
43	**Subcriterion 8: Stream Depletion Factor**						
44	0	poor	1	less than 30 days.			
45	30	fair	2	between 30 days and 90 days.			
46	90	good	3	between 90 days and 150 days.			
47	150	excellent	4	150 days or more.			
48	**Subcriterion 9: Water Source Timing**				**Overall Component Rating**		
49	Late Spring	poor	1			1 poor	
50	Early Spring	fair	2			2 fair	
51	Winter	good	3			3 good	
52	Fall	excellent	4			4 excellent	
53							
54							

Figure V-3. CAT Rule Base

Microsoft Excel - CSPAM.xls

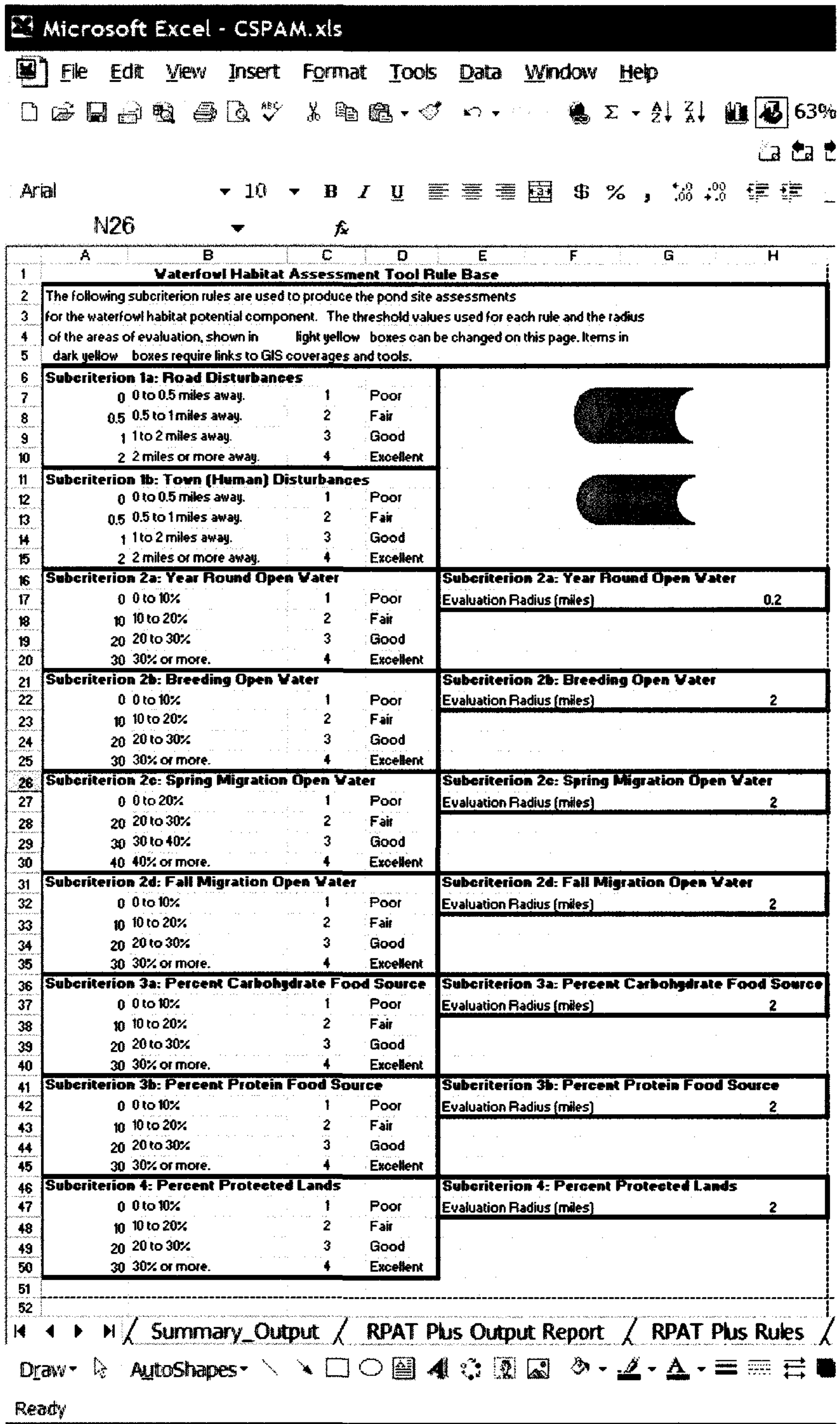
Pond Site Development Cost Assessment Tool Rule Base

The following subcriterion rules (item cost estimates) are used to produce the pond site assessments for cost estimate component. The threshold values used for each rule, shown in light yellow boxes can be changed on this page.
The rule explanations are shown in lavender on the output report.

Subcriterion 1: Headgate Costs			
is	2000		
is not	0		
Subcriterion 2: Flume/Recorder Costs			
is	3000		
is not	0		
Subcriterion 3: Lift Station/Headgate/Flume Recorder Costs			
is	10000		
is not	0		
Subcriterion 4: Well Installation			
is	25000		
is not	0		
Subcriterion 5: Pipe Installation (cost per linear foot)			
Low	5		
Medium	7.5		
High	10		
Subcriterion 6a: Pond Excavation (with clay lens)			
Low	1000		
Medium	1250		
High	1500		
Subcriterion 6b: Pond Excavation (without clay lens)			
Low	200		
Medium	350		
High	500		
Total Pond Site Development Cost Estimate Rating			
$0	less than $15000	excellent	4
$15,000	between $15000 and $25000	good	3
$25,000	between $25000 and $35000	fair	2
$35,000	more than $35000	poor	1

Inputs&Weights / Summary_Output / RPAT Plus Output Report / RPAT Plus Rules / Sedgwick Soil Types / Cost

Figure V-4. WHAT Rule Base



Microsoft Excel - CSPAM.xls

File Edit View Insert Format Tools Data Window Help

Arial 10 N26

	A	B	C	D	E	H
1	Waterfowl Habitat Assessment Tool Rule Base					
2	The following subcriterion rules are used to produce the pond site assessments					
3	for the waterfowl habitat potential component. The threshold values used for each rule and the radius					
4	of the areas of evaluation, shown in light yellow boxes can be changed on this page. Items in					
5	dark yellow boxes require links to GIS coverages and tools.					
6	Subcriterion 1a: Road Disturbances					
7	0	0 to 0.5 miles away.	1	Poor		
8	0.5	0.5 to 1 miles away.	2	Fair		
9	1	1 to 2 miles away.	3	Good		
10	2	2 miles or more away.	4	Excellent		
11	Subcriterion 1b: Town (Human) Disturbances					
12	0	0 to 0.5 miles away.	1	Poor		
13	0.5	0.5 to 1 miles away.	2	Fair		
14	1	1 to 2 miles away.	3	Good		
15	2	2 miles or more away.	4	Excellent		
16	Subcriterion 2a: Year Round Open Water				Subcriterion 2a: Year Round Open Water	
17	0	0 to 10%	1	Poor	Evaluation Radius (miles)	0.2
18	10	10 to 20%	2	Fair		
19	20	20 to 30%	3	Good		
20	30	30% or more.	4	Excellent		
21	Subcriterion 2b: Breeding Open Water				Subcriterion 2b: Breeding Open Water	
22	0	0 to 10%	1	Poor	Evaluation Radius (miles)	2
23	10	10 to 20%	2	Fair		
24	20	20 to 30%	3	Good		
25	30	30% or more.	4	Excellent		
26	Subcriterion 2c: Spring Migration Open Water				Subcriterion 2c: Spring Migration Open Water	
27	0	0 to 20%	1	Poor	Evaluation Radius (miles)	2
28	20	20 to 30%	2	Fair		
29	30	30 to 40%	3	Good		
30	40	40% or more.	4	Excellent		
31	Subcriterion 2d: Fall Migration Open Water				Subcriterion 2d: Fall Migration Open Water	
32	0	0 to 10%	1	Poor	Evaluation Radius (miles)	2
33	10	10 to 20%	2	Fair		
34	20	20 to 30%	3	Good		
35	30	30% or more.	4	Excellent		
36	Subcriterion 3a: Percent Carbohydrate Food Source				Subcriterion 3a: Percent Carbohydrate Food Source	
37	0	0 to 10%	1	Poor	Evaluation Radius (miles)	2
38	10	10 to 20%	2	Fair		
39	20	20 to 30%	3	Good		
40	30	30% or more.	4	Excellent		
41	Subcriterion 3b: Percent Protein Food Source				Subcriterion 3b: Percent Protein Food Source	
42	0	0 to 10%	1	Poor	Evaluation Radius (miles)	2
43	10	10 to 20%	2	Fair		
44	20	20 to 30%	3	Good		
45	30	30% or more.	4	Excellent		
46	Subcriterion 4: Percent Protected Lands				Subcriterion 4: Percent Protected Lands	
47	0	0 to 10%	1	Poor	Evaluation Radius (miles)	2
48	10	10 to 20%	2	Fair		
49	20	20 to 30%	3	Good		
50	30	30% or more.	4	Excellent		
51						
52						

Summary_Output / RPAT Plus Output Report / RPAT Plus Rules

Draw AutoShapes

Ready

Figure V-5. RPAT Output Report

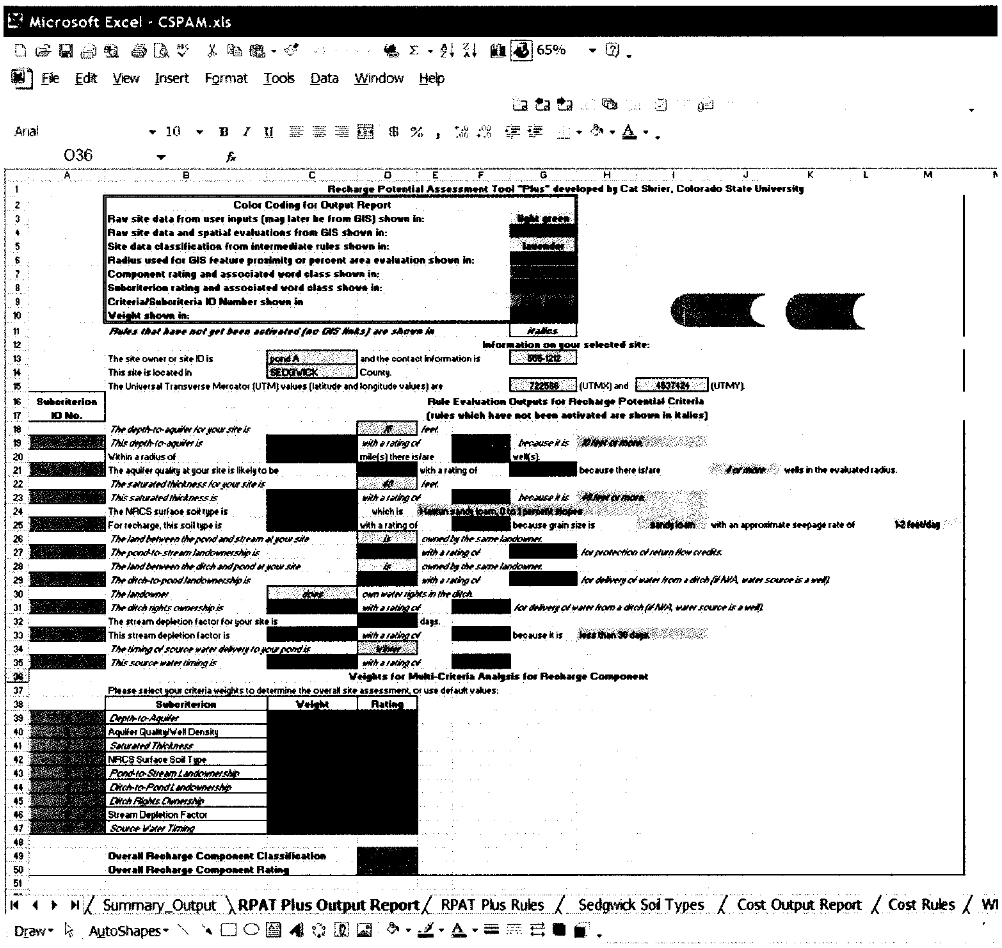
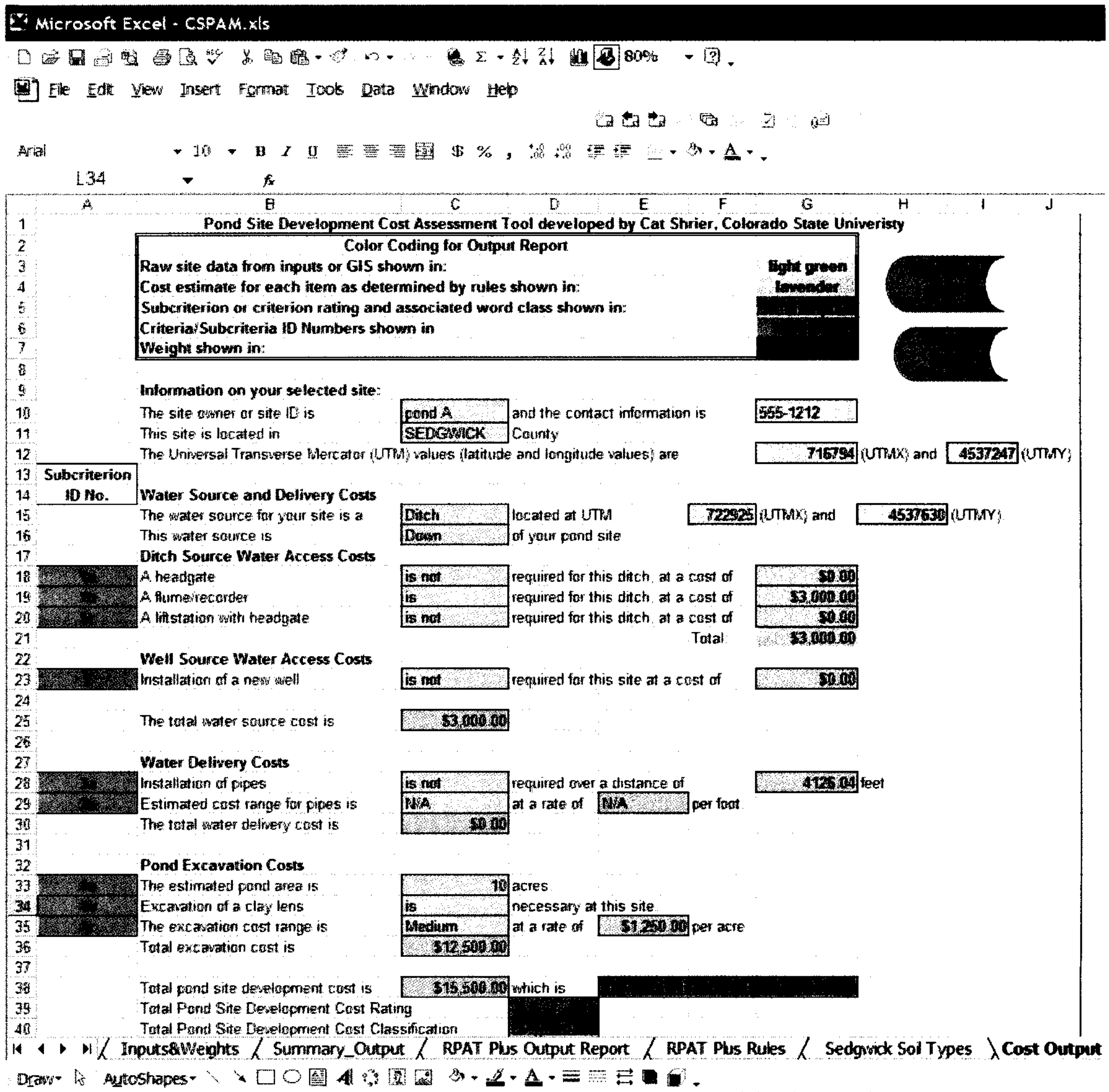


Figure V-6. CAT Output Report



Microsoft Excel - CSPAM.xls

File Edit View Insert Format Tools Data Window Help

Arial 10 | 80% | L34

Pond Site Development Cost Assessment Tool developed by Cat Shrier, Colorado State Univeristy

Color Coding for Output Report

Raw site data from inputs or GIS shown in: **light green**

Cost estimate for each item as determined by rules shown in: **lavendar**

Subcriterion or criterion rating and associated word class shown in:

Criteria/Subcriteria ID Numbers shown in

Weight shown in:

Information on your selected site:

The site owner or site ID is pond A and the contact information is 555-1212

This site is located in SEDGWICK County

The Universal Transverse Mercator (UTM) values (latitude and longitude values) are 716794 (UTMX) and 4537247 (UTMY)

Subcriterion ID No.

Water Source and Delivery Costs

The water source for your site is a Ditch located at UTM 722925 (UTMX) and 4537630 (UTMY)

This water source is Down of your pond site

Ditch Source Water Access Costs

A headgate is not required for this ditch, at a cost of $0.00

A flume/recorder is required for this ditch, at a cost of $3,000.00

A liftstation with headgate is not required for this ditch, at a cost of $0.00

Total $3,000.00

Well Source Water Access Costs

Installation of a new well is not required for this site at a cost of $0.00

The total water source cost is $3,000.00

Water Delivery Costs

Installation of pipes is not required over a distance of 4126.04 feet

Estimated cost range for pipes is N/A at a rate of N/A per foot

The total water delivery cost is $0.00

Pond Excavation Costs

The estimated pond area is 10 acres

Excavation of a clay lens is necessary at this site

The excavation cost range is Medium at a rate of $1,250.00 per acre

Total excavation cost is $12,500.00

Total pond site development cost is $15,500.00 which is

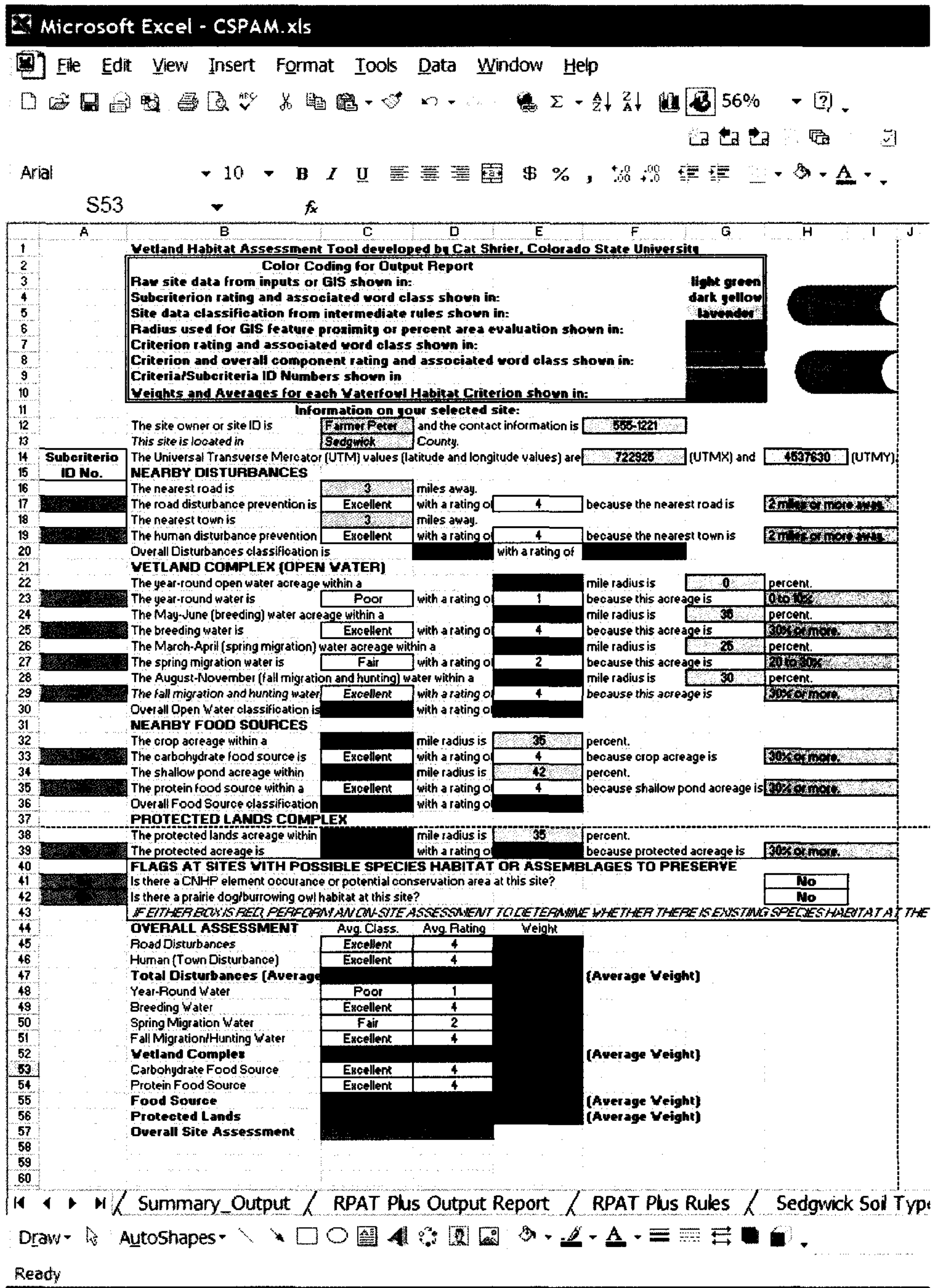
Total Pond Site Development Cost Rating

Total Pond Site Development Cost Classification

Inputs&Weights / Summary_Output / RPAT Plus Output Report / RPAT Plus Rules / Sedgwick Soil Types / Cost Output

Draw AutoShapes

Figure V-7. WHAT Output Report



Microsoft Excel - CSPAM.xls

	A	B	C	D	E	F	G	H
1		**Wetland Habitat Assessment Tool developed by Cat Shrier, Colorado State University**						
2		**Color Coding for Output Report**						
3		**Raw site data from inputs or GIS shown in:**					**light green**	
4		**Subcriterion rating and associated word class shown in:**					**dark yellow**	
5		**Site data classification from intermediate rules shown in:**					**lavender**	
6		**Radius used for GIS feature proximity or percent area evaluation shown in:**						
7		**Criterion rating and associated word class shown in:**						
8		**Criterion and overall component rating and associated word class shown in:**						
9		**Criteria/Subcriteria ID Numbers shown in**						
10		**Weights and Averages for each Waterfowl Habitat Criterion shown in:**						
11		**Information on your selected site:**						
12		The site owner or site ID is	Farmer Peter	and the contact information is		555-1221		
13		*This site is located in*	Sedgwick	*County.*				
14	**Subcriterio**	The Universal Transverse Mercator (UTM) values (latitude and longitude values) are				722925	(UTMX) and	4537630 (UTMY)
15	**ID No.**	**NEARBY DISTURBANCES**						
16		The nearest road is	3	miles away.				
17		The road disturbance prevention is	Excellent	with a rating of	4	because the nearest road is		2 miles or more away.
18		The nearest town is	3	miles away.				
19		The human disturbance prevention	Excellent	with a rating of	4	because the nearest town is		2 miles or more away.
20		Overall Disturbances classification is			with a rating of			
21		**WETLAND COMPLEX (OPEN WATER)**						
22		The year-round open water acreage within a				mile radius is	0	percent.
23		The year-round water is	Poor	with a rating of	1	because this acreage is		0 to 10%
24		The May-June (breeding) water acreage within a				mile radius is	38	percent.
25		The breeding water is	Excellent	with a rating of	4	because this acreage is		30% or more.
26		The March-April (spring migration) water acreage within a				mile radius is	26	percent.
27		The spring migration water is	Fair	with a rating of	2	because this acreage is		20 to 30%
28		The August-November (fall migration and hunting) water within a				mile radius is	30	percent.
29		*The fall migration and hunting water*	*Excellent*	*with a rating of*	4	*because this acreage is*		30% or more.
30		Overall Open Water classification is		with a rating of				
31		**NEARBY FOOD SOURCES**						
32		The crop acreage within a		mile radius is	35	percent.		
33		The carbohydrate food source is	Excellent	with a rating of	4	because crop acreage is		30% or more.
34		The shallow pond acreage within		mile radius is	42	percent.		
35		The protein food source within a	Excellent	with a rating of	4	because shallow pond acreage is		30% or more.
36		Overall Food Source classification		with a rating of				
37		**PROTECTED LANDS COMPLEX**						
38		The protected lands acreage within		mile radius is	35	percent.		
39		The protected acreage is		with a rating of		because protected acreage is		30% or more.
40		**FLAGS AT SITES WITH POSSIBLE SPECIES HABITAT OR ASSEMBLAGES TO PRESERVE**						
41		Is there a CNHP element occurance or potential conservation area at this site?						No
42		Is there a prairie dog/burrowing owl habitat at this site?						No
43		*IF EITHER BOX IS RED, PERFORM AN ON-SITE ASSESSMENT TO DETERMINE WHETHER THERE IS EXISTING SPECIES HABITAT AT THE*						
44		**OVERALL ASSESSMENT**	Avg. Class.	Avg. Rating	Weight			
45		*Road Disturbances*	Excellent	4				
46		Human (Town Disturbance)	Excellent	4				
47		**Total Disturbances (Average**				**(Average Weight)**		
48		Year-Round Water	Poor	1				
49		Breeding Water	Excellent	4				
50		Spring Migration Water	Fair	2				
51		Fall Migration/Hunting Water	Excellent	4				
52		**Wetland Complex**				**(Average Weight)**		
53		Carbohydrate Food Source	Excellent	4				
54		Protein Food Source	Excellent	4				
55		**Food Source**				**(Average Weight)**		
56		**Protected Lands**				**(Average Weight)**		
57		**Overall Site Assessment**						
58								
59								
60								

Summary_Output / RPAT Plus Output Report / RPAT Plus Rules / Sedgwick Soil Typ

Ready

Figure V-8

WAPSAM GIS Spatial Analysis Results (ArcView)

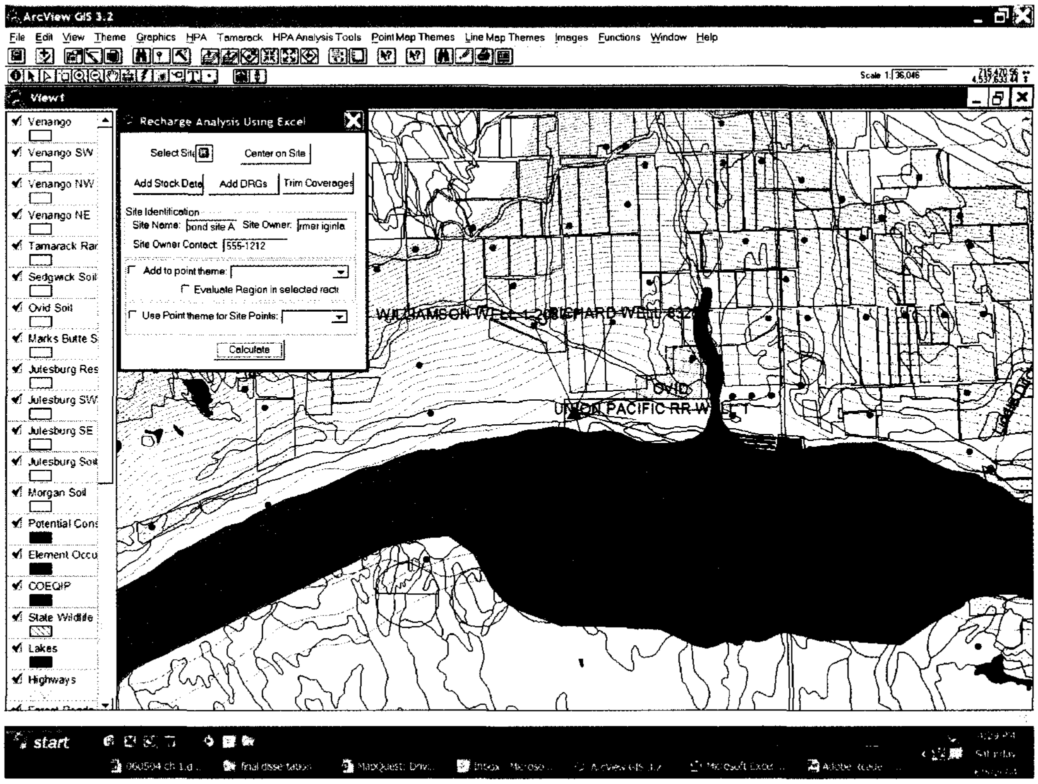


Figure V-9. WAPSAM "Inputs&Weights" Worksheet

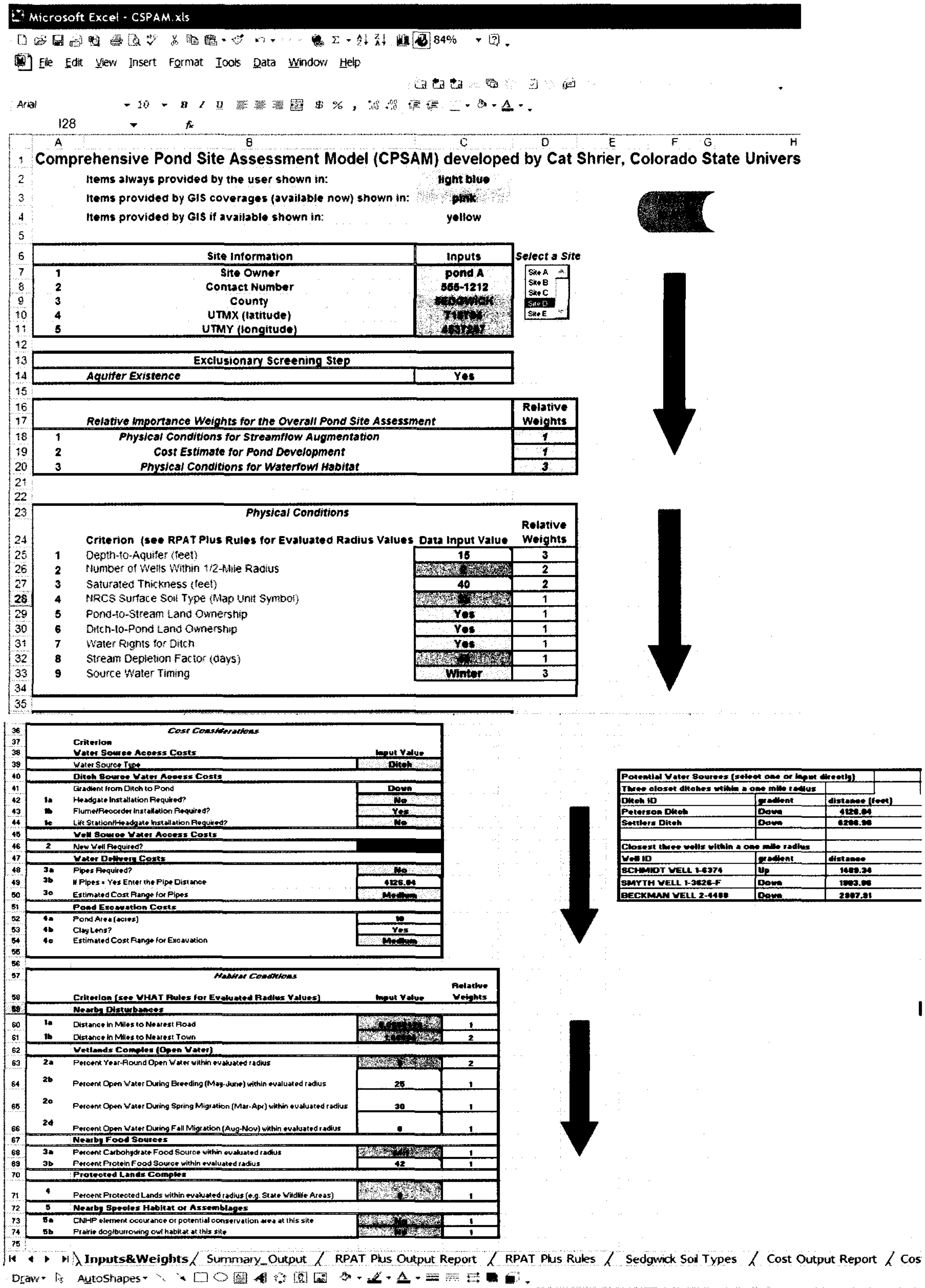


Figure V-10. WAPSAM Sample Site Data Worksheet

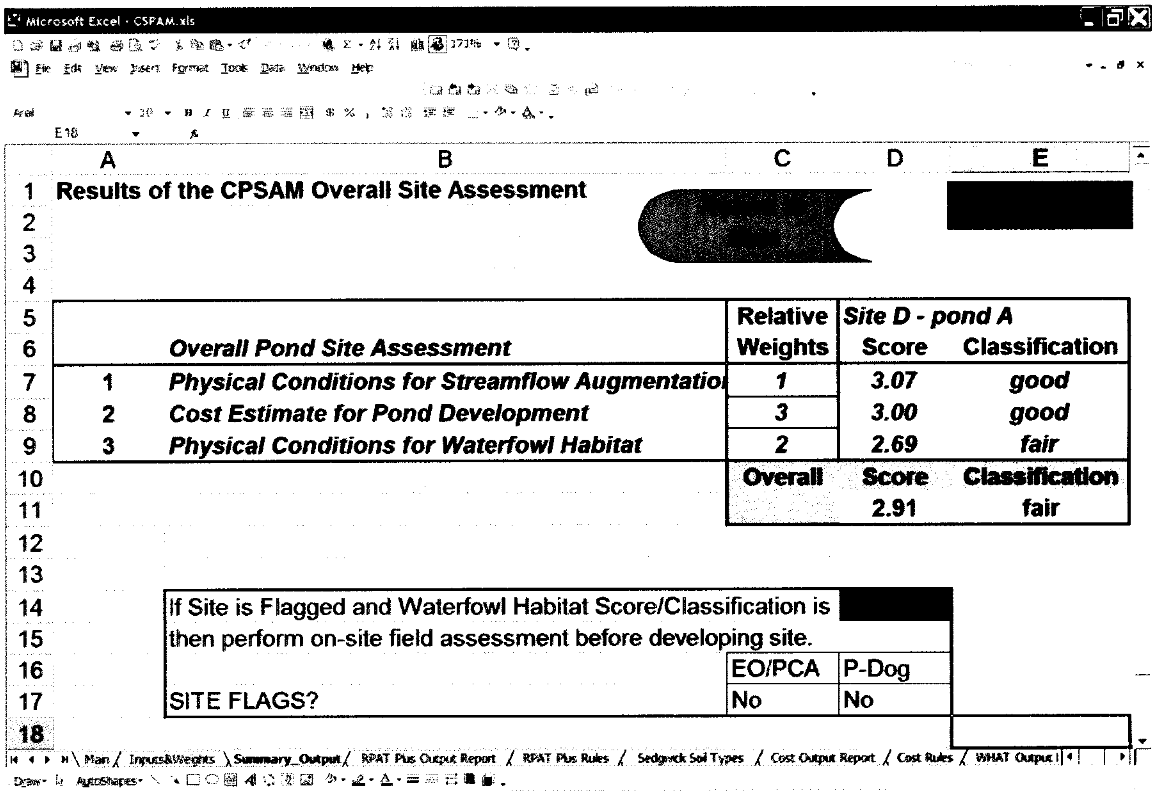
Microsoft Excel - CSPAM.xls

File Edit View Insert Format Tools Data Window Help

	A	B	C	D	E	F
3	**Site ID Information**	**Site A**	**Site B**	**Site C**	**Site D**	**Site E**
4	Site Owner	Farmer Joe	Farmer Alex	Farmer Milan	Farmer Peter	Farmer Rob
5	Contact Number	555-1219	555-1218	555-1223	555-1221	555-1204
6	County	Sedgwick	Sedgwick	Sedgwick	Sedgwick	Sedgwick
7	UTMX (latitude)	722925	722925	722925	722925	722925
8	UTMY (longitude)	4537630	4537630	4537630	4537630	4537630
9	**Criteria/Subcriteria**					
10	Aquifer Existence	Yes	Yes	Yes	Yes	Yes
11	Depth-to-Aquifer (feet)	5	5	15	15	15
12	Number of Wells Within 1/2-Mile Radius	1	2	3	4	5
13	Saturated Thickness (feet)	10	20	30	40	50
14	NRCS Surface Soil Type (Map Unit Symbol)	HzA	KgB	KtA	Ls	CpB
15	Pond-to-Stream Land Ownership	Yes	Yes	Yes	Yes	Yes
16	Ditch-to-Pond Land Ownership	Yes	Yes	Yes	Yes	Yes
17	Water Rights for Ditch	Yes	Yes	Yes	Yes	Yes
18	Stream Depletion Factor (days)	79	251	456	21	99
19	Source Water Timing	Late Spring	Late Spring	Late Spring	Winter	Late Spring
20	Water Source Type	Ditch	Well	Ditch	Ditch	Well
21	Gradient from Ditch to Pond	Upgradient	Upgradient	Upgradient	Downgradient	Downgradient
22	Headgate Installation Required?	Yes	Yes	Yes	No	Yes
23	Flume/Recorder Installation Required?	Yes	Yes	Yes	Yes	Yes
24	Lift Station/Headgate Installation Required?	Yes	Yes	Yes	No	Yes
25	New Well Required?	No	No	No	No	No
26	Pipes Required?	Yes	Yes	Yes	No	Yes
27	If Pipes = Yes Enter the Pipe Distance	50	50	50	50	50
28	Estimated Cost Range for Pipes	Medium	Medium	Medium	Medium	Medium
29	Pond Area (acres)	10	10	10	10	10
30	Clay Lens?	Yes	Yes	Yes	Yes	Yes
31	Estimated Cost Range for Excavation	Medium	Medium	Medium	Medium	Medium
32	Distance in Miles to Nearest Road	0.75	0.75	0.75	3	2
33	Distance in Miles to Nearest Town	3	3	3	3	5
34	Percent Year-Round Open Water within 2 mile radius	40	20	5	35	52
35	Percent Open Water During Breeding (May-June) within 2 mile radius	12	5	12	25	20
36	Percent Open Water During Spring Migration (Mar-Apr) within 2 mile radius	30	10	50	30	15
37	Percent Open Water During Fall Migration (Aug-Nov) within 2 mile radius	0	5	0	0	40
38	Percent Carbohydrate Food Source within 2 mile radius	35	75	35	35	35
39	Percent Protein Food Source within 2 mile radius	30	10	42	42	42
40	Percent Protected Lands within 2 mile radius	20	35	35	35	35
41	CNHP element occurance or potential conservation area	Yes	No	No	No	No
42	Prairie dog/burrowing owl habitat	No	No	No	No	Yes
43						
44						

Sedgwick Soil Types / Cost Output Report / Cost Rules / WHAT Output Report / WHAT

Figure V-11. WAPSAM Summary Output Worksheet



Microsoft Excel - CSPAM.xls

Results of the CPSAM Overall Site Assessment [redacted]

	Overall Pond Site Assessment	Relative Weights	Site D - pond A Score	Classification
1	Physical Conditions for Streamflow Augmentatio	1	3.07	good
2	Cost Estimate for Pond Development	3	3.00	good
3	Physical Conditions for Waterfowl Habitat	2	2.69	fair
		Overall	Score	Classification
			2.91	fair

If Site is Flagged and Waterfowl Habitat Score/Classification is [redacted]
then perform on-site field assessment before developing site.

	EO/PCA	P-Dog
SITE FLAGS?	No	No

Figure V-12. WAPSAM Stored Results Worksheet

Microsoft Excel - CSPAM.xls

		Site B - Farmer Alex			Site B - Pond A			Site B - pond site A			Site D - Farmer Peter		
	Overall Pond Site Assessment	Weights	Score	Classification	Weights	Score	Classification	Weights	Score	Classification	Weights	Score	Classification
1	Physical Conditions	1	2.38	fair	1	2.44	fair	1	2.19	fair	1	3.00	good
2	Cost Estimate	1	2.00	fair	1	2.00	fair	1	1.00	poor	3	3.00	good
3	Waterfowl Habitat	3	2.68	fair	3	2.47	fair	3	2.37	fair	2	3.08	good
		Overall	Score	Classification	Overall	Score	Classification	Overall	Score	Classification	Overall	Score	Classification
			2.48	fair		2.37	fair		2.06	fair		3.03	good

Table V-1 Rule Knowledge Base for System Evaluation: Potential Recharge Site Assessment for Stream Augmentation in Sedgwick County, CO

Criterion	Knowledge Sought	Raw Data Sources and Derivation Tools	Measurement Scale (M.S.) Range	M.S. Score	M.S. Class Name
Well Density (WD)	Aquifer availability as determined by density of wells	Well Location Coverage RPAT tool to calculate no. of wells within ½ mile of site	0 wells	1	Poor
			1 well	2	Fair
			2 wells	3	Good
			≥ 3 wells	4	Excellent
Stream Depletion Factor (SD)	Ability to augment streamflow as determined by the stream depletion factor (SDF) in units of days	GIS SDF coverage (available in SPMAP)	>30 days	1	Poor
			30-90 days	2	Fair
			90-150 days	3	Good
			≥ 150 days	4	Excellent
Soil Type (SD)	Seepage rate to recharge aquifer as determined by surface soil type	NRCS SSURGO Surface Soil Coverage to determine grain size, grain size converted to recharge rate	< 0.5 ft/day	1	Poor
			0.5-1 ft/day	2	Fair
			1-2 ft/day	3	Good
			≥ 2 ft/day	4	Excellent

M.S. = measurement scale
NRCS = Natural Resources Conservation Service
GIS = geographic information systems
SSURGO = Soil Survey Geographic Database

Table V-2 Matrix of RPAT-II Results for All Sedgwick County Recharge Sites

SOIL TYPE	NUMBER OF WELLS WITHIN ½ MILE 0	1	2	3	4	5	6+
Silt loam	331 (C)						
Loam	366 (FF) 1231 (O)	56 (L) 209 (Z)	72 (G) 199 (J)	**1351 (CC)**	110 (GG)	*115 (HH)* 132 (R) 228 (M) **291 (DD)**	93 (H) 159 (U) **193 (EE)** **651 (II)** 790 (P)
Sandy loam	331 (K)	271 (AA)	199 (Y) 271 (I)		271 (BB) 341 (S) 456 (W) 1280 (E)		128 (V)
Loamy sand				21 (F) 1229 (N)	409 (T) 784 (X)		
Fine sand			191 (B) 815 (A)		1415 (D)		

BOLD: Rejected sites
Italics: Site under development
Shaded boxes: Sites selected for KBS testing.

Table V-3 Summary of RPAT-II Results for Selected Test Sites

Site ID	SDF Value	RPAT SDF Grade	Soil Type	RPAT Soil Grade	Wells w/in ½ mile	RPAT Wells Grade	RPAT Overall Site Grade
C	331	A	Sandy Loam	B	0	D	B-
D	1415	A	Fine Sand	A	4	A	A
F	21	D	Loamy Sand	B	3	B	B-
L	56	C	Loam	C	1	D	C
R	132	B	Loam	C	5	A	B
W	456	A	Sandy Loam	B	4	A	A-
FF	366	A	Loam	C	0	D	C+
HH	115	B	Loam	C	5	A	B
II	651	A	Loam	C	12	A	B+

Table V-4 RPAT Testing Results from Questionnaire Responses

Site Data from RPAT Knowledge Bases		Tester A Grade:	Tester A Weight:	Tester B Grade:	Tester B Weight:	Tester C Grade:	Tester C Weight:
Site ID: C							
SDF	331	B	1	A	1.5	C	1
Soil Type:	Sandy Loam	B	2	B	1	C	1
Wells w/in 1/2 mi.	0	D	3	D	1	D	1
Overall Site Grade	RPAT: B-	C		C		C-	
Site ID: D							
SDF	1415	B	1	B	1.5	A	1
Soil Type:	Fine Sand	A+	2	A	1	A	1
Wells w/in 1/2 mi.	4	B	3	A	1	C	1
Overall Site Grade	RPAT: A	B+		A-		B+	
Site ID: F							
SDF	21	D	1	D	1.5	D	1
Soil Type:	Loamy Sand	A	2	A	1	A	1
Wells w/in 1/2 mi.	3	B	3	B	1	C	1
Overall Site Grade	RPAT: B-	C		D		C-	
Site ID: L							
SDF	56	D	1	C	1.5	D	1
Soil Type:	Loam	B-	2	C	1	C	1
Wells w/in 1/2 mi.	1	C	3	C	1	D	1
Overall Site Grade	RPAT: C	C		C		D+	
Site ID: R							
SDF	132	C	1	A	1.5	D	1
Soil Type:	Loam	B-	2	C	1	C	1
Wells w/in 1/2 mi.	5	A	3	A	1	B	1
Overall Site Grade	RPAT: B	B-		A-		C	
Site ID: W							
SDF	456	B	1	B	1.5	C	1
Soil Type:	Sandy Loam	B	2	B	1	C	1
Wells w/in 1/2 mi.	4	B	3	A	1	C	1
Overall Site Grade	RPAT: A-	B		B+		C	
Site ID: FF							
SDF	366	B	1	A	1.5	C-	1
Soil Type:	Loam	B-	2	C	1	C-	1
Wells w/in 1/2 mi.	0	D	3	D	1	D	1
Overall Site Grade	RPAT: C+	C		C		C-	
Site ID: HH							
SDF	115	B	1	A	1.5	D	1
Soil Type:	Loam	B-	2	C	1	C	1
Wells w/in 1/2 mi.	5	A	3	A	1	B	1
Overall Site Grade	RPAT: B	B		A		C	
Site ID: II							
SDF	651	B	1	B	1.5	B	1
Soil Type:	Loam	B-	2	C	1	C	1
Wells w/in 1/2 mi.	12	A	3	A	1	A	1
Overall Site Grade	RPAT: B+	B		B		B	

Table V-5 Measurement Scales and Weights Assigned by Testers

Measurement Scales					
		RPAT	Tester A	Tester B	Tester C
Soil Type	clay loam	D	D	D	D
	silt loam	C	C	C	D
	Loam	C	B-	C	C
	Sandy loam	B	B-	B	C
	Gravelly loam	B	A-	B	B
	Loamy fine sand	B	B+	A	B
	Loamy sand	B	A-	A	A
	fine sand	A	A+	A	A
SDF values		**RPAT**	Tester A	Tester B	Tester C
	A	150+	180-250	120+	1000+
	B	90-150	250-1500	80-120	500-999
	C	30-90	90-180	60-80	250-499
	D	< 30	30-90	20-60	< 250
No. of wells w/in 1/2 mile		**RPAT**	Tester A	Tester B	Tester C
	A	4+	5+	5+	10+
	B	3	3 TO 4	3 TO 4	5 TO 9
	C	2	1 TO 2	1 TO 2	2 TO 4
	D	0 TO 1	0	0	0 TO 1

Parameter Weight				
	RPAT	Tester A	Tester B	Tester C
Soil Type	1	3	1.5	1
SDF Value	1	2	1	1
No. of wells w/in 1/2 mile	1	1	1	1

Figure V-13 Comparison of Soil Type Scaling Functions

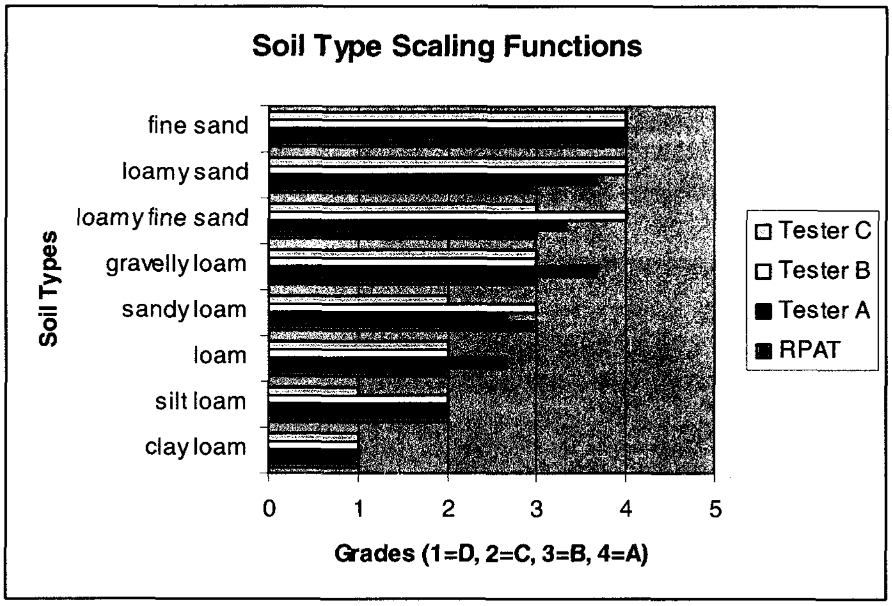
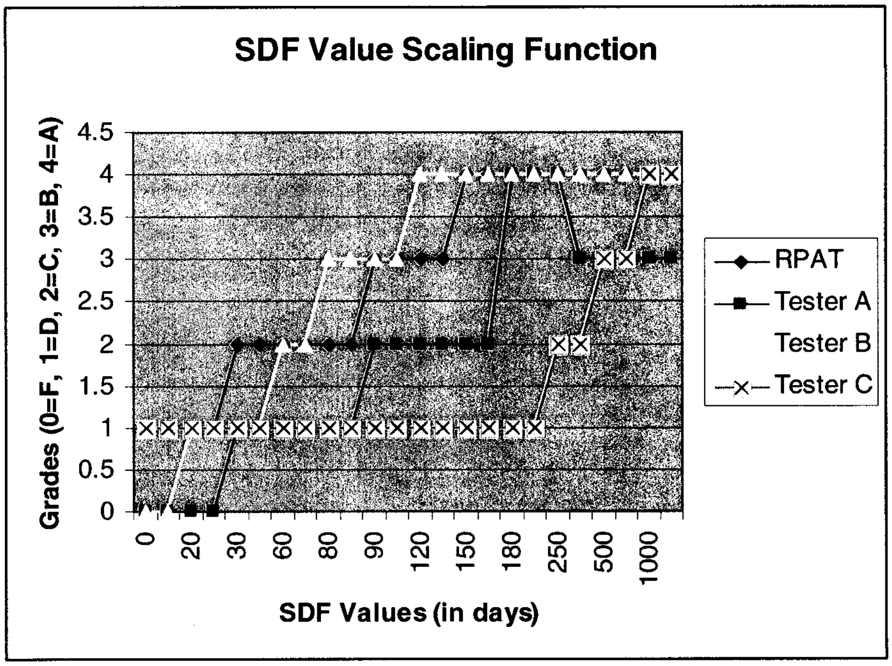
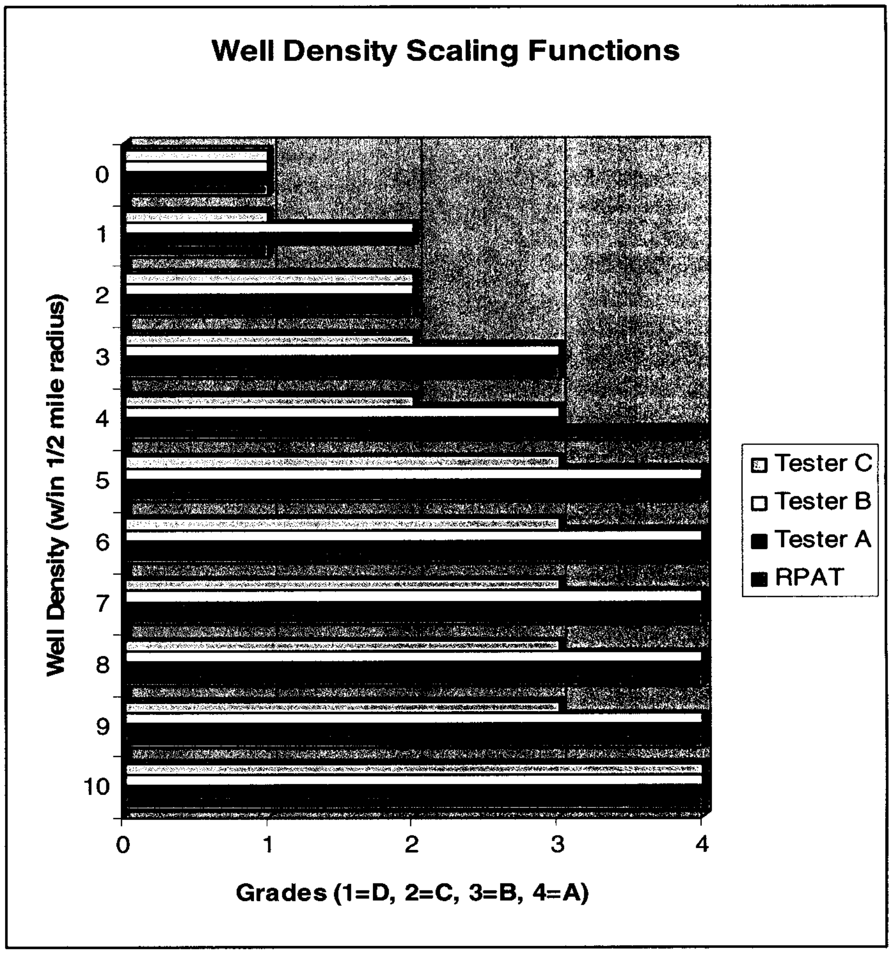


Figure V-14 Comparison of SDF Value Scaling Functions



V-15 Comparison of Well Density Scaling Functions (two graphs)



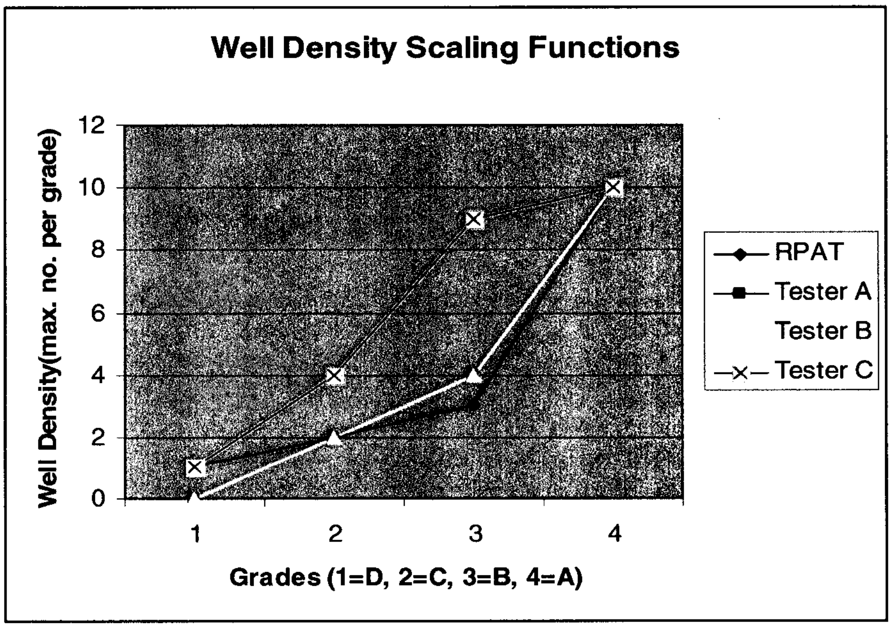


Figure V-16 RPAT vs Tester Results: Site Rankings

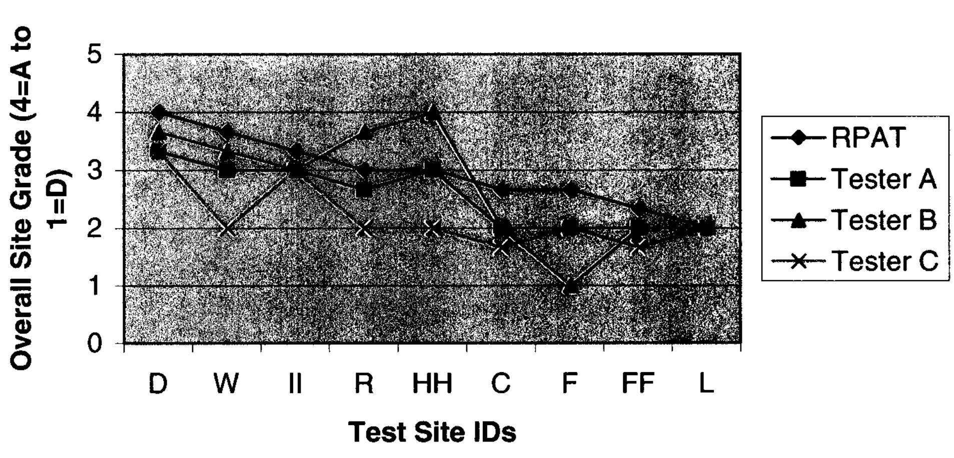


Figure V-17 RPAT vs Tester Results: Site Grades

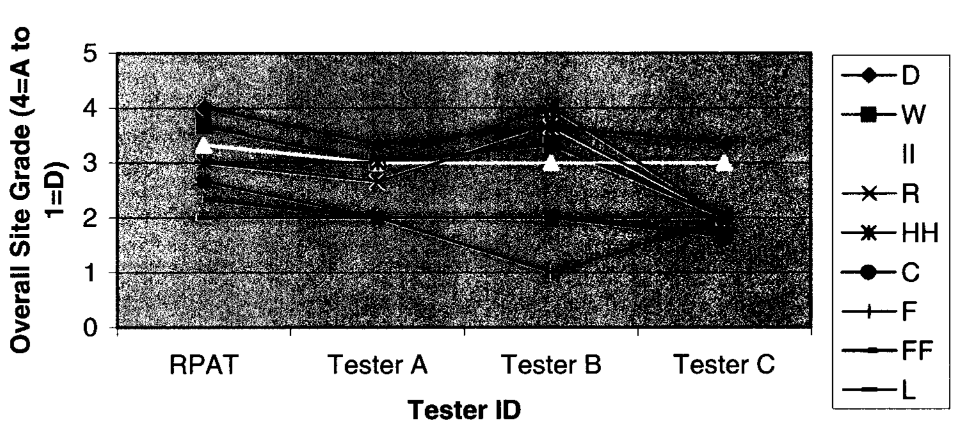


Table V-6 Comparison of Overall Grades for All Testers and RPAT-II

GRADE	RPAT	Tester A	Tester B	Tester C
A	D		HH	
A-	W		D, R	
B+	II	D	W	D
B	R, HH	W, HH, II	II	II
B-	C, F	R		
C+	FF			
C	L	C, F, L, FF	C, L, FF	F, L, R, W, HH
C-				C, FF
D+				
D			F	

Table V-7 MCDA Sensitivity Analysis

Site ID	RPAT Av	No SDF	No Soil	No Well	Diff RPAT/ No SDF	Diff RPAT/ No Soil	Diff RPAT/ No Well
A	3.333	3	3	4	0.33	0.33	-0.667
B	3.333	3	3	4	0.33	0.33	-0.667
C	2.667	2	2.5	3.5	[illegible]	[illegible]	[illegible]
D	4	4	[illegible]	4	[illegible]	[illegible]	[illegible]
E	3.667	3.5	4	3.5	0.17	-0.33	0.1667
F	2.333	3	2	2	[illegible]	[illegible]	[illegible]
G	2	2	2	2	0	0	0
H	3	3	3.5	[illegible]	[illegible]	[illegible]	[illegible]
I	3	2.5	3	3.5	0.5	0	-0.5
J	2.667	2	3	3	0.67	-0.33	-0.333
K	2.333	1.5	2.5	3	0.83	-0.17	-0.667
L	1.667	1.5	1.5	2	[illegible]	[illegible]	[illegible]
M	3.333	3	4	3	0.33	-0.67	0.3333
N	3.667	3.5	3.5	4	0.17	0.17	-0.333
O	2.333	1.5	2.5	3	0.83	-0.17	-0.667
P	3.333	3	4	3	0.33	-0.67	0.3333
GG	3	3	3.5	2.5	0	-0.5	0.5
R	3	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
S	3.667	3.5	4	3.5	0.17	-0.33	0.1667
T	3.667	3.5	4	3.5	0.17	-0.33	0.1667
U	3.333	3	4	3	0.33	-0.67	0.3333
V	3.333	3.5	3.5	3	-0.2	-0.17	0.3333
W	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
X	3.333	3	3.5	3.5	0.33	-0.17	-0.167
Y	3	2.5	3	3.5	0.5	0	-0.5
Z	2.333	1.5	2.5	3	0.83	-0.17	-0.667
AA	2.667	2	2.5	3.5	0.67	0.17	-0.833
BB	3.667	3.5	4	3.5	0.17	-0.33	0.1667
CC	3	2.5	3.5	3	0.5	-0.5	0
DD	3.333	3	4	3	0.33	-0.67	0.3333
EE	3.333	3	4	3	0.33	-0.67	0.3333
FF	2.333	1.5	2.5	[illegible]	[illegible]	[illegible]	[illegible]
HH	[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
II	3.333	3	4	3	0.33	-0.67	0.3333
Average	3.049	2.75	3.2794	3.1176	0.3	-0.23	-0.069
Maximum Difference from RPAT					0.83	-0.67	-0.69

Table V-8 Site Rankings with MCDA Sensitivity Analysis

ID	SDF Grade	Soils Grade	Wells Grade	RPAT Avg	RPAT Rank	No SDF Avg	No SDF Rank	No Soil Avg	No Soil Rank	No Well Avg	No Well Rank
A	**4**	**4**	**2**	3.33	3rd	3	3rd	3	3rd	**4**	**1st**
B	**4**	**4**	**2**	3.33	3rd	3	3rd	3	3rd	**4**	**1st**
C	**4**	**3**	**1**	2.67	5th	2	5th	2.5	4th	**3.5**	**2nd**
D	4	4	4	4	1st	4	1st	4	1st	4	1st
E	4	3	4	3.67	2nd	3.5	2nd	4	1st	3.5	2nd
F	**1**	**3**	**3**	2.33	6th	**3**	**3rd**	2	5th	2	5th
G	**2**	**2**	**2**	2	7th	**2**	**5th**	**2**	**5th**	**2**	**5th**
H	**3**	**2**	**4**	3	4th	3	3rd	**3.5**	**2nd**	2.5	4th
I	**4**	**3**	**2**	3	4th	2.5	4th	3	3rd	**3.5**	**2nd**
J	**4**	**2**	**2**	2.67	5th	2	5th	**3**	**3rd**	**3**	**3rd**
K	**4**	**2**	**1**	2.33	6th	1.5	6th	**2.5**	**4th**	**3**	**3rd**
L	2	2	1	1.67	8th	1.5	6th	1.5	6th	2	5th
M	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
N	4	4	3	3.67	2nd	3.5	2nd	3.5	2nd	4	1st
O	4	2	1	2.33	6th	1.5	6th	**2.5**	**4th**	**3**	**3rd**
P	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
GG	**3**	**2**	**4**	3	4th	3	3rd	**3.5**	**2nd**	2.5	4th
R	**3**	**2**	**4**	3	4th	3	3rd	**3.5**	**2nd**	2.5	4th
S	4	3	4	3.67	2nd	3.5	2nd	4	1st	3.5	2nd
T	4	3	4	3.67	2nd	3.5	2nd	4	1st	3.5	2nd
U	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
V	3	3	4	3.33	3rd	3.5	2nd	3.5	2nd	3	3rd
W	4	3	4	3.67	2nd	3.5	2nd	4	1st	3.5	2nd
X	4	3	3	3.33	3rd	3	3rd	3.5	2nd	3.5	2nd
Y	**4**	**3**	**2**	3	4th	2.5	4th	3	3rd	**3.5**	**2nd**
Z	**4**	**2**	**1**	2.33	6th	1.5	6th	**2.5**	**4th**	**3**	**3rd**
AA	**4**	**3**	**1**	2.67	5th	2	5th	2.5	4th	**3.5**	**3rd**
BB	4	3	4	3.67	2nd	3.5	2nd	4	1st	3.5	2nd
CC	**4**	**2**	**3**	3	4th	2.5	4th	**3.5**	**2nd**	3	3rd
DD	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
EE	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
FF	**4**	**2**	**1**	2.33	6th	1.5	6th	**2.5**	**4th**	**3**	**3rd**
HH	**3**	**2**	**4**	3	4th	3	3rd	**3.5**	**2nd**	2.5	4th
II	**4**	**2**	**4**	3.33	3rd	3	3rd	**4**	**1st**	3	3rd
Avg Overall Site Grade				3.05		2.75		3.28		3.12	
Rank changes by more than 2 rankings							2/34		17/34		12/34

BOLD = Site rank changes by more than two rankings

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

VI.A. Summary

The research described in this dissertation meets the objective of the development of a methodology and prototype application that combines the use of knowledge-based systems (KBS), geographic information systems (GIS), and multi-criteria decision analysis (MCDA) in a flexible and transparent system, which can be applied to evaluation of recharge pond sites for streamflow augmentation, pond development costs, and waterfowl habitat restoration benefits, drawing upon the experience and understanding of local water and wildlife managers. The methodology that was developed and applied towards the creation of the Waterfowl and Augmentation Pond Site Assessment Model (WAPSAM) prototype included the following nine steps:

1. Pre-Development Analysis of the Suitability of a KBS for the Target Problem
2. Knowledge Acquisition
3. Knowledge Translation and Ontology Analysis
4. Data Source Evaluation
5. Domain Knowledge Base and Rule Knowledge Base Development
6. Development of User Interface and Links with Other Input Sources
7. MCDA Development
8. Integration of MCDA into KBS as a Reasoning Engine
9. System Evaluation

This methodology was used for the development of an Excel-based prototype model that:

- is linked to GIS coverages for data acquisition and spatial analysis, so that the only required user input is the selection of the site location to be evaluated;
- provides complete explanations to the user of the multiple criteria and subcriteria analysis results and the rules and raw data behind the results of those analyses as applied to the specific alternatives being analyzed; and
- includes adaptable rule/criterion parameters that can be easily changed by the user for instantaneous updates to the model outputs to reflect new understanding of site assessment criteria by the user, or to reflect new situations (e.g. assessment for different waterfowl species or changes in cost estimation parameters).

WAPSAM was developed as a prototype containing all of the decision parameters cited by the local parameters for which spatial data could support an automated evaluation process if such spatial data were available. WAPSAM was developed in a modular approach consisting of separate components, i.e. physical attributes of sites to be developed for streamflow augmentation credits; pond development costs; and waterfowl habitat benefits. These components are referred to as the Recharge Pond Assessment Tool (RPAT), Cost Assessment Tool (CAT), and Waterfowl Habitat Assessment Tool (WHAT), respectively.

The target region for a demonstration application of the methodology is the Lower South Platte River of Colorado, specifically within an area of Sedgwick County. The demonstration application is designed to maximize the ability to evaluate potential recharge sites using 1) available knowledge from both local experts and published literature sources and 2) available databases and GIS tools assembled and updated to provide data necessary for site evaluation in an appropriate format, with minimal input requirements from KBS users.

At the time of prototype development, not all of the databases to support automated site evaluation were available. For system evaluation purposes, testing of real sites was performed only on a reduced version of the streamflow augmentation component of the prototype (i.e. RPAT) for those evaluation subcriteria for which databases were available at the time of testing, so that real data could be used for actual pond sites. The criteria included in the system evaluation were selected following an evaluation of databases to provide attribute values and knowledge acquisition to determine for which site attributes measurement methods and threshold values could be determined by local experts. The evaluation of available databases and knowledge was also used to identify the need for future research to support a more comprehensive evaluation of sites. The complete prototype was designed so that new rules could be added and rule parameters and threshold values could be changed as new databases becomes available or as new understanding of the decision making process is gained through future research.

VI.B. Significant Contributions

Specific contributions to be made by this research include the following:

1. Combination of KBS and MCDA methodologies to provide flexibility and adaptability for a rule-based system.
2. Design and development of the KBS in a format that is transparent, is easily identifiable by users and experts, and in a commonly-available Excel-based software package that mimics the functions of more expensive and less commonly used software packages, and which supports rapid and adjustable rule development.
3. Design and development of the KBS to be easily and rapidly adaptable by users so that the threshold values and radius of the area of spatial analysis can be changed to reflect changing site scenarios, user preferences and management priorities, or improved understanding of the decision process.
4. Capture of the decision process of pond site selection for each of the domains of physical site characteristics for groundwater recharge for streamflow augmentation; pond development costs; and waterfowl habitat benefits.
5. Organization of the information on that decision process into domain and rule knowledge bases, including the acquisition and organization of both tabular and spatial databases to support the decision process, in a transparent format that can be incorporated into an automated knowledge-based system.
6. Design and development of a model to link spatial databases in an ArcView/GIS format with site assessment rules for each component criterion and subcriterion programmed into an Excel-based format; linkage of criterion and subcriterion analyses for each component (i.e. physical site characteristics for recharge for streamflow augmentation; pond development costs; and waterfowl habitat

benefits) with MCDAs for each component; and linkage of the MCDAs for each component with an overall site assessment MCDA, with explanations of each component evaluation result and raw data provided in a transparent format, and with the ability to save the results for individual sites to enable comparison of multiple sites or the development of regional analyses.

VI.C. Conclusions

KBS and MCDA can be valuable tools for the development of automated site evaluation tools that can assist water users and habitat managers both in evaluating the potential benefits and costs associated with pond site development, and in identifying opportunities for cooperation between water users and wildlife programs.

Decision support tools vary in accordance with the steps taken during any decision-making process. The first step towards making a decision is to identify the criteria and data needed to make a decision, and to collect that data. The second step in decision-making is to evaluate each piece of data as it relates to the decision to be made. For example, a piece of raw data is assigned a measurement value (e.g. the infiltration rate assigned to a soil type) and put into a category or classification (e.g. the poor-fair-good-excellent classifications used in this prototype). The final step in a decision-making process is to determine the relative importance, or weight, or each individual consideration in the determination of an overall decision.

There are tools called “decision support tools” or “decision support systems” that range from those that merely assemble and present data, to those that perform simple data analysis and evaluation of individual criteria or subcriteria, to those that actually perform an overall evaluation of a specific alternative and provide a recommendation for the user's decision based upon the evaluation of all of the considerations or criteria. The more a decision support tool moves from the provision of collected data towards the performance of the evaluation process in a decision support tool, the more essential it is that the decision support tool be fully transparent, providing a complete explanation of the raw data that was considered and the evaluation process that was used.

In addition to transparency, flexibility is another essential trait in the development of knowledge-based systems, since the state of human knowledge about decision-making processes is continuously changing. The prototype developed for this research allows the user to change the threshold values and compare results of those changes, and to add rules and databases as new understanding and new data becomes available.

VI.D. Recommendations for Future Work

The prototype developed in this research provides a framework for decision making on the evaluation of potential recharge sites for streamflow augmentation, pond site costs, and waterfowl habitat. In developing this prototype, I have attempted to capture the full array of criteria and subcriteria considered by local experts in their decision-making processes, and to compile and modify, as appropriate, spatial databases to support criterion and subcriterion evaluation.

The subcriteria and associated data requirements at the time of prototype development are summarized for RPAT, CAT, and WHAT in Tables V-1, V-2, and V-3, respectively. Future work may include development of spatial databases to provide some of the data requirements for site evaluation that currently would need to be met with user inputs.

The threshold values for the classifications of subcriteria were developed through interviews with local experts. As shown in the system evaluation for the modified version of RPAT, some of these threshold values, e.g. for the stream depletion values, vary greatly depending upon whether the recharge ponds are being developed for municipal well use, irrigation well use, or to meet stateline flow requirements for habitat restoration efforts in a neighboring state. Further study of the threshold values that provide the greatest benefit for specific pond development goals may be warranted, along with field research to determine whether those goals are being met with existing recharge ponds. The use of pond site evaluations to review the overall impact of existing and planned future recharge pond sites on regional water supply needs and interstate agreements may also be warranted.

CHAPTER VII
LITERATURE CITED

Adamus, P.R. 1983. A Method for Wetland Functional Assessment: Volume I. Office of Research and Development, Federal Highways Administration, U.S. Department of Transportation Report FHWA-IP-82-23, Washington, DC.

Adamus, P.R. and L.T. Stockwell. 1983. A Method for Wetland Functional Assessment: Volume II. Office of Research and Development, Federal Highways Administration, U.S. Department of Transportation Report FHWA-IP-82-23, Washington, DC.

Adamus, P.R., L.T. Stockwell, E.J Clairain, Jr., M.E. Morrow, L.P. Rozas, and R.D. Smith. 1991. Wetland Evaluation Technique (WET); Volume I: Literature Review and Evaluation Rationale. Technical Report WRP-DE-2, U.S. Army Engineer Waterways Experiments Station, Vicksburg, MS.

Anderson, J.R., 1983. A Spreading Activation Theory of Memory. Journal of Verbal Learning and Verbal Behavior 22:261-295.

Armstrong, M.P., 1993. Perspectives on the Development of Group Decision Support Systems for Locations Problem Solving. Geographical Systems 1(1):69-81.

Balci, O. and R.E. Nance, 1985. Formulated Problem Verification as an Explicit Requirement of Model Credibility. Simulation 45(2):76-86.

Balci, O. and R.G. Sargent, 1984. A Bibliography of the Credibility and Validation of Simulation and Mathematical Models. Simuletter 15(3):15-27.

Balci, O. and R.G. Sargent, 1981. A Methodology for Cost-Risk Analysis in the Statistical Validation of Simulation Models. Communications of the Association for Computing Machinery 24(11):190-197.

Baldassarre, G.A., R.J. Whyte, E.E. Quinlan, and E.G. Bolen. 1983. Dynamics and Quality of Waste Corn Available to Postbreeding Waterfowl in Texas. Wildlife Society Bulletin 11:25-31.

Bana e Costa, C. and M.P. Changas, 2002. A Career Choice Problem: An Example of How to Use MACBETH to Build a Quantitative Value Model Based on Qualitative Value Judgements. Working Paper LSEOR 02.53, London School of Economics, London.

Bartoldus, C.C., 1999. A Comprehensive Review of Wetland Assessment Procedures: A Guide for Wetland Practitioners. Environmental Concern Inc., St. Michaels, MD.

Bella, A., L. Duckstein, and F. Szidarovsky, 1996. A Multicriterion Analysis of the Water Allocation Conflict in the Upper Rio Grande Basin. Applied Mathematics and Computation. 77(2-3): 245-265.

Bhattacharya, J., 2000. Sustainable Development of Natural Resources: Implications for Mining of Minerals. Mineral Resources Engineering 9(4):451-464.

Bischofberger, W., and G. Pomberger, 1992. Prototyping-Oriented Software Development: Concepts and Tools. Springer-Verlag: New York.

Boar, B.H., 1984. Application Prototyping – A Requirements Definition Strategy for the 80s. John Wiley & Sons, New York.

Bodini, A., A. Ricci, and P. Viaroli, 2000. A Multimethodological Approach for the Sustainable Management of Perifluvial Wetlands of the Po River (Italy). Environmental Management 26(1):59-72.

Bouwer, H., 2002. Artificial Recharge of Groundwater: Hydrogeology and Engineering. Hydrogeology Journal 10:121-142.

Bowerman, R.G., and D.E. Glover, 1988. Putting Expert Systems into Practice. Van Nostrand Reinhold, New York.

Brans, J.P., Ph. Vincke, and B. Mareschal, 1986. How to Select and How to Rank Projects: the PROMETHEE Method. European Journal of Operational Research 24(2): 228-238.

Bridges, C. and the Bureau of Land Management Waterfowl Habitat Team (ed.). 1989. Waterfowl habitat management on public lands: a strategy for the future. U.S. Department of the Interior, Bureau of Land Management. Washington, DC.

Briggs, S., Colorado Division of Wildlife, Brush, Colorado. Personal communication, September 11, 2001.

Brison, M.M., 1993. Changes in the Functioning of Wetlands Along Environmental Gradients. Wetlands 13(2): 65-74.

Brinson, M.M. and R. Rheinhardt, 1996. The Role of Reference Wetlands in Functional Assessment and Mitigation. Ecological Applications 6(1): 69-76.

Brogden, M.J., and J.B. Greenberg, 2003. The Fight for the West: A Political Ecology of Land Use Conflicts in Arizona. Human Organization 62(3): 289-298.

Brokenshaw, D., M. Warren, and O. Werner, eds., 1980. Indigenous Knowledge Systems and Development. New York: University Press of America.

Buchanan, B.G., D. Barstow, R. Bechtal, J. Bennett, W. Clancey, C. Kulikowski, T. Mitchell, and D.A. Waterman, 1983. Constructing Expert Systems. *In:* Building

Expert Systems, F. Hayes-Roth, D.A. Waterman, and D.B. Lenat, Editors. Addison-Wesley Publishing Company, Inc., Reading, MA.

Buchanan, B.G., and E.H. Shortliffe, eds. Rule-based Expert Systems: the MYCIN Experiments of the Stanford Heuristic Programming Project. Addison-Wesley Publishing Company, Inc., Reading, MA.

Burns, A.W., 1984. Simulated Effects of an Artificial-Recharge Experiment Near Proctor, Logan County, Colorado. U.S. Geological Survey, Denver, CO.

Burns, A.W., 1980. Hydrologic Analysis of the Proposed Badger-Beaver Creeks Artificial-Recharge Project, Morgan County, Colorado. U.S, Geological Survey, Lakewood, CO.

Buech, R.R., C.J. Martin, and H.M. Rauscher, 1990. An Application of Expert Systems for Wildlife: Identifying Forest Stand Prescriptions for Deer. AI Applications 4(3):18.

Campbell, C.S., and M. Ogden. 1999. Constructed Wetlands in the Sustainable Landscape. Wiley, New York.

Carsey, K., D. Cooper, K. Decker, D. Culver, and G. Kittel, 2003. Statewide Wetlands Classification and Characterization. Colorado Natural Heritage Program, Fort Collins, CO.

Casey, T., 1989. Picking the Right Expert System Application. AI Expert 9:44-47.

Cedfeldt, P.T., M.C. Watzin, and B.D.Richardson, 2000. Using GIS to Identify Functionally Significant Wetlands in the Northeastern United States. Environmental Management 26(1):13-24.

Chao, P.T., B.F. Hobbs, and B.N. Venkatesh, 1999. How Climate Uncertainty Should Be Included in Great Lakes Management: Modeling Workshop Results. Journal of the American Water Resources Association 35(6):1485-1497.

Chowdhury, A.K.M.M. and L.W. Canter, 1998. Expert Systems for Ground Water Management. Journal of Environmental Systems 26(1):89-110.

Clairain, E.J., D.R. Sanders, H.K. Smith, and C.V. Klimas. Wetland Functions and Values Study Plan. Technical Report Y-83-2, U.S. Army Engineer Waterways Experiments Station, Vicksburg, MS.

Clark, M.J. and K.J. Richards, 2002. Supporting Complex Decisions for Sustainable River Management in England and Wales. Aquatic Conservation-Marine and Freshwater Ecosystems 12(4):471-483.

Clark, M.J., 2002. Dealing with Uncertainty: Adaptive Approaches to Sustainable River Management. Aquatic Conservation-Marine and Freshwater Ecosystems 12 (4): 347-363.

Clevenger, A.P., J. Wierzchowski, B. Chruszcz, and K. Gunson, 2002. GIS-Generated, Expert-Based Models for Identifying Wildlife Habitat Linkages and Planning Mitigation Passages. Conservation Biology 16(2):503-514.

Connel, J.L. and L.B. Shafer, 1989. Structured Rapid Prototyping. Yourdon Press, New York.

Cooke, N.M. and J.E. McDonald, 1987. The Application of Psychological Scaling Techniques to Knowledge Elicitation for Knowledge-Based Systems. International Journal of Man-Machine Studies 26:533-330.

Couclelis, H. and M. Monmonier, 1995. Using SUSS to Resolve NIMBY: How Spatial Understanding Support Systems Can Help with the "Not in my Back Yard" Syndrome. Geographical Systems 2(2):83-101.

Cowardin, L. M., V. Carter, F. C. Golet, E. T. LaRoe. 1979. Classification of Wetlands and Deepwater Habitats of the United States. U. S. Department of the Interior, Fish and Wildlife Service, Washington, D.C.

Cowen, D., 1988. GIS Versus CAD Versus DBMS: What Are the Differences. Photogrammetric Engineering and Remote Sensing 54(2):1551-1555.

Cross, D.H. and P. Vohs (ed.), 1988. Waterfowl Management Handbook. U.S. Department of the Interior, Fish and Wildlife Service. Fort Collins, CO.

Davis, J.R. and P.M. Nanninga, 1985. GEOMYCIN: Towards a Geographic Expert System for Resource Management. Journal of Environmental Management 21:377-390.

de Azavedo, L.G.T., T.K. Gates, D.G. Fontane, J.W. Labadie, and R.L. Porto, 2000. Integration of Water Quantity and Quality in Strategic River Basin Planning. Journal of Water Resources Planning and Management-ASCE. 126(2):85-97.

Densham, P.J., 1991. Spatial Decision Support Systems. *In:* D.J. Maguire, M.F. Goodchild and D.W. Rhind (Editors). Geographical Information Systems: Principles and Applications. John Wiley & Sons, New York, NY, pp. 403-412.

Dovers S.R., Lindenmayer D.B., 1997. Managing the Environment: Rhetoric, Policy and Reality. Australian Journal of Public Administration 56(2): 65-80.

Doukidis, G.I., and R.J. Paul, 1992. A Survey of the Application of Artificial Intelligence Techniques within the OR Society. *In:* Georgios I. Doukidis and Ray J. Paul (eds.), Artificial Intelligence in Operational Research, pp. 9-21. Macmillan Press: London.

Duckstein, L. and S. Opricovic, 1980. Multi-Objective Optimization in River Basin Development. Water Resources Research, 16(1): 14-20.

Durkin, J., 1997. Expert System Development Tools. *In:* The Handbook of Applied Expert Systems, Jay Liebowitz (Editor). CRC Press LLC, Boca Raton, FL, pp. 4-1 – 4-26.

Dutta, D., A. Das Gupta, and V. Rumnarong, 1998. Design and Optimization of a Ground Water Monitoring System using GIS and Multicriteria Decision Analysis. Ground Water Monitoring and Remediation. 18(1):139-147.

Elmagnouni, S. and W. Treichel, 1994. A Multicriterion Approach to Groundwater-Management. Water Resources Research. 30(6):1881-1895.

ESRI, 1996a. Using ArcView GIS, the geographic information system for everyone. Environmental Systems Research Institute, Inc.

ESRI, 1996b. Using Avenue, customization and application development for ArcView GIS. Environmental Systems Research Institute, Inc.

ESRI, 1997. Using ArcView 3D Analyst, 3D surface creation, visualization, and analysis. Environmental Systems Research Institute, Inc.

Federal Geographic Data Committee, Vegetation Subcommittee, 1997. Vegetation Classification Standard. FGDC-STD-005. U.S. Geological Survey, Reston, VA.

Fedra, K, 1995. Decision Support for Natural Resources Management: Models, GIS and Expert Systems. AI Applications 9(3):3-19.

Fetter, C.W., 1994. Applied Hydrogeology (Third Edition). Macmillan College Publishing Company, New York, NY.

Flick, U., 2002. Qualitative Forschung: An Introduction to Qualitative Research. SAGE Publications, Thousand Oaks, CA.

Floyd, C., 1984. A Systematic Look at Prototyping. *In* Approaches to Prototyping, Springer Verlag, New York.

Flug, M., D.G. Fontane, and G.A. Ghoneim, 1990. Modeling to Generate Recreational Alternatives. Journal of Water Resources Planning and Management-ASCE. 116(5):625-638.

Flug, M., H.L.H. Seitz, and J.F. Scott, 2000. Multicriteria Decision Analysis Applied to Glen Canyon Dam. Journal of Water Resources Planning and Management-ASCE. 126(5):270-276.

Fontane, D.G., T.K. Gates, and E. Moncada, 1997. Planning Reservoir Operations with Imprecise Objectives. Journal of Water Resources Planning and Management-ASCE. 123(3):154-162.

Foote, K.E. and M. Lynch, 1996. Geographic Information Systems as an Integrating Technology: Context, Concepts, and Definitions. *In:* The Geographer's Craft Project. Department of Geographic, University of Texas at Austin, Austin, TX.

Fredericks, J.W., J.W. Labadie, and J.M. Altenhofen, 1998. Decision Support System for Conjunctive Stream-Aquifer Management. ASCE Journal of Water Resources Planning and Management 124(2):69-79.

Frederickson, L.H. and F.A. Reid. 1988. Waterfowl use of wetland complexes. *In* Cross and Vohs, 1988, Waterfowl Management Handbook. U.S. Fish and Wildlife Service, Fort Collins, CO.

Frederickson, L.H. and T.S. Taylor. 1982. Management of Seasonally Flooded Impoundments for Wildlife. U.S. Fish and Wildlife Service Resource Publication 148. Fort Collins, CO.

Gammonly, J.H. and M.K. Laubhan, 2002. Patterns of Food Abundance for Breeding Waterbirds in the San Luis Valley of Colorado. Wetlands 22(3): 499-508.

Garcia, L.A. and M. Armbruster, 1997. A Decision Support System for Evaluation of Wildlife Habitat. Ecological Modelling 102(2-3):287-300.

Garcia, L.A., D. Patterson, and R.W. Lange, 2001. South Platte Mapping and Analysis Program (SPMAP) Decision Support Tools for the Lower South Platte. Completion Report No. 193. Colorado Water Resources Research Institute, Fort Collins, CO.

Gates, T.K., W.E. Heyder, D.G. Fontane, and J.D. Salas, 1991. Multicriterion Strategic-Planning for Improved Irrigation Delivery 1. Approach. Journal of Irrigation and Drainage Engineering-ASCE. 117(6):897-913.

Geertman, S., 2000. Participatory Planning and GIS: a PSS to Bridge the Gap. Environment and Planning B-Planning and Design 29(1):21-35.

Geertman, S., 2002. Information Systems for Urban Planning: a Hypermedia Co-operative Approach. Environment and Planning A 34(8): 1521-1522.

Gillis, D., and D. Ellis, 1995. The Georgia Strait Herring "Stock" Problem, Inclusive of the First Nations TEK (Traditional Ecological Knowledge) Perspective. *In* Hay, D.E. and P.B. McCarter (eds.). Proceedings of the 7th Pacific Coast Herring Workshop, January 27-28, 1994. Canadian Technical Report Fisheries and Aquatic Science No. 2060, pp. 171-178.

Glover, R.E., 1964. Ground Water Movement. Engineering Monograph 31, U.S. Bureau of Reclamation, Denver, CO.

Goiceochea, A., D.R. Hansen, and L. Duckstein, 1982. Multiobjective Decision Analysis with Engineering and Business Applications. John Wiley & Sons, New York, 1982.

Goldberg, D.E., 1989. Genetic Algorithms in Search, Optimization, and Machine Learning. Reading, MA: Addison-Wesley Publishing Company, Inc.

Gomez-Limon, J.A., M. Arriaza, and J. Berbel, 2002. Conflicting implementation of agricultural and water policies in irrigated areas in the EU. Journal of Agricultural Economics 53(2):259-281.

Grimshaw, D.J., 1994. Bringing Geographical Information Systems into Business. Longman Scientific and Technical, Harlow, Essex, England.

Guidice, J.H. and J.T. Ratti, 1995. Interior Wetlands of the United States: A Review of Wetland Status, General Ecology, Biodiversity, and Management. Wetlands Research Program Technical Report WRP-SM-9, U.S. Army Engineer Waterways Experiments Station, Vicksburg, MS.

Gupta, A.P., R. Harboe, and M.T. Tabucanon, 2000. Fuzzy Multiple-Criteria Decision Making for Crop Area Planning in Narmada River Basin. Agricultural Systems. 62(1):1-18.

Harris, T.M., D. Weinger, T. Warner, and R. Levin, 1995. Pursuing Social Goals through Participatory GIS: Redressing South Africa's Historical Political Economy. Photogrammetric Engineering and Remote Sensing 58(8):1209-1212.

Hart, A., 1989. Knowledge Acquisition for Expert Systems. New Technology Modular Series. Kogan Page, London.

Hartwell, A., 1987. Artificial Recharge in the South Platte River Basin, Colorado: A Comparison of Four Models. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, CO.

Haupt, D.M., C.J. Bruce, and B.P. Bledsoe, 1998. A Geographic Information System for Targeting Wetland Restoration. *In:* Wetlands Engineering and River Restoration Conference: Protecting, Restoring, and Managing the World's Water Resources. American Society of Civil Engineers, Denver, CO, March 1998.

Hayes-Roth, F., D.A. Waterman, and D.B. Lenat, Editors. Building Expert Systems. Addison-Wesley Publishing Company, Inc., Reading, MA.

Hebb, D.O., 1949. Organization of Behavior. New York: Science Editions.

Heyder, W.E., T.K. Gates, D.G. Fontane, and J.D. Salas, 1991. Multicriterion Strategic-Planning for Improved Irrigation Delivery 2. Application. Journal of Irrigation and drainage Engineering-ASCE. 117(6):914-934.

Hillyer, T.M., 1996. Water Supply Handbook: A Handbook on Water Supply Planning and Resource Management. U.S. Army Engineer Institute for Water Resources, Fort Belvoir, VA.

Hollnagel, E., 1989. Issues in the reliability of expert systems. *In*: The Reliability of Expert Systems, E. Hollnagel, ed. Ellis Horwood, Chichester, UK, pp. 169-209.

Ignizio, J.P, 1991. Introduction to Expert Systems: The Development and Implementation of Rule-Based Expert Systems. McGraw-Hill, Inc., St. Louis, MO.

Jacobs, J.W., 2002. Broadening US Water Resources Project Planning and Evaluation. Natural Resources Journal 42 (1): 21-31

Jankowski, Piotr and M. Stasik, 1997. Design Considerations for Space and Time Distributed Collaborative Spatial Decision Making. Journal of Geographic Information and Decision Analysis 1(1):1-8.

Jentoft, S., and T. Kristoffersen, 1989. Fishermen's Co-Management: The Case of the Lofoten Fishery. Human Organization 48:355-365.

Jensen, M.E., K. Reynolds, J. Andreasen, and I.A. Goodman, 2000. A Knowledge-Based Approach to the Assessment of Watershed Condition. Environmental Monitoring and Assessment 64(1):271-283.

Ji, W., and J. B. Johnston. 1994. A GIS-based Decision Support System for Wetland Permit Analysis. Pages 471-476 in GIS/LIS Proceedings of the American Society for Photogrammetry and Remote Sensing, Phoenix, AZ, October 22-28, 1994.

Johannes, R.E., 1978. Words of the Lagoon: Fishing and Marine Law in the Palau District of Micronesia. University of California press, Berkeley, 245 p.

Johnson N.L., N. Lilja, and J.A. Ashby, 2003. Measuring the Impact of User Participation in Agricultural and Natural Resource Management Research. Agricultural Systems 78(2): 287-306.

Johnson P.A., R.L. Tereska, and E.R. Brown, 2002. Using Technical Adaptive Management to Improve Design Guidelines for Urban Instream Structures. Journal of the American Water Resources Association 38 (4): 1143-1152.

Johnson, T.R., 1999. Community-based Forest Management in the Philippines. Journal of Forestry 97 (11): 26-30.

Kam S.P., J.C. Castella, C.T. Hoanh, G. Trebuil, and F. Bousquet, 2002. Methodological Integration for Sustainable Natural Resource Management Beyond Field/Farm Level: Lessons from the Ecoregional Initiative for the Humid and Sub-Humid Tropics of Asia. International Journal of Sustainable Development and World Ecology 9(4): 383-395 DEC 2002.

Karamouz, M., R. Kerachian, B. Zahraie, and S. Araghi-Nejhad, 2002. Monitoring and Evaluation Scheme Using the Multiple-Criteria-Decision-Making Technique: Application to Irrigation Projects. Journal of Irrigation and Drainage Engineering-ASCE. 128(6):341-350.

Kay, J.J., H.A. Regier, M. Boyle, and G. Francis, 1999. An Ecosystem Approach for Sustainability: Addressing the Challenge of Complexity. Futures. 31 (7): 721-742.

Kew, M.J.E. and J.R. Griggs, 1991. Native Indians of the Fraser basin: towards a model of sustainable development in water management; towards agreement in the Fraser basin. Westwater Research Centre, University of British Columbia. Vancouver, B.C., pp. 17-18.

Klaus, R., D.A. Jones, J Turner, N. Simoes, and D. Vousden, 2003. Integrated Marine and Coastal Management: A Strategy for the Conservation and Sustainable Use of Marine Biological Resources in the Socotra Archipelago, Yemen. Journal of Arid Environments 54(1):71-80.

Kline, P.J. and S.B. Dolins, 1985. Choosing Architectures for Expert Systems. Final Technical Report RADC-TR-86-192. Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York. 13441-5700.

Ko, S.K., D.G. Fontane, and J. Margeta, 1994. Multiple Reservoir System Operational Planning Using Multi-Criterion Decision-Analysis. European Journal of Operational Research. 76(3):428-439.

Koreny, J.S., W.J. Mitsch, E.S. Bair, and X. Wu. 1999. Regional and Local Hydrology of a Created Riparian Wetland System. Wetlands 19: 182-193.

Krapu, G., P. Pietz, D. Brandt, and R. Cox, Jr. 2000. Mallard Brood Survival in Prairie Pothole Landscapes. *Waterfowl* 13(1):18.

Kufeld, R. C., and D. C. Bowden. 1995. Mule Deer and White-Tailed Deer Inhabiting Eastern Colorado Plains River Bottoms. Colorado Division of Wildlife Technical Publication 41. Denver.

Kundhardt, H.H. and D.G. Fontane, 1995. Initiating a Water Management Decision Support System for the South Platte River Basin. Water in the Balance No. 2, Colorado Water Resources Research Institute, Fort Collins, CO.

Kwanyuen, B. and D.G. Fontane, 1998. Heuristic Branch-and-Bound Method for Ground Water Development Planning. Journal of Water Resources Planning and Management-ASCE. 124(3): 140-148.

Labadie, J.W., L.E. Brazil, I. Corbu, and L.E. Johnson, 1989. Computerized Decision Support Systems for Water Managers. *In:* Proceedings of the 3rd Water Resources Operations Workshop, Colorado State University, Fort Collins, Co, June 27-30, 1988. American Society for Civil Engineers, New York, NY.

LaBaugh, J.W., T.C. Winter, V.A. Adomaitis, and G.A. Swanson, 1987. Hydrology and Chemistry of Selected Prairie Wetlands in the Cottonwood Lake Area, Stutsman County, North Dakota. Professional Paper 1431. U.S. Geological Survey, Reston, VA. 10p.

Laufmann, S.C., D.M. DeVaney, and M.A. Whiting, 1990. A Methodology for Evaluating Potential KBS Applications. IEEE Expert 12:43-60.

Laukkanen, S., A. Kangas, and J. Kangas, 2002. Applying Voting Theory in Natural Resource Management: A Case of Multiple-Criteria Group Decision Support. Journal of Environmental Management 64(2):127-137.

Layden, P.C., M.J. Manfredo, and P. Tucker, 2003. Integrating Public Values Toward Wildlife into Land Use Planning: A Case Study in La Plata County, Colorado. Wildlife Society Bulletin 31(1):174-184.

Lee, S., and R.M. O'Keefe, 1994. Developing a Strategy for Expert System Verification and Validation. IEEE Transactions on Systems, Man and Cybernetics, 24(4):643 - 655.

Lilburne L., J. Watt, and K. Vincent, 1998. A Prototype DSS to Evaluate Irrigation Management Plans. Computers and Electronics in Agriculture 21(3):195-205

Lissey, A., 1971. Depression-Focused Transient Groundwater Flow Patters in Manitoba. Geol. Assoc. Can. Spec. Pap. No. 9:333-341.

Llewellyn, D.W., G.P. Shaffer, N.J. Craig, L. Creasman, D. Pashley, M. Swan, and C. Brown, 1996. A Decision-Support System for Prioritizing Restoration Sites on the Mississippi River Alluvial Plain. Conservation Biology 10(5): 1446-1455.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich, 2000. Measuring the Total Economic Value of Restoring Ecosystem Services in an Impaired River Basin: Results from a Contingent Valuation Survey. Ecological Economics 33(1):103-117.

Lyle, John Tillman, 1985. Design for Human Ecosystems: Landscape, Land Use, and Natural Resources. Van Nostrand Reinhold: New York.

Lyon, J.G., J.T. Heinen, R.A. Mead, and N.E.G. Roller, 1987. Spatial Data for Modeling Wildlife Habitat. ASCE Journal of Surveying Engineering 113(2): 88-100.

Mackinson, S., University of British Columbia, Vancouver, British Columbia. Personal communication, October 23, 2003.

Mackinson, S., 2001. Integrating Local and Scientific Knowledge: An Example in Fisheries Science. Environmental Management 27(4):533-545.

Mackinson, S., 2000. An Adaptive Fuzzy Expert System for Predicting Structure, Dynamics and Distribution of Herring Shoals. Ecological Modelling 126:155-178.

Mackinson, S. and N. Newlands, 1998. Using Local and Scientific Knowledge to Predict Distribution and Structure of Herring Shoals. *In:* Proceedings of ICES CM 1998, Session J(11).

Mackinson, S. and L. Nottestad, 1998. Combining Local and Scientific Knowledge. Reviews in Fish Biology and Fisheries 8(4): 481-490.

Mahoud, M.R., H. Fahmy, and J.W. Labadie, 2002. Multicriteria Siting and Sizing of Desalination Facilities with Geographic Information System. ASCE Journal of Water Resources Planning and Management 128(2):113-120.

Malczewski, J., 1999. GIS and Multicriteria Decision Analysis. John Wiley & Sons, Inc., New York, NY.

Malczewski, J., 1996. A GIS-Based Approach to Multiple Criteria Group Decision Making. International Journal of Geographical Information Systems 18(8):955-971.

Masciopinto, C., V. Palmisano, F. Tangorra, and M. Vurro, 1991. A Decision Support System for Artificial Recharge Plant. Water Science and Technology 24(9): 331-342.

McAllister, L.S., B.E. Peniston, S.G. Leibowitz, B. Abbruzzese, and J.B. Hyman, 2000. A Synoptic Assessment for Prioritizing Wetland Restoration Efforts to Optimize Flood Attenuation. Wetlands 20(1):70-83.

McKinney, D., C., J. Burgin, and D.R. Maidment, 1995. Water Supply Planning Using An Expert Geographic Information System (TR-162). Texas Water Resources Institute, Texas A&M University, College Station, TX.

McKinney, D.C., D.R. Maidment, and M. Tanriverdi, 1993. Expert Geographic Information-System for Texas Water Planning. Journal of Water Resources Planning and Management-ASCE 119(2):170-183.

Michaelski, R.S., J.G. Carbonell, and T.M. Mitchell, eds., 1986. Machine Learning: An Artificial Intelligence Approach, Volume 2. Los Altos, CA: Morgan Kaufmann Publishers.

Microsoft. 1995. Microsoft Excel for Windows '95, version 7.0 Microsoft Corp., Redmond, WA.

Mills, J.G. and M.A. Zwarich, 1986. Transient Groundwater-Flow Surrounding a Recharge Slough in a Till Plain. Canadian Journal of Soil Science 66(1):121-134.

Mushtaq H., L.W. Mays, and K.E. Lansey, 1994. Optimum Operation of Recharge Basins. ASCE Journal of Water Resources Planning and Management 120(6):927-943.

National Biological Survey, 1995. Waterfowl management handbook. National Biological Service, Information Transfer Center. Fort Collins, CO.

Naugle D.E., R.R. Johnson RR, M.E. Estey, and K.F. Higgins, 2001. A Landscape Approach to Conserving Wetland Bird Habitat in the Prairie Pothole Region of Eastern South Dakota. Wetlands 21 (1):1-17.

Neder, K.D., G.A. Carnelro, T.R. Quelroz, and M.A.A. de Souza, 2002. Selection of Natural Treatment Processes for Algae Removal from Stabilisation Ponds Effluents in

Brasilia, Using Multicriterion Methods. Water Science and Technology, 2002. 46(4-5): 347-354.

Neis, B., L. Felt, R.L. Haedrich, and D.C. Schneider, 1999. An Interdisciplinary Method for Collecting and Integrating Fishers' Ecological Knowledge into Resource Management. Pages 217-238 *in* D. Newell and R. Ommer (eds.), Fishing People, Fishing Places: Traditions and Issues in Canadian Small-scale Fisheries. University of Toronto Press, Toronto.

Netto, O.C., E. Parent, and L. Duckstein, 1996. Multicriterion Design of Long-Term Water Supply in Southern France. Journal of Water Resources Planning and Management-ASCE. 122-(6):403-413.

Nesler, T. et al., 1996. Inventory and Status of South Platte River Native Fishes in Colorado. Colorado Division of Wildlife. Denver, CO.

Nijkamp, P., P. Rietveld, and H. Voogd, 1990. Multicriteria Evaluation in Physical Planning. Elsevier Science Publishers B.V., New York.

Norton, B.G. and A.C. Steinemann, 2001. Environmental Values and Adaptive Management. Environmental Values. 10 (4): 473-506.

Nyerges, T., P. Jankowski, and C Drew, 2002. Data-Gathering Strategies for Social-Behavioral Research about Participatory Geographical Information System Use. International Journal of Geographical Information Science 16(1):1-22.

Nyerges, T.L., 1995. Cognitive Task Performance Using a Spatial Decision Support System for Groups. *In:* Cognitive Aspects of Human-Computer Interaction for Geographic Information Systems. Proceedings of the NATO ARW, Mallorca, Spain, March 21-25, 1995, Dordrecht, Netherlands. T. Nyerges, D.M. Mark, R. Laurini, and M. Egenhofer (Editors). Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 311-323.

O'Keefe, R.M., O. Balci, and E.P. Smith, 1987. Validating Expert System Performance. IEEE Expert 2(4):81-90.

O'Leary, T.J., M.Goul, K.E. Moffitt, and A.E. Radwan, 1990. Validating Expert Systems. IEEE Expert, 5(3):51 -58.

Patil, G.P., R.P. Brooks, W.L. Myers, D.J. Rapport, and C. Taillie, 2001. Ecosystem Health and its Measurement at Landscape Scale: Toward the Next Generation of Quantitative Assessments. Ecosystem Health. 7(4):307-316.

Pedroli B., G. de Blust, K. van Looy, and S. van Rooji, 2002. Setting Targets in Strategies for River Restoration. Landscape Ecology 17:5-18 Suppl. 1.

Pinkerton, , E., and M. Weinstein, 1995. Fisheries that Work. Sustainability through Community Based Management. A Report to the David Suzuki Foundation, Vancouver, BC, Canada.

Prato, T., 2003. Adaptive Management of Large Rivers with Special Reference to the Missouri River. Journal of the American Water Resources Association 39 (4): 935-946.

Prerau, D.S., 1985. Selection of an Appropriate Domain for an Expert System. AI Magazine 6(2):26-30.

Rajabi, S., K.W. Hipel, and D.M. Kilgour, 1999. Water Supply Planning Under Interdependence of Actions: Theory and Application. Water Resources Research. 35(7) 2225-2235.

Raju, K.S., L. Duckstein, and C. Arondel, 2000. Multicriterion Analysis for Sustainable Water Resources Planning: A Case Study in Spain. Water Resources Management. 14(6):435-456.

Raju, K.S. and D.N. Kumar, 1999. Multicriterion Decision Making in Irrigation Planning. Agricultural Systems. 62(2):117-129.

Raju, K.S. and C.R.S. Pillai, 1999a. Multicriterion Decision Making in River Basin Planning and Development. European Journal of Operational Research. 112(2):249-257.

Raju, K.S. and C.R.S. Pillai, 1999b. Multicriterion Decision Making in Performance Evaluation of an Irrigation System. European Journal of Operational Research. 112(3):479-488.

Randhir, T.O., J.G. Lee, and B. Engel, 2000. Multiple Criterion Dynamic Spatial Optimization to Manage Water Quality on a Watershed Scale. 43(2):291-299.

Reynolds, K.M., 2001. Using a Logic Framework to Assess Forest Ecosystem Sustainability. Journal of Forestry 99:26-30.

Reynolds, K.M. 1999. EMDS Users Guide (Version 2.0): Knowledge-Based Decision Support for Ecological Assessment. Gen. Tech. Rep. PNW-GTR-470. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 63 p.

Reynolds, K.M., C. Cunningham, L. Bednar, M. Saunders, M. Foster, R. Olson, D. Schmoldt, D. Latham, B. Miller, and J. Steffenson, 1996. A Knowledge-Based Information Management System for Watershed Analysis in the Pacific Northwest U.S. AI Applications 10:9-22.

Reynolds, K.M., M. Jensen, J. Andreasen, and I. Goodman, 1999. Knowledge-Based Assessment of Watershed Condition. Computers and Electronics in Agriculture 27:315-333.

Ringelman, J.K., 1991. Evaluation and Managing Waterfowl Habitat: A General Reference on the Biological Requirements and Management of Ducks and Geese Common to Colorado. Colorado Division of Wildlife, Division Report No. 16. June 1991.

Roloff, G.J. and B.J. Kernohan, 1999. Evaluating Reliability of Habitat Suitability Index Models. Wildlife Society Bulletin, 27(4): 973-985.

Roy, Bernard, 1968. Ranking and Choice in Pace of Multiple Points of View (ELECTRE Method), 1968. Revue Francaise d'Ionformatique de Recherche Operationnelle 2(8):57+.

Royle, J.A., M.D. Koneff, and R.E. Reynolds, 2002. Spatial Modeling of Wetland Condition in the U.S. Prairie Pothole Region. Biometrics 58(2): 270-279.

Saaty, T.L., 1980. The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill International Book Co., New York.

Saila, S.B., 1996. Guide to Some Computerised Artificial Intelligence Methods. *In* Mergrey, B.A. and E. Moksness, eds. Computers in Fisheries Research. Chapman and Hall, London, pp. 8-37.

Schmoldt, D.L., and D.L. Peterson, 2000. Analytical Group Decision Making in Natural Resources: Methodology and Application. Forest Science 46(1): 62-75.

Schmoldt, D.L. and H.M. Rauscher, 1996. Building Knowledge-Based Systems for Natural Resources Management. Chapman & Hall, New York, NY.

Schmoldt, D.L., 1987. Evaluation of an Expert System Approach to Forest Pest Management of Red Pine (Pinue resinosa). Ph.D. dissertation. University Microfilms International.

Schott, Robert, Lower South Platte Water Conservancy District, Sterling, Colorado. Personal communication, May 20, 2001

Schroeder, R.L., 1996. Wildlife Community Habitat Evaluation Using and Modified Species-Area Relationship. Wetlands Research Program Technical Report WRP-ED-12, U.S. Army Engineer Waterways Experiments Station, Vicksburg, MS.

Schweickert, R., A.M. Rurton, N.K. Taylor, E.N. Corlett, N.R. Shadbold, and A.P. Hedgecock, 1987. Comparing Knowledge Elicitation Techniques: A Case Study. Artificial Intelligence Review 1:245-253.

Shafer, G, 1976. A Mathematical Theory of Evidence. Princeton University Press, Princeton, NJ.

Shannon, Michael, Ducks Unlimited, Sterling, Colorado. Personal communication, October 9, 2001

Shaw, C.G., F.H. Everest, D.N. Swanston, 2000. Working with Knowledge at the Science/Policy Interface: A Unique Example from Developing the Tongass Land Management Plan. Computers and Electronics in Agriculture 27(1-3):377-387.

Shaw, S.P. and C.G. Fredine, 1956. Wetlands of the United States - Their Extent and Their Value to Waterfowl and Other Wildlife. U.S. Department of the Interior, Washington, D.C. Circular 39.

Shim, K.-C., D.G. Fontane, and J.W. Labadie, 2002. Spatial Decision Support System for Integrated River Basin Flood Control. ASCE Journal of Water Resources Planning and Management 128(3):190-201.

Shortliffe, E.H., 1976. Computer-Based Medical Consultations: MYCIN. American Elsevier, New York.

Shortliffe, E.H. and B.G. Buchanan, 1975. A Model of Inexact Reasoning in Medicine. Mathematical Biosciences 23: 351-379.

Siegel, D.I., 1988. The Recharge-Discharge Function of Wetlands Near Juneau, Alaska: 1. Hydrogeological Investigations. Ground Water 26(4):427-434.

Smith, R.D., A. Amman, C. Bartoldus, and M.M. Brinson, 1995. An Approach for Assessing Wetland Functions Using Hydrogeomorphic Classification, Reference Wetlands, and Functional Indices. U.S. Army Engineer Waterways Experiment Station: Vicksburg, MS.

Soil Survey Staff, U.S. Department of Agriculture, 1951. Soil Survey Manual. U.S. Department of Agriculture Handbook No. 18.

Sojda, R.S., 2002. Artificial Intelligence Based Decision Support for Trumpeter Swan Management. Ph.D. dissertation. Colorado State University. Fort Collins, CO.

Sojda, R.S., J.E. Cornely, and A.E. Howe, 2002. Development of an Expert System for Assessing Trumpeter Swan Breeding Habitat in the Northern Rocky Mountains. Waterbirds 25:313-318 Supp. 1.

Sophocleous, M., A. Koussis, J. Martin, and S. Perkins, 1995. Evaluation of Simplified Stream-Aquifer Depletion Models for Water Rights Administration. Ground Water 33(4):579-588.

Stephenson, R., 1997. In-season management in the 4WX herring fishery. DFO Maritime Regional Fisheries Status Report 97/2E.

Stevenson, R. J. and F. R. Hauer. 2002. Integrating Hydrogeomorphic and Index of Biotic Integrity Approaches for Environmental Assessment of Wetlands. Journal of North American Benthological Society 21(3):502-513.

Stewart, T.J. and L. Scott, 1995. A Scenario-Based Framework for Multicriterion Decision-Analysis in Water Resources Planning. Water Resources Research. 31(11):2835-2843.

Stoms, D.M., J.M. McDonald, and F.W. Davis, 2002. Fuzzy Assessment of Land Suitability for Scientific Research Reserves. Environmental Management 29(4):545-558.

Store, R. and J. Kangas, 2001. Integrating Spatial Multi-Criteria Evaluation and Expert Knowledge for GIS-Based Habitat Suitability Modelling. Landscape and Urban Planning 55(2):79-93.

Strauss, S., 1997. Fisheries Decision Overshadows Scientists' Debate. The Globe and Mail. September 6, 1997.

Surko, P., 1989. Tips for Knowledge Acquisition. PC AI 3(3):14-18.

Thill, J.-C. (Editor), 1999. Multicriteria Decision-Making and Analysis: A Geographic Information Sciences Approach. Ashgate Publishing, Brookfield, VT.

Thom R.M., 2000. Adaptive Management of Coastal Ecosystem Restoration Projects. Ecological Engineering 15 (3-4): 365-372.

Timberman, R., US Fish and Wildlife Service, Brush, Colorado. Personal communication, May 31, 2001;

Tkach, R.J. and S.P. Simonovic, 1997. A New Approach to Multi-Criteria Decision Making in Water Resources. Journal of Geographic Information and Decision Analysis 1(1):25-44.

Vadas, R.G., L.A. Garcia and J.W. Labadie. 1995 A Methodology for Water Quantity and Quality Assessment for Wetland Development. Water Science and Technology 31 (8):293–300

Vlahavas, I., I. Stamelos, I. Refanidis, and A. Tsoukias, 1999. ESSE: An Expert System for Software Evaluation. Knowledge-Based Systems 12(4):183-197.

Warner, J.W., J Altenhofen, J. Odor, and B. Welch, 1994. Recharge as Augmentation in the South Platte River Basin. Groundwater Program Technical Report 21. Colorado Water Resources Research Institute, Fort Collins, CO.

Whittecar, G.R. and W.L. Daniels, 1999. Use of Hydrogeomorphic Concepts to Design Created Wetlands in Southeastern Virginia. Geomorphology 31 (1-4): 355-371.

Willig, Carla, 2001. Introducing Qualitative Research in Psychology: Adventures in Theory and Method. Open University Press: Philadelphia.

Winter, T.C., 1999. Relation of Streams, Lakes and Wetlands to Groundwater Flow Systems. Hydrogeology Journal 7(1):28-45.

Wood, W.W. and W.R. Osterkamp, 1987. Playa-Lake Basins on the Southern High-Plains of Texas and New Mexico. Geological Society of America Bulletin 99 (2): 215-230.

Worrall, L., 1991. Spatial Analysis and Spatial Policy Using Geographic Information Systems. Belhaven Press, London.

Xie, J., J. Liu, and R. Doepker, 2001. DeerKBS: a Knowledge-Based System for White-Tailed Deer Management. Ecological Modelling 140:177-192.

Zadah, L.A., 1999. Fuzzy Sets as a Basis for a Theory of Possibility. Fuzzy Sets and Systems 100: 9-34 Supplemental Spring 1999.

Zadeh, L.A., 1973. Outline of a New Approach to the Analysis of Complex Systems and Decision Processes. IEEE transactions on systems, man and cybernetics, Vol. SMC-3, No. 1, January 1973.

Zadeh, L.A., 1965. Fuzzy Sets. Information and Control. 8(3):338-353.

Zeleny, M., 1973. Compromise Programming. *In:* J. L. Cochrane and M. Zeleny (eds.) Multiple Criteria Decision Making, Univ. of South Carolina Press, Columbia, 1973.

APPENDIX A
BACKGROUND ON RECHARGE PONDS IN THE LOWER SOUTH PLATTE

Recharge ponds are a means by which the alluvial aquifers and streams are conjunctively managed to take advantage of the temporal variability in streamflows and the storage capacity of the aquifers. Water is taken from the stream during high flow/low demand periods, when unappropriated water is available, and placed in a recharge pond.[1] The water seeps from the pond into the aquifer, and flows back to the stream at a rate determined by the properties of the aquifer. Figure A-1 illustrates how these recharge facilities have been used to augment streamflows to satisfy water law requirements associated with the replacement of out-of-priority depletions caused by junior water rights, to meet interstate compact requirements, and for species restoration programs.

These ponds have become particularly important in the Lower South Platte River Basin of Colorado (see Figure A-2). This river basin encompasses a region that is largely agricultural. Water users utilize managed groundwater recharge to allow the pumping of wells, particularly for seasonal water use to support irrigated agriculture, as well as to re-time river stream flows in support of a multi-state endangered species recovery program and species restoration activities within Colorado. The Lower South Platte Basin, which includes Sedgwick County, has relied heavily on the work of a handful of individuals to select, develop and manage recharge sites, and particularly on one individual water resources engineer.

The development of new recharge ponds in the target region has accelerated rapidly, particularly in response to emerging legal and administrative issues related to the development of permanent decrees and plans to augment streamflows to offset well depletions. As of 1994, there were about 60 recharge ponds in the entire South Platte basin, representing about ¾ of all artificial recharge activities in the State of Colorado (Warner et al. 1994). By 2002, there were a total of 163 active recharge sites in the Lower South Platte Basin alone (encompassing State Engineer's Office Districts 1, 2, and 64), of which 119 sites became operational for the first time in 2001 and 2002. Just within District 64, which covers the northeastern corner of Colorado including all of Sedgwick County, there were 73 operational sites by 2002, of which 42 became newly operational in 2001 and 2002. During 2001, a total of 150,688 acre-feet of water was recharged in ponds in these three SEO divisions, as shown in Figure A-3. Although dozens of new recharge ponds were developed in the Lower South Platte basin in 2002, less total water was recharged into both new and existing ponds because of lack of availability of water during the 2002 drought in Colorado. This drought has further raised awareness of the importance of recharge ponds as a tool for water management in this region.

Recent court and legislative activities have led to a severe reduction in the number of wells allowed to operate in this region. Prior to 2003, when well augmentation legislation ("Senate Bill 73") was passed, there were more than 5,000 wells operating in the Lower South Platte region. More than 1,000 of these wells were prevented from

[1] Managed groundwater recharge can also be developed by running water through irrigation ditches during times when irrigation is not occurring. The ditch company receives recharge credits for stream augmentation from the water seeping from the irrigation ditches into the aquifer.

operating in 2003 because the well owners lacked streamflow augmentation plans, which often include recharge facilities, to replace depletions from these wells.

With dozens of new recharge sites being developed in the Lower South Platte basin in a year, and more than one thousand wells requiring streamflow augmentation in order to become operational again, there is a need for computer support for the selection and evaluation of potential recharge pond sites. By capturing the expertise of the individuals who have been primarily responsible for the selection, development, and management of recharge ponds, the continued growth of recharge pond development can be supported. A systematic approach to the analysis of potential recharge sites, as demonstrated in the methodology presented here, can also form the basis for regional analysis and planning of pond development and conjunctive management of the region's water resources.

Another important component of this research has been the review of existing databases, GIS coverages, and potential evaluation criteria to identify criteria that were measurable and for which data was available or could be readily developed in computerized databases and GIS coverages to support evaluation using computer-based tools. With regard to the target region for this case study application, several changes are underway in the availability of data, particularly due to a state-funded effort to develop a basin-wide decision support system for the South Platte (SPDSS), for which new data will be collected, and ongoing developments associated with the South Platte mapping and analysis program (SPMAP).

In addition to these efforts, several new water user organizations have been created to coordinate recharge pond development and recharge credit transfers in the basin in response to changes in Colorado water law. These new water organizations are collecting their own data on their members' water use and recharge needs. Existing water user organizations have been changing the manner in which they request and store data on water use and recharge requirements from member well owners, and developing tools to provide better water management support and accounting services to their members. These water user organizations are often the "front line" in dealing with individual well owners, and the Colorado State Engineer's Office (SEO) relies upon data provided by these organizations for databases, planning, and regulation of water rights. A better understanding of the quality of the data currently available and the ways in which collected data can be used to support planning and management decisions is critical at this time when new databases and management tools are under development.

In Colorado, return flows from recharge ponds can be used as "credits" in water rights accounting to offset stream depletions created by well withdrawals. Credits from return flows can only be applied to offset depletions from withdrawals that occur within a specific reach of the river and at the same time period as those depletions.

There is a lag time in the impacts of both the recharge ponds and the well withdrawals. Typically, and as allowed by the SEO, the stream depletion caused by a well, or stream accretion created by a recharge pond, is calculated by the "Glover Method" (Glover, 1964), which is represented graphically in the Lower South Platte by U.S. Geological Survey (USGS) (Jenkins, 1968) and is referred to as the Stream Depletion Factor (SDF). The SDF is the time (in days) where the volume of stream depletion is 28% of the net volume pumped during time t, as expressed in:

$$SDF = \frac{\alpha^2 S}{T}$$

where α = perpendicular distance from the well to the stream, S = specific yield of the aquifer, and T = transmissivity. The same SDF factors used to determine stream depletions caused by well withdrawals are typically used to determine stream accretions resulting from groundwater recharge to the alluvial aquifer. The recharge ponds are, in effect, represented as injection wells (negative pumping wells) for modeling purposes. The USGS has calibrated the SDF factors using finite-difference modeling techniques, and created isochronic maps of the region with lines indicating locations with the same length of time over which 28% of recharged water would reach the South Platte River, as illustrated in Figure A-4. These SDF lines are used to determine the location of ponds and the timing and quantity of recharge needed to augment stream flows and offset well depletions

Well owners must file augmentation plans in water court, through the SEO (which acts as an agent of the courts), in which the well owner states the amount and timing of out-of-priority stream depletions created by well withdrawals and the amount and timing of stream accretions to be created through recharge credits from a recharge pond. Other sources of stream augmentation, such as dam releases, may also be used. Well owners may file their augmentation plans directly or through a water user organization.

If a recharge pond creates more return flows than a well owner needs to provide as streamflow augmentation to offset the impacts of his or her own wells, those excess "recharge credits" can be leased to downstream water users to augment their depletions. Water user organizations such as the Groundwater Appropriators of the South Platte (GASP) and the South Platte Lower River Group (SPLRG) historically have accepted or leased out excess credits created by member water users. Water user organizations and ditch companies also may share the costs for pond development, operation and maintenance with the landowner, or contribute technical support, typically in exchange for some of the recharge credits generated by the pond. The Northern Colorado Water Conservancy District (NCWCD) provides an Augmentation/Recharge Accounting (ARA) service to water users in the Lower South Platte basin, and prepares reports for the State Engineer's Office on behalf of area water users stating the timing and amount of water placed in the ponds, timing and amount of stream accretions, and ownership of the accretion credits.

Figure A-1. Schematic of a Recharge Pond for Streamflow Augmentation

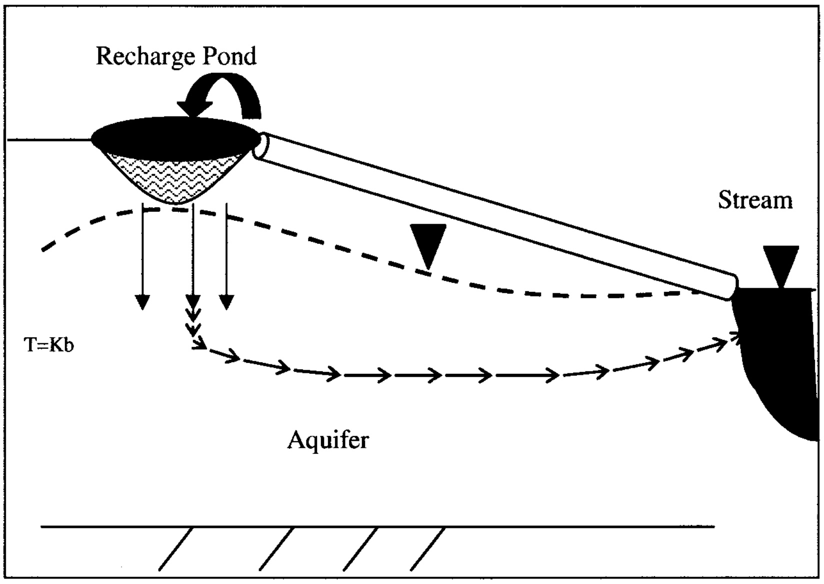


Figure A-2. Map of Lower South Platte Basin of Colorado

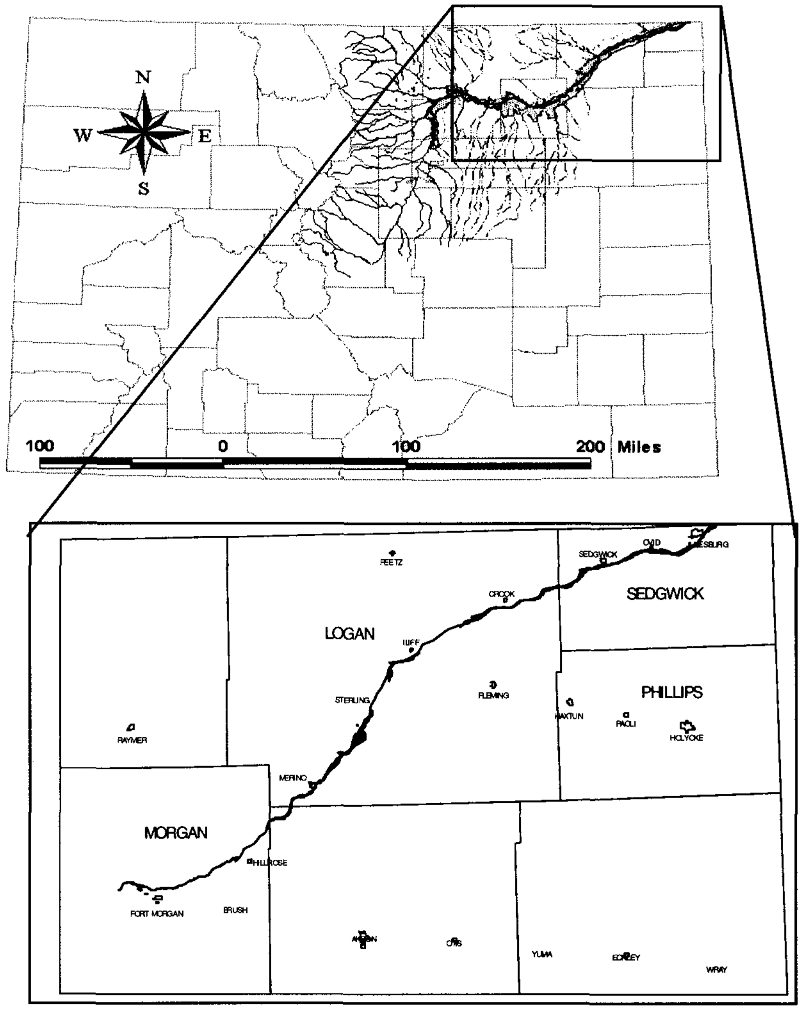
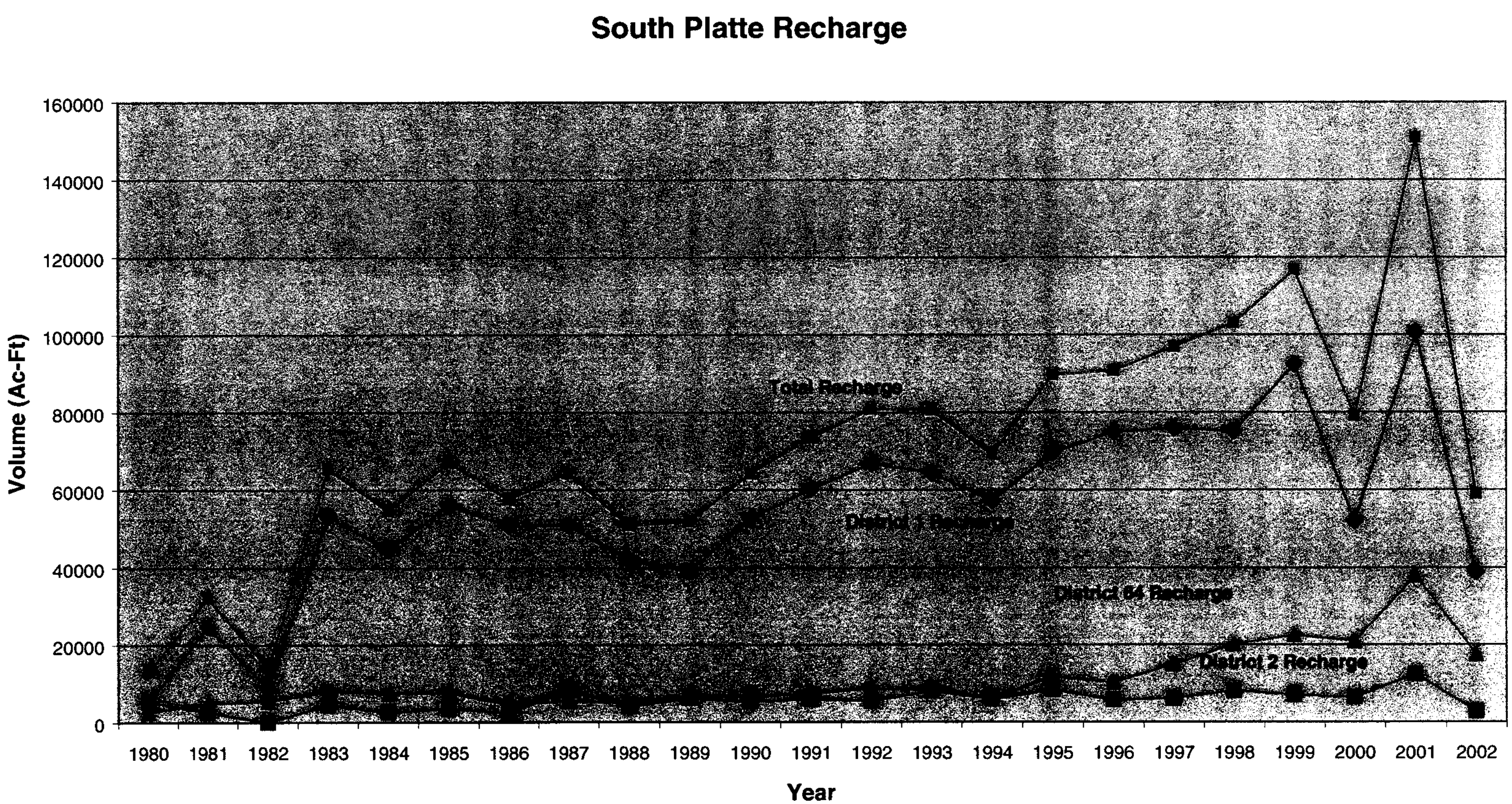
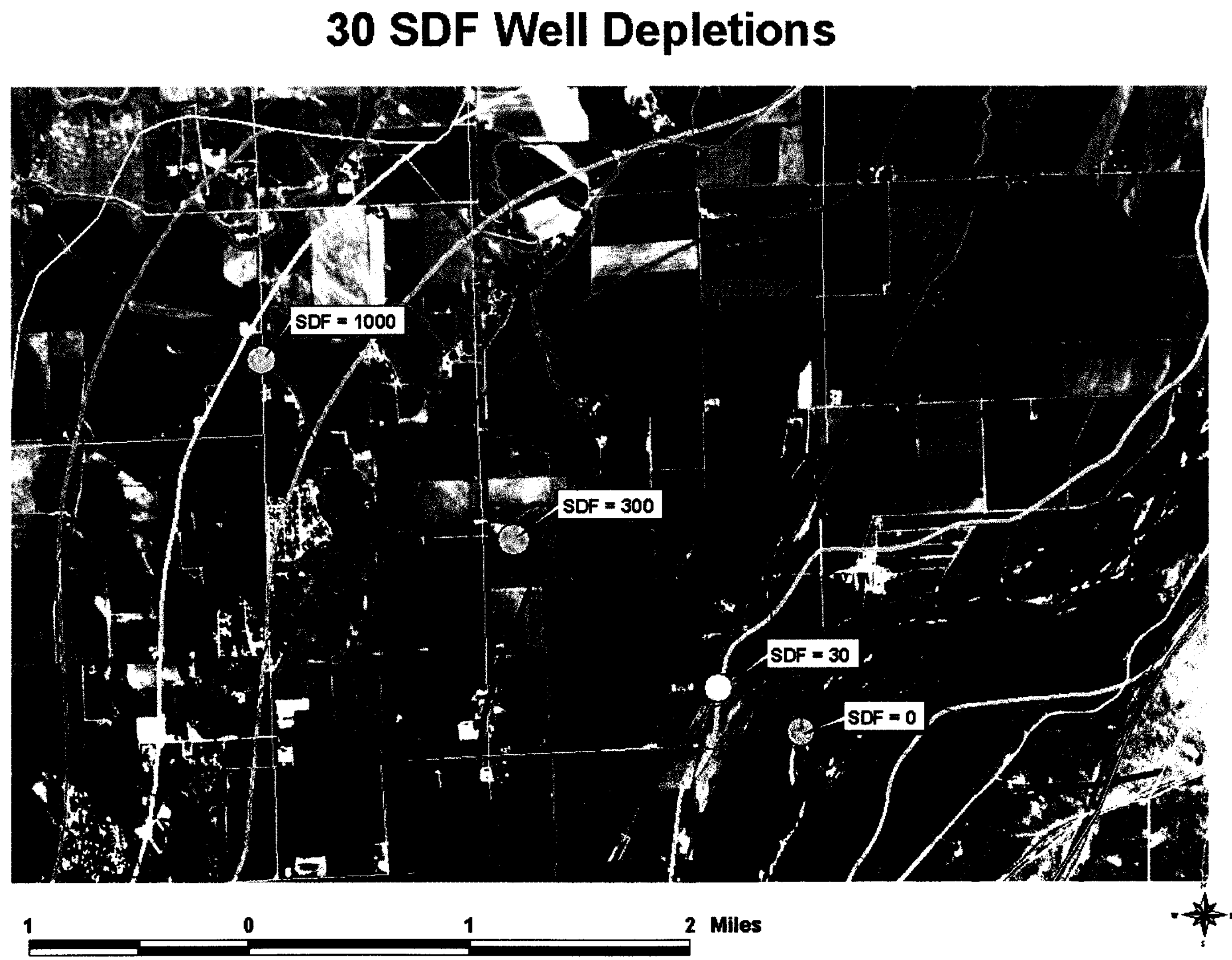


Figure A-3. Volume of Water (in acre-feet) Recharged to Alluvial Aquifer Via Recharge Ponds in Lower South Platte Water Districts 1, 2, and 64



Source: Colorado Division of Water Resources/State Engineer's Office, Division One, August 20, 2003

Figure A-4. SPMAP printout showing Stream Depletion Factor Lines



APPENDIX B
BACKGROUND ON WATERFOWL HABITAT AND WETLANDS
RESTORATION IN THE LOWER SOUTH PLATTE

B-1 Background on Waterfowl and Other Riparian Species Habitat in the Lower South Platte of Colorado

The Lower South Platte of Colorado provides important habitat for waterfowl and several other species, including several wetland-dependent species listed by the Colorado Division of Wildlife (CDOW) as species of concerned, threatened, or endangered. The Colorado Statewide Waterfowl Management Plan (1989) notes that, "[a]s a mid-latitude state, Colorado provides valuable habitat for breeding, migrating, and wintering waterfowl." (CDOW 1989, page 1) In particular, this plan identifies the eastern plains riverbottom habitat in the High Plains Riverine region, which includes the Lower South Platte, as "the most important region for migrating and wintering waterfowl, and of high importance for breeding waterfowl."

This region has been determined to be attractive to waterfowl primarily for its variety of water bodies, with the associated range of aquatic habitats provided by these water bodies, and variety and abundance of food sources. The CDOW Statewide Waterfowl Management Plan notes that the regions reservoirs, rivers, and canals provide secure areas for roosting and courtship. Smaller, shallow natural and man-made wetlands with emergent vegetation provide seeds from moist-soil plants as well as aquatic invertebrates that are important dietary requirements during the fall, as waterfowl prepare for migration and wintering. Warmwater sloughs, which do not freeze during the winter, provide "fall back" wetlands habitat for ducks and some geese during extremely cold weather, as do other, manmade water bodies (e.g. canals and parts of reservoirs) which remain unfrozen (CDOW 1989, page 25). In addition to the aquatic habitats provided in this region, the Lower South Platte and similar High Plains Riverine areas in eastern Colorado provide important sources of carbohydrate-rich food sources, particularly the waste cereal grains from the agricultural activities in the region, which provide high energy foods needed by the birds for migration. The CDOW Statewide Waterfowl Management Plan notes that "[t]he well-being of waterfowl in this region is closely tied to agricultural practices." Waste grains, particularly from corn, has been found to comprise more than half of the mallard's winter diet (Baldassarre et al. 1983, Jorde et al. 1983, Gordon 1981) and an important component of the diet of Canada geese (e.g. Staffon 19760 and snow geese (e.g. Frederick et al. 1987) as well.

The South Platte basin has been found to provide breeding habitat for numerous waterfowl species, as cited in the South Platte Wetlands Focus Area Committee (SPWFAC) Strategic Plan for Landscape Level Wetlands Conservation. SPWFAC estimates that roughly "20,000 duck pairs breed within the South Platte basin with the primary species being Mallard ($\bar{x}$ = 12,468 pairs), Gadwall ($\bar{x}$ = 2,229 pairs), Redheads ($\bar{x}$ = 1,844 pairs), Northern Shoveler ($\bar{x}$ = 1,572 pairs), Blue-winged Teal ($\bar{x}$ = 977 pairs), and Canada Geese." (SPWFAC 2002, page 11) Other wetland-dependent bird species that breed in the Lower South Platte region White Pelicans, Double-crested Cormorants, Western and Clarks grebes, Sora, Virginia Rail, American Coot, Killdeer, Spotted Sandpiper, and American Avocet, while "both Red-winged and Yellow-headed blackbirds and Marsh Wrens use emergent wetland vegetation in the valley for nesting."

(SPWFAC 2002, page 11) Shorebirds commonly stop in this region during fall migration, including Western and Baird's sandpipers; Franklins, California, Ringbilled gulls; and Forester's and Black terns. Waterbird species that remain in the region for wintering, particularly at or near unfrozen micro-habitats, include Canada Geese, mallards, Common Goldeneye, Common Mergansers, rail, common snipe, and killdeer.

The Lower South Platte provides important habitat for several species other than waterbirds. The Final Environmental Assessment (EA) for the Tamarack Managed Groundwater Recharge Project at Tamarack Ranch State Wildlife Area and Pony Express State Wildlife Area (CDOW 1999) notes that the Lower South Platte region contains riparian plant communities that support some of the most productive and diversified ecosystems in the western United States. More than one third of all vertebrate species in Colorado have been recorded in river and stream riparian zones. According to Fitzgerald (1978), the South Platte bottomlands are home to 109 bird species, 23 mammal species, 14 species of reptiles, and 5 species of amphibians. Knopf (1986) observed 83 species of birds frequenting the South Platte River. Kufeld and Bowden (1995) found that shrub and forest dominated wetland/riparian communities are the prime habitats for 80% of the white-tailed and mule deer surveyed. Common upland species in the region that use riparian habitat in the Lower South Platte region, as noted in the EA (CDOW 1999) include mule deer, white-tailed deer, wild turkey, cottontail rabbit, coyote, western box turtle, lesser earless lizard, bullsnake, meadow lark, mourning dove, bobwhite quail, ring-necked pheasant, black-billed magpie, and American Kestral.

During the winter, the federally-listed bald eagle is also seen in this region, particularly in migratory waterfowl resting areas. The bald eagles find both mature cottonwood trees for perching and roosting and waterfowl to provide a prey base, and it is not uncommon to find twenty to thirty bald eagles at many reservoirs in the region during the waterfowl migration period (CDOW 1999). Federally and state listed threatened and endangered species in the Lower South Platte, as identified by CDOW habitat biologist Shane Briggs, are identified in Table B-1. This table also lists Colorado species of special concern in the region; species of special concern are those species identified by CDOW for restoration efforts to prevent their listing on state or federal threatened and endangered species lists.

B-2. Opportunities for Dual-Purpose Pond Development for Habitat and Stream Augmentation Benefits in the Lower South Platte

Managed groundwater recharge facilities, or "recharge ponds," have been developed as a means of conjunctive water resources management in accordance with the *prior appropriation* doctrine of water law. If designed properly, recharge ponds can serve as wetlands habitat for various wildlife species. There are several incentives for the development of "dual-purpose" ponds which can provide both stream habitat and streamflow augmentation credit benefits. There is extensive alluvial land along the Lower South Platte owned by CDOW as "State Wildlife Areas" which may provide suitable sites for recharge ponds as part of a regional conjunctive use management plan. Landowners may also be able to benefit from fees they can charge for hunting of waterfowl on their property. Integration of wildlife habitat into recharge facilities developed on these CDOW lands is necessary to meet the purchase agreement requirements for the use of those state properties. In addition, integration of wildlife habitat into recharge facilities on private lands has potential benefits for these landowners, who can participate in partnership programs that provide technical and financial support for recharge pond development in cases where habitat benefits are accrued. Finally, both public and private landowners support wildlife restoration goals for the region, particularly if locally-based restoration efforts can prevent the need for federal intervention.

Water user organizations and habitat partnership programs, along with state water and wildlife agencies, have begun to work cooperatively in the Lower South Platte to plan the development of ponds to support regional water management goals as well as regional wetlands development to support restoration of habitat, particularly for waterfowl. Ducks Unlimited (DU), the U.S. Fish and Wildlife Service's Partnership for Fish and Wildlife (PFW) program, and the Natural Resources Conservation Service's Wetlands Reserves Program (WRP) have all wetlands at pond sites that were also intended to serve as recharge ponds (Mike Shannon, Ducks Unlimited, personal communication, October 9, 2001; Bob Timberman, US Fish and Wildlife Service, personal communication, May 31, 2001; personal communication, Bob Schott, May 20, 2001).

These pond sites have typically been designed for resident or migratory waterfowl. To design these sites, area habitat biologists refer to several handbooks that provide guidance on waterfowl habitat management (Cross and Vohs, 1988; National Biological Survey, 1995; U.S. Bureau of Land Management, 1989). Habitat partnership programs have found the seasonal nature of recharge ponds to be well suited for the support of both migratory and resident waterfowl (Mike Shannon, personal communication, October 9, 2001; Bob Timberman, US Fish and Wildlife Service, personal communication, May 31, 2001). The annual cycle of breeding, migration and overwintering results in changes in the birds' dietary requirements throughout the year. Area wildlife biologists have stated that shallow standing water (typically less than 18 inches deep) is required during the spring months, so that the birds can feed on water insects to increase their protein intake for egg production. If the standing ponds are allowed to drain to create mud flats, the waterfowl feed off the seeds. Waterfowl also feed on corn grown in the area, increasing their carbohydrate intake as required for overwintering and migration. Recharge facilities can be set up to feed year-round water bodies, such as lined ponds and live streams, for species that require water all year, including fish (Jay Stafford and Shane Briggs, personal communication, September 11, 2001).

The Tamarack Plan Recharge, Minnow Stream & Wetland Habitat Project, a demonstration project on the west side of the Tamarack Ranch State Wildlife Area, is one of the first sites at which a recharge facility has deliberately been designed and operated to maximize both the recharge credits produced at the site and the habitat benefits. This project, developed as part of the Colorado Tamarack Plan, was designed and created cooperatively by South Platte Lower River Group (SPLRG) water resources engineers, CDOW aquatic and habitat biologists and geomorphologists, and DU ecologists.

The Tamarack Plan Recharge, Minnow Stream & Wetland Habitat Project includes two recharge ponds fed from water piped up from wells along the river (such wells are considered "direct diversions" under Colorado Water Law and do not require augmentation plans). Some of the water from the recharge ponds is diverted into the three storage ponds, which are lined at the bottom so that water does not seep into the aquifer. These storage ponds serve as temperature control ponds for use during the summer months, when the water temperature in the live stream needs to be above the temperature of groundwater. SPLRG water engineers estimated that, during the summer months, the water stored in the ponds would increase in temperature by up to 5 degrees Fahrenheit per pond during a storage period of approximately one week. The water flows through the temperature control ponds into a live minnow stream. With three temperature control ponds, the maximum potential temperature increase is 15 degrees Fahrenheit. The source water is groundwater, which is typically 57 degrees Fahrenheit in Colorado. The three temperature control ponds were expected to increase the water temperature to roughly 70 degrees Fahrenheit, a temperature more suitable for minnows. Temperature measurements have been taken weekly by Lower South Platte Water Conservancy District (LSPWCD) staff on behalf of CDOW at the upper recharge pond, the stream headgate, and the stream outlet, and the water temperature has been found to increase as predicted.

The live minnow stream was designed to serve as a study site for three minnow species that are native to the Lower South Platte. The minnow species (namely the brassy minnow, suckermouth minnow, and plains minnow) had been added to the state's list of threatened and endangered species in 1998 as a result of CDOW's Inventory and Status of South Platte River Native Fishes in Colorado (Nesler et al., 1997). The suckermouth minnow and plains minnow were added to the Colorado endangered list, and the brassy minnow was added to the Colorado threatened list (CDOW press release, May 8, 1998). All three species had previously been designated "species of special concern" in Colorado. Although the CDOW inventory showed declining populations of these species, little was known regarding their life cycles and habitat requirements, which are being studied at the Tamarack Ranch facility. CDOW Aquatic Biologist Jay Stafford has been monitoring the transplanted fish populations and has found that the minnows have survived as of September 2002.

Water flowing out of the live stream is then diverted into another constructed habitat site: a series of three wetland cells designed and constructed by DU under the supervision of DU Biologist Mike Shannon. The DU staff has designed the wetland cells on a flat portion of the riparian land that is underlain by clay, so that water in the wetland cells seeps more slowly into the aquifer. The cells have water control structures that are designed to allow for complete drainage of the cells. During the spring, the wetland cells are filled with water from the live stream to a maximum depth of 18 inches. This type of habitat allows the ducks to feed on aquatic insects to increase their protein intake for egg production. During the late spring, the water control structure is removed and the standing water drained to the river, turning the wetland cells into mudflats which serve as feeding grounds for the waterfowl, providing seeds for the waterfowl to feed on. The Demonstration Project is the first of several planned projects to be developed jointly by CDOW and SPLRG, with seed funding provided by the Colorado Water Conservation Board.

B-3. Background on Waterfowl Habitat Partnership Programs and Restoration Efforts in the Lower South Platte and Associated Automated Approaches to Waterfowl Habitat and Wetlands Assessment and Available Data Sources for the Lower South Platte

The Lower South Platte lies on the boundary between two Joint Ventures under the U.S. Fish and Wildlife North American Waterfowl Management Plan, which is a voluntary, non-regulatory approach to conserving migrating birds and their habitat. Joint Ventures are habitat-based partnerships comprised of individuals, corporations, conservation organizations, and local, state, and federal agencies. One of the largest joint ventures in the United States is the Intermountain West Joint Venture, which includes the northern side of the South Platte Basin, along with most of central and western Colorado, plus all or part of 10 other western states from Mexico to Canada. The Playa Lakes Joint Venture, which includes the southern part of the Lower South Platte basin as well as most of southeastern Colorado, focuses on the more than 25,000 wetlands known as "playas" across the southern High Plains of the U.S. Playas are 10 to 100 acre shallow, circular basins. Over 200 playas have been identified in southeastern Colorado. Depending on the season, these basins can provide habitat for waterfowl, shorebirds, cranes and other migratory birds.

As part of Colorado's participation in the North American Waterfowl Management Plan, the CDOW Colorado Wetlands Program has organized several Wetlands Focus Area Committees around the state and has charged these committees with developing strategic plans for wetlands conservation in their respective regions. SPWFAC is the local implementation arm of the Colorado Division of Wildlife Wetlands Program, the Intermountain West Joint Venture, and the Playa Lakes Joint Venture for the South Platte basin. The SPWFAC is a working group of public and private partners organized to facilitate the development of wetland conservation projects. The purpose of this committee is to conserve wetlands that provide ecological services and societal benefits. SPWFAC's partners include the Colorado Division of Wildlife, Centennial Land Trust, Ducks Unlimited, Natural Resources Conservation Service (particularly the NRCS Wetlands Reserves Program), U.S. Fish and Wildlife Partners for Fish and Wildlife Program, Rocky Mountain Bird Observatory, Colorado Natural Heritage Program, and SPLRG, as well as several private landowners. As of November 2002, SPWFAC is finalizing its Strategic Plan for Landscape Level Wetland Conservation to promote collaboration and communication among organizations and individuals involved in wetland conservation in the region.

Because of the ecological significance of this region, CDOW identified Area 3, which includes the Lower South Platte from Brush to the Nebraska State Line, as one of two regions for which a prototype Integrated Management Process (IMP) system would be developed. Funded under Work Package 230 during the 2001-2002 fiscal year, these IMPs were intended to serve as a support system for landscape management decisions and plan development. IMPs are GIS-based systems included to provide a means of categorizing data and conditions and to manage data which support analysis of specific landscape conditions and management decision making. The IMPs are a conglomeration of various databases and assessment tools which are intended to support a wide range of tasks. Specific tasks the IMPs were expected to support include: understanding existing conditions, projecting future conditions, evaluating suitability, estimating sensitivity, monitoring change or performing other custom inquiries supported by the data and geographic data analysis assumptions (CDOW document 2001). The South Platte IMP workgroup, including the author, met monthly and compiled several GIS databases for the South Platte IMP prototype. The funding for Work Package 230 was not continued for fiscal year 2003 due to budget constraints.

Several modeling and mapping efforts related to wildlife habitat exist or are under development for all or part of the Lower South Platte region. These efforts were developed for different purposes, with maps and levels of accuracy at different scales, and several of these were GIS-based efforts identified during the South Platte IMP prototype development process. The following is a summary of some of the habitat modeling and mapping efforts identified in the Lower South Platte region and throughout Colorado, as of January 2003:

- **Natural Diversity Information Source (NDIS).** NDIS is not a specific mapping project but provides a web site through which a variety of biodiversity related information and analytical tools can be accessed. The project is being performed jointly by the Colorado Division of Wildlife (CDOW), the Colorado Department of Natural Resources (CDNR), and Colorado State University (CSU), with additional funding support by Great Outdoors Colorado, the Rocky Mountain Elk Foundation, CDOW, and CSU. The mission of the Natural Diversity Information Source (NDIS) is to provide data and analysis needed to enhance decisions on land-use affecting Colorado's animals, plants, and natural communities.
- **National GAP Project.** The National Gap Analysis Program (GAP) was developed by the USGS to provide broad geographic information on the status of ordinary species (those not threatened with extinction or naturally rare) and their habitats in order to provide land managers, planners, scientists, and policy makers with the information they need to make better-informed decisions.
- **ReGAP.** The Southwestern Regional GAP (ReGAP) was a five-state effort by the states of Colorado, Arizona, New Mexico, Utah, and Nevada, to refine the GAP for the purpose of identifying and managing for biological diversity in those states. During the development of the ReGAP, each state used different methods to develop land cover coverages (two states, including Colorado used visual processing, while three states used machine processing).
- **Colorado GAP.** The Colorado GAP was initiated in 1991 as a cooperative effort, led by the Colorado Division of Wildlife in collaboration with the Natural Resource Ecology Center (NERC/USFWS), and state, federal, and private natural resources groups in Colorado. For the Colorado GAP project, new imagery is being used and the land use coverages are being re-developed with machine processing. Using this method, better plant identification is expected. Colorado GAP will also include ecological modeling using the improved coverages and the addition of coverages indicating soils, slope, aspect, and moisture, with ground-truthing used to support the data identified from the imagery. Other data sets may be incorporated as needed for specific species. Four of the layers are tied to work completed by the Bureau of Land Management, with a resolution of 1:150,000. The GAP vegetation maps are derived from LANSAT satellite imagery, and have a resolution ranging from 1:100,000 to 1:250,000. Completion of Colorado GAP is targeted for 2004. Ultimately, CDOW expects Colorado GAP to have base data

that will support the development of decision rules to identify potentially suitable habitat for various species.

- **CDOW's Wildlife Resources Inventory System (WRIS).** WRIS is CDOW's field-based data capture which, as of October 2002, includes 44 species, including selected big game, small game, and threatened or endangered species. CDOW personnel note that not all species are conducive to mapping with the WRIS methodology, which is to send personnel to the field and mark species habitat on 1:150,000 county sheets. The maps have been converted to GIS files (some in shapefiles but most coverages), and include the overall range and the range of mappable activities (e.g. winter range, summer concentration, and production areas.) This project is based entirely on field-based knowledge, not on modeling. These maps have been updated on a 5-year cycle and are now being updated on a 4-year cycle, one region per year, with the state divided into four regions. A prototype WRIS for aquatic species is being added under a new small grant.
- **Colorado Riparian Vegetation Mapping Project.** The Colorado Riparian Vegetation Maps were developed by CDOW contractor James Ward, with data provided by CDOW and the US Forest Service. The data is 1:12000 delineation data, mapped at 1:24000. The NAPP color infrared photography was provided by the US Forest Service, who began the photointerpretation of the vegetation types, and the remainder of the photointerpretation was completed by the contractor.
- **Basinwide.** The Basinwide maps also indicate land cover and vegetation types, but because these coverages were derived from LANSAT satellite imagery, they are less detailed than the Riparian Vegetation maps, with coverages developed at a 1:50,000 scale. Basinwide also uses a different vegetation classification scheme from the one used in the Colorado Riparian Vegetation Mapping Project.
- **CDOW ADAMAS Project.** The CDOW is developing its Aquatic Database Management System (ADAMAS), which will include CDOW aquatic species sampling data. An internal "intranet" web-based version of ADAMAS and GIS coverages based upon the ADAMAS databases are under development, but are not currently available. Ultimately, an external "internet" version will also be available.
- **Rocky Mountain Bird Observatory (RMBO) Wetlands Monitoring and Evaluation Project (WMEP).** This project is being conducted by RMBO in cooperation with CDOW, the North American Waterfowl Management Plan Joint Ventures, SPWFAC, and others to implement conservation for wetland-dependant birds. WMEP includes the development of a database of projects funded by the Colorado Wetlands Program, and will include further monitoring data. A point database is being developed to tie the data to a GIS coverage.
- **Colorado Natural Heritage Program (CNHP) mapping projects and GIS coverages.** CNHP is a non-profit organization which provides "sound, reliable information for responsible resource decision making" related to Colorado rare species, subspecies and natural communities (or ecosystems). CNHP has developed several GIS coverages including:
    - **CNHP Potential Conservation Areas.** These coverages show primary areas that CNHP biologists determined to be important to conserve for rare species over time. The resolution of these coverages range from 1:24,000 to

1:100,000, as indicated in the coverage attribute tables. The species included in these coverages are those that have been identified by CNHP as globally rare (G1-G3 species), as well as globally common species that are rare in Colorado. Some data for element occurrences dates back to the 1800s.

- **CNHP Element Occurrences Maps.** These maps are available at three different scales, of which the highest resolution map series is at a 1:24,000 scale. These maps are polygon coverages showing the locations where rare and imperiled species or natural communities were documented to occur at one point in time, as seen in the field and reported by credible personnel (e.g. CNHP, CDOW, or U.S. Forest Service personnel). Depending upon the mapping precision of the occurrence of the species, the occurrences could be represented as points or as entire counties. Unlike WRIS, these maps do not indicate range or season. Coverages include plants, birds, mammals, natural communities, insects, mollusks, fish, amphibians and reptile species. The Lower South Platte counties, including Morgan, Washington, Logan, and Sedgwick Counties, have not yet been thoroughly surveyed although data from a variety of other projects are available.
- **CNHP Comprehensive Statewide Wetlands Classification and Characterization.** This project was developed by CNHP in partnership with CSU, the Colorado Department of Natural Resources, and the CDOW Wetlands Program to integrate previously collected data and develop a floristic (i.e. plant-based) classification for the wetlands of Colorado. The location of wetlands from CNHP and CDOW wetland inventories is included in a database that is being converted to a point coverage with an associated database indicating the wetland type according to the CNHP classification system.

B-4. Habitat Partnership Program Profiles

The main programs in the Lower South Platte involved in the development of waterfowl habitat ponds for which recharge facilities could be used to meet their program objectives were: 1) Ducks Unlimited, Inc. which administers North American Wetlands Conservation Act (NAWCA) grant money; 2) three of the Natural Resources Conservation Service Habitat Programs (namely the Environmental Quality Incentives Program, Wildlife Habitat Improvement Program, and Wetlands Reserve Program); and 3) the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program. There are several other programs available that partner with private landowners on the development of habitat, but some only were interested in uplands habitat or were otherwise not interested in types of habitat that could be created with recharge ponds. For example, the CDOW Pheasants Habitat Improvement Program and local chapters of Pheasants Forever support habitat development activities in the Lower South Platte region, but only in upland habitat areas, which are suitable for pheasants.

The three main habitat partnership programs differed in the way in which they interacted with the landowners and the level of flexibility with which field agents could select participating sites and set up agreements with landowners. These programs also varied in the types of projects they targeted. The method by which sites were selected for inclusion in their programs, and the types of information they sought in determining whether to include a site within their program. Information on each program is available in Appendix B. A brief description of each of these programs and their interest in recharge facilities is provided below:

1) **Ducks Unlimited, Inc.** Ducks Unlimited, Inc. (DU) is one of the oldest wetlands and wildlife conservation organizations in the United States. DU has been restoring wetlands since the 1930s, and is a source of expertise in the practical applications of wetlands restoration methods. DU's principal interest is in waterfowl. DU's role in wetland creation, restoration, and enhancement projects is primarily technical, ranging from provision of advice and site design to construction oversight. While DU has some funds available in the form of DU's MARSH (Matching Aid to Restore States Habitat) grants, DU's support for the funding of projects typically comes from outside sources. In other words, if DU finds a wetland project that will benefit waterfowl, the DU staff will find appropriate funding sources and prepare grant proposals. In Colorado, DU's main sources of funds have been from DU MARSH grants, North American Wetlands Conservation Act (NAWCA) grants, and CDOW Colorado Wetlands Initiative grants. Because of the effort required to obtain funding for projects, DU often is involved in larger projects, mainly on public lands, although DU also partners on some smaller projects and projects on private lands.

   In the Lower South Platte region, DU has been involved in the development of waterfowl habitat in association with individual recharge facilities since 1998, when DU partnered with USFWS's Partners for Fish and Wildlife Program on a 20-acre site near Merino that included a large recharge pond. DU designed this pond to provide varied water depths and an irregular shoreline to provide a variety of microhabitats within the pond. DU also played an active role in the design and development of the wetland cells at the Tamarack Ranch Recharge, Live Stream & Wetlands facilities.

   Current DU initiatives in the Lower South Platte region include their Habitat in the Heartland Initiative, including several projects under a North American Wetlands Conservation Act (NAWCA) grant. Habitat in the Heartland, as described on the DU web site (http://www.ducks.org/conservation/heartland.asp), targets critical mid-continent migration habitats that occur in the Rainwater Basin region of Nebraska and along the Platte River as in Colorado and Wyoming. DU received a NAWCA grant to support restoration activities in the Lower South Platte region in 2001. NAWCA was enacted in December 1989 and provides Federal cost-share funding to support the North American Waterfowl Management Plan. Its purpose is to stimulate public-private partnerships to protect, restore, and manage a diversity of wetland habitat for migratory birds and other wildlife. It also helps to maintain the proper distribution and abundance of migratory birds. DU has mainly been involved with larger restoration projects, e.g. the development of wetland cells on State Wildlife Areas (Tamarack Ranch and Brush Prairie Ponds).

   DU has been a partner in several CDOW initiatives, including the South Platte Wetlands Focus Area Committee (SPWFAC). DU has provided technical support for SPWFAC, including the development of GIS-based maps for the SPWFAC Strategic Plan, using HPAT coverages.

2) **Natural Resources Conservation Service Habitat Programs.** There are nearly two dozen separate agricultural conservation programs with a combined funding of $2.5 billion per year available from the 2002 Farm Bill, including several programs administered by the Natural Resources Conservation Service, often in conjunction with state wildlife agencies. The 1996 Farm Bill was described as "the strongest package of private-land wildlife habitat opportunities ever assembled" (CDOW May 2002). In 2002, the Farm Bill was approved for continued funding, with new programs and new objectives added. Some of the Farm Bill programs are applicable to the development of wetland habitat or other habitat types that may be associated with recharge facilities. These programs include the Environmental Quality Incentives Program (EQIP), the Wildlife Habitat Improvement Program (WHIP), the Wetlands Reserve Program (WRP), and the Conservation Reserve Enhancement Program (CREP). CREP, which targets irrigated agricultural lands, is still under development in Colorado, although the Conservation Reserve Program (CRP), which targets dryland agricultural lands, is already established in Colorado. EQIP, WHIP, and WRP, which have been used in Colorado since the late 1990s, are described below:

- **Environmental Quality Incentives Program (EQIP)**. EQIP is a land-management program that provides incentives to address conservation needs, including (but not limited to) fish and wildlife habitat, on croplands or land used for agricultural operations. Its purpose is to "promote agricultural production and environmental quality as compatible national goals." It is a locally driven program focused on priority resource needs. In addition to fish and wildlife habitat concerns, EQIP sites may be used to address such issues as soil erosion and water quality. EQIP may cost-share up to 75 percent of the costs of certain conservation practices. Incentive payments may be provided to encourage producers to carry out management practices they may not otherwise use without the incentive. However, limited resource producers and beginning farmers and ranchers may be eligible for cost-shares up to 90 percent. Farmers and ranchers may elect to use a certified third-party provider for technical assistance. An individual or entity may not receive, directly or indirectly, cost-share or incentive payments that, in the aggregate, exceed $450,000 for all EQIP contracts entered during the term of the Farm Bill. In the Lower South Platte, EQIP eligibility is typically determined by the NRCS Field Office staff for the county in which the site is located. The NRCS Field Office Staff complete a ranking sheet for the site. Several parameters must be determined and calculations completed using formulae provided on the forms to determine the site's EQIP ranking. Landowners are not required to give public access to their lands. However, the landowner must provide access to NRCS personnel to the land to monitor the effectiveness of management practices during the agreement period. There is a Ground and Surface Water Conservation provision that provides cost-share and incentive payments to producers where the assistance will result in a net savings in ground or surface water resources in the agricultural operation of the producer. In Colorado, this provision has been used in a portion of eastern Colorado that overlies the High Plains/Ogallala Aquifer, including parts of Logan, Sedgwick, Phillips, Yuma, and Washington Counties.

- **Wildlife Habitat Incentives Program (WHIP).** WHIP is a voluntary program for people who want to develop and improve wildlife habitat primarily on private land. Through WHIP, USDA's Natural Resources Conservation Service provides both technical assistance and financial assistance of up to 75 percent of the cost of practice installation to establish and improve fish and wildlife habitat. WHIP agreements between NRCS and the participant generally last from 5 to 10 years from the date the agreement is signed. Landowners may voluntarily limit future use on the land for a period of time, but retain private ownership, and are not required to provide public access to their lands. However, the landowner must provide access to NRCS personnel to the land to monitor the effectiveness of management practices during the agreement period. Sites are ranked according to a locally-developed ranking process to achieve State-specific wildlife goals and objectives, as determined by the NRCS Field Technical Committee with input from local work groups. In the Lower South Platte, WHIP eligibility is typically determined by the NRCS Field Office staff for the county in which the site is located. The NRCS Field Office Staff complete a ranking sheet for the site, referring to various indices and guides including several Colorado NRCS Technical Memoranda on habitat management practices, especially for specific species. Several parameters must be determined on the NRCS forms to determine the site's WHIP ranking.

- **Wetlands Reserve Program (WRP).** WRP is a voluntary program that provides technical and financial assistance to eligible landowners to address wetland, wildlife habitat, soil, water, and related natural resources concerns on private lands. The program provides an opportunity for landowners to receive financial incentives to restore and/or enhance wetlands. In addition to payment for easements and restoration costs in accordance with the enrollment option, USDA provides biological, engineering, and other technical support for the restoration and maintenance of the restored site. Some lands are ineligible, including wetlands converted after December 23, 1985. The landowner must own the land for at least 12 months prior to enrolling it, unless the land was inherited or meets other exemptions. There are three enrollment options:

1) A *permanent easement* is a conservation easement in perpetuity. Easement payments for this option are the lowest of: the agricultural value of the land; an established payment cap; or an amount offered by the landowner. In addition to paying for the easement, USDA pays 100 percent of the costs of restoring the land. USDA also pays all costs associated with recording the easement in the local land records officer, including recording fees, charges for abstracts, survey and appraisal fees, and title insurance.

2) A *30-year easement* is a conservation easement agreement that covers a

30-year period. For this easement, USDA pays 75 percent of what would be paid for a permanent easement, plus 75% of the restoration costs. USDA also pays all costs associated with recording the easement in the local land records officer, including recording fees, charges for abstracts, survey and appraisal fees, and title insurance.

3) A *Restoration Cost-Share Agreement* is a shorter-term agreement, typically for a minimum of 10 years) to re-establish degraded or lost wetland habitat. USDA pays 75 percent of the restoration costs. This option does NOT place an easement on the property. Other agencies or programs may provide additional assistance for easement payments and wetland restoration costs., and such partnerships are encouraged.

Further information is available in the CDOW May 2002 publication entitled Private Land Habitat Programs in Colorado and through the NRCS web site at: http://www.nrcs.usda.gov/programs/.

1) **U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program (PFW).** PFW has been operating within Colorado since 1988, and has developed more than 600 agreements with Colorado landowners. These projects have involved the restoration, creation or enhancement of more than 11,000 acres of wetlands, 49,000 acres of upland habitats, and 88 miles of riparian fencing through December 2001 (CDOW, May 2002). PFW completed its first wetlands restoration project involving a recharge pond in 1996 on a one-acre site near Snyder, CO. PFW does not target any specific species or habitat type, but has focused on wetlands for waterfowl and riparian habitats in the Lower South Platte region. PFW works only with privately owned lands. PFW develops cost-share agreements with the landowner. PFW and the landowner sign an agreement that states that the landowner will not return the project area to its former use, or damage or destroy the restoration project, during the agreement period without reimbursing the Service for the funds spent on the project. The length of the agreement is based on the level of the technical and financial assistance provided by the Service. Most agreements are for 10 years. According to the PFW web site (partners.fws.gov), PFW focuses projects in watersheds where conservation efforts will provide the greatest benefits for Federal trust species which include: migratory birds, anadromous (migratory) fish, and threatened and endangered species. The service also gives special consideration to projects that 1) are on permanently protected private lands; 2) are identified as high priority by federal or State fish and wildlife agencies and other partners; 3) are located near National Wildlife Refuges; 4) reduce habitat fragmentation; 5) conserve or restore natural communities which the state Natural Heritage Programs or Heritage Data Base have designated as globally or nationally imperiled; and 6) are self-sustaining systems that are not dependant on artificial structures. Length of time of the conservation easement, involvement by additional partners, and cost-effectiveness are also considerations. PFW operates under a block grant and is not required to assign a ranking number to individual sites, unlike the NRCS programs.

Consequently, PFW may be able to develop projects more quickly than NRCS. The landowner retains complete control of their property, and there is no obligation to allow public access. Further information on PFW can be found on the PFW web site at: http://partners.fws.gov/

The following pages provide specific information on each of the main programs in this region.

B-4. Ducks Unlimited Program Profile

Ducks Unlimited (DU) conserves, restores, and manages wetlands and associated habitats for North America's waterfowl. These habitats also benefit other wildlife and people. DU has been active in the Lower South Platte basin, which lies along the western tier of the Central Flyway, because the bottomlands and associated wetlands in this basin provide important resources for breeding, migrating, and wintering waterfowl. According to DU's Conservation Program Overview, the mid-continent migration habitats along the South Platte River provide critical "refueling stops" for waterfowl in spring, and afford excellent stopover sites in autumn as well. During the past decade, throughout the State of Colorado, DU has restored and enhanced 24,600 acres of wetlands and associated uplands and protected in perpetuity 4,600 acres, with an investment of $6.8 million.

Eligibility Requirements:

DU works with owners of land with wetlands, including public and private lands.

Types of Habitats that Qualify:

DU considers primarily sites within their priority areas, which includes high waterfowl use areas along the South Platte River corridor. DU targets wetlands, particularly those that will benefit waterfowl.

Length of Time for Easements:

DU uses only perpetual easements, typically with limited development as specified in the easement agreement. For perpetual easements, water rights associated with the land, if any, would be tied to the land, although DU is also interested in land with natural water areas e.g. sloughs and other wetlands. The landowner maintains control of the land, and DU will develop a management plan cooperatively with the landowner. DU also uses fee title purchases to protect high priority wetlands. If the property is purchased by DU, DU will typically re-sell that property to an agency or private landowner after placing a conservation easement on the parcel.

Limits to Dollar Amounts:

There are no dollar limits. Landowner may be required to provide matching funds depending on project type and scope. Appraisals will be used to determine the value of the easement or fee title. DU provides estimates for restoration activities, and work with various organizations (e.g. NAWCA, GOCO, Colorado Duck Stamp, Partners for Fish and Wildlife) to secure funding.

Support Provided:

DU provides a variety of types of support, depending upon whether the project objective is protection, restoration, or management.

If the objective is protection, DU uses perpetual easements and fee title purchases. In either case, the landowner can benefit from tax deductions for the value of the donated easement based on a professional appraisal. DU will work with landowners who donate conservation easements to develop a management plan for the property.

If the objective is restoration, DU will construct levees, install water control structures, and improve water delivery.

If the objective is management, DU will develop a management plan and provide technical assistance for sites in high priority areas. DU also provides technical support on a consulting basis for landowners with wetland and waterfowl restoration objectives.

Lower South Platte Contact Information:
Greg Kernohan, Wetland Manager, (970) 481-7793
Ducks Unlimited
1011 36th Street, Apartment 1
Evans, CO 80620
Gkernohan@ducks.org
http://www.ducks.org/conservation/heartland.asp

B-5. Natural Resources Conservation Service (NRCS) Wetlands Reserve Program Profile

The **Wetlands Reserve Program** (WRP) is a voluntary program that provides landowners with financial incentives to restore and protect wetlands in exchange for retiring marginal agricultural land. Landowners may sell a conservation easement or enter into a cost-share restoration agreement. Landowners voluntarily limit future use of the land, but retain private ownership. Landowners and the Natural Resources Conservation Service develop a plan for the restoration and maintenance of the wetland in an environmentally beneficial and cost-effective manner.

Eligibility Requirements:

To offer a conservation easement, the landowner must have owned the land for at least 12 months prior to enrolling it in the program, unless the land was inherited, the landowner exercised the landowner's right of redemption after foreclosure, or the landowner can prove the land was not obtained for the purpose of enrolling it in the program. To participate in a restoration cost-share agreement, the landowner must show evidence of ownership.

Types of Habitats that Qualify:

To be eligible for WRP, land must be restorable and be suitable for wildlife benefits. This includes:

- Wetlands farmed under natural conditions;
- Farmed wetlands;
- Prior converted cropland;
- Farmed wetland pasture;
- Land substantially altered as a result of flooding;
- Range of land, pasture or production forest land where the hydrology has been significantly degraded and can be restored;
- Riparian areas which link protected wetlands;
- Lands adjacent to protected wetlands that contribute significantly to wetland functions and values; and
- Previously restored wetlands that need long-term protection.

Ineligible Land: Ineligible land includes wetlands converted after December 23, 1985; lands with timber stands established under a Conservation Reserve Program contract; Federal lands; and lands where conditions make restoration impossible.

Length of Time for Easements:

WRP provides three options to the landowner:

Permanent Easement: This is a conservation easement in perpetuity. Easement payments for this option equal the lowest of three amounts: the agricultural value of the land, an established payment cap, or an amount offered by the landowner. In addition to paying for the easement, USDA pays 100 percent of the costs of restoring the wetland.

30-Year Easement: Easement payments through this option are 75 percent of what would be paid for a permanent easement. USDA also pays 75 percent of restoration costs.

Restoration Cost-Share Agreement: This is an agreement (generally for a minimum of 10 years) to re-establish degraded or lost wetland habitat. USDA pays 75 percent of the cost of the restoration activity. This enrollment option does not place an easement on the property. Other agencies, conservation districts, and private conservation organizations may provide additional assistance for easement payments and wetland restoration costs as a way to reduce the landowner's share of the costs. Such special partnerships are encouraged.

Limits to Dollar Amounts:

The program requires acreage authorization levels, not funding levels. Funds are provided to meet acreage levels.

Support Provided:

Financial and technical support is provided for restoring and protecting wetland functions and values.

For both permanent and 30-year easements, USDA pays all costs associated with recording the easement in the local land records office, including recording fees, charges for abstracts, survey and appraisal fees, and title insurance.

NRCS and its partners, including conservation districts, continue to provide assistance to landowners after completion of restoration activities. This assistance may be in the form of reviewing restoration measures, clarifying technical and administrative aspects of the easement and project management needs, and providing basic biological and engineering advice on how to achieve optimum results for wetland dependent species.

Lower South Platte Contact Information:

Tony Puga—Resource Conservationist (Programs)
Natural Resources Conservation Service

Address:	655 Parfet Street
	Lakewood, CO 80215
Phone:	(720) 544-2821
Fax:	(720) 544-2962
Email:	Anthony.puga@co.usda.gov
Web Site:	http://www.nrcs.usda.gov/programs/wrp/

B-6. NRCS Environmental Quality Incentives Program Profile

The **Environmental Quality Incentives Program** (EQIP) is a voluntary conservation program for farmers and ranchers that promotes agricultural production and environmental quality as compatible national goals. Through EQIP, farmers and ranchers may receive financial and technical help to install or implement structural and management conservation practices on eligible agricultural land.

Eligibility Requirements:

Producers engaged in livestock or crop production on eligible land may apply for the program. Eligible land includes cropland; rangeland; pasture; private non-industrial forestland; and other farm or ranch lands as determined by the Secretary.

Types of Habitats that Qualify:

Eligible land includes cropland; rangeland; pasture; private non-industrial forestland; and other farm or ranch lands as determined by the Secretary.

Length of Time for Easements:

EQIP offers contracts with a minimum term that ends one year after the implementation of the last scheduled practices and a maximum term of ten years.

Limits to Dollar Amounts:

EQIP may cost-share up to 75 percent of the costs of certain conservation practices. Incentive payments may be provided for up to three years to encourage producers to carry out management practices they may not otherwise use without the incentive. However, limited resource producers and beginning farmers and ranchers may be eligible for cost-shares up to 90 percent. An individual or entity may not receive, directly or indirectly, cost-share or incentive payments that, in the aggregate, exceed $450,000 for all EQIP contracts entered during the term of the 2002 Farm Bill.

Support Provided:

These contracts provide incentive payments and cost-shares to implement conservation practices. EQIP activities are carried out according to an environmental quality incentives program plan of operations developed in conjunction with the producer that identifies the appropriate conservation practice or practices to address the resource concerns. The practices are subject to NRCS technical standards adapted for local conditions. The local conservation district approves the plan.

Special Restrictions or Preferred Sites:
EQIP is available primarily in priority areas where there are significant natural resource concerns and objectives. Higher priority is given to projects that encourage the use of

cost-effective conservation practices, address National conservation priorities, and optimize environmental benefits.

EQIP provides additional funding specifically to promote ground and surface water conservation activities to promote ground and surface water conservation activities to improve irrigation systems, convert to the production of less water intensive agricultural commodities, improve water storage through measures such as water banking and groundwater recharge, or institute other measures that improve groundwater and surface water conservation as determined by the Secretary.

Lower South Platte Contact Information:

Tony Puga—Resource Conservationist (Programs)
Natural Resources Conservation Service

Address:	655 Parfet Street
	Lakewood, CO 80215
Phone:	(720) 544-2821
Fax:	(720) 544-2962
Email:	Anthony.puga@co.usda.gov
Web Site:	http://www.nrcs.usda.gov/programs/eqip/

B-7 NRCS Wildlife Habitat Incentives Program Profile

The **Wildlife Habitat Incentives Program** (WHIP) is a voluntary program for people who want to develop and improve wildlife habitat primarily on private lands. It provides both technical assistance and cost-share payments to help establish and improve fish and wildlife habitat.

Eligibility Requirements:

Eligible participants include those who own or have control of the land under consideration. All lands are eligible for WHIP, except:

- Federal land;
- Land currently enrolled in the Water Bank Program, Conservation Reserve Program, Wetlands Reserve Program, or other similar programs;
- Land subject to an Emergency Watershed Protection Program floodplain easement; and
- Land where USDA determines that impacts from onsite or offsite conditions make the success of habitat improvement unlikely.

Types of Habitats that Qualify:

WHIP supports creation of high quality wildlife habitat. Upland, wetland, riparian, and aquatic habitats qualify.

Length of Time for Easements:

The USDA and the participant enter into a cost-share agreement for wildlife habitat development, which generally lasts from 5 to 10 years from the date the agreement is signed. Some money is available for 15-year agreements.

Limits to Dollar Amounts:

USDA pays up to 75 percent of the cost of installing wildlife practices.

Support Provided:

Technical and financial. The U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) offers participants technical and financial assistance for the establishment of wildlife habitat development practices. In addition, if the landowner agrees, cooperating State wildlife agencies and nonprofit or private organizations may provide expertise or additional funding to help complete a project.

NRCS helps participants prepare a wildlife habitat development plan in consultation with the local conservation district. The plan describes the landowner's goals for improving wildlife habitat, includes a list of practices and a schedule for installing them, and details the steps necessary to maintain the habitat for the life of the agreement. This plan may or may not be part of a larger conservation plan that addresses other resource needs such as water quality and soil erosion.

Special Restrictions or Preferred Sites:

WHIP funds are distributed to States based on State wildlife habitat priorities, which may include wildlife habitat areas, targeted species and their habitats, and specific practices. State priorities are developed through a locally led process that identifies wildlife resource needs and finalized in consultation with the State Technical Committee.

WHIP funds cannot be used for mitigation or on land designated as converted wetland.

Lower South Platte Contact Information:

Tony Puga—Resource Conservationist (Programs)
Natural Resources Conservation Service

Address:	655 Parfet Street Lakewood, CO 80215
Phone:	(720) 544-2821
Fax:	(720) 544-2962
Email:	Anthony.puga@co.usda.gov
Web Site:	http://www.nrcs.usda.gov/programs/whip/

B-8 U.S. Fish and Wildlife Service Partners for Fish and Wildlife Program Profile

The **Partners for Fish and Wildlife** (PFW) program is a U.S. Fish and Wildlife Service program devoted to furthering the Service's mission of working with others to conserve, protect, and enhance fish and wildlife and their habitats for the continuing benefit of the American people. Since 1988, PFW has offered technical and financial assistance to private landowners in Colorado to voluntarily restore wetlands and other fish and wildlife habitats on their land. According to the PFW program summary in the CDOW Private Land Habitat Programs in Colorado guide (May 2002), PFW has completed more than 600 agreements with landowner. These projects have resulted in the restoration, creation or enhancement of more than 11,000 acres of wetland, 49,000 acres of upland habitats, and approximately 88 miles of riparian fencing through December 2001. PFW has participated in projects with total expenditures for habitat conservation, protection, and enhancement activities totaling more than $6 million, including funding from landowners and partner organizations.

Eligibility Requirements:

Any private land will be considered for inclusion in the PFW program, regardless of size, provided the project meets the goals and guidelines of the program.

Types of Habitats that Qualify:

Projects are selected based on their benefits to migratory birds, native fishes, rare and unique species, and their habitats. PFW has targeted priority areas in Colorado, including the South Platte Valley. The South Platte River is an important migration stopover for waterfowl, shorebirds, and neotropical migrants. Restoration of the habitat values historically provided by overbank flooding is the Partners major effort. The program is not limited to specific habitat types, although wetlands have been a primary focus, along with riparian habitat. Additionally, assisting in efforts to address flow issues in the Platte River through Nebraska is also a focus of the group's efforts along the South Platte.

Length of Time for Easements:

PFW does not use easements. Instead, a management agreement, called a Wildlife Extension Agreement, is developed between the U.S. Fish and Wildlife Service and the landowner. Agreements last at least 10 years. Landowners participating in the program retain complete control of their property, and are under no obligation to allow public access.

Limits to Dollar Amounts:

Usually a cost-share of 50 to 75 percent of the cost of habitat enhancements is achieved by working with landowners and a host of nationally based and local entities.

Support Provided:

Technical and financial.

Special Restrictions or Preferred Sites:

Agreements for 20 years or longer are preferred.

Lower South Platte Contact Information:

Bill Noonan, State Coordinator; (303) 275-2435
755 Parfet Street, Suite 361
Lakewood, Co 80215
Bill_Noonan@fws.gov
http://partners.fws.gov/pdfs/CO-intro-needs.pdf

Table B-1. State and Federally Listed Threatened and Endangered Vertebrate Species Known or Likely to Occur in Northeastern Colorado (CDOW Area 3)

Source: Shane Briggs, CDOW, Personal Communication, September 12, 2001, with revisions October 21, 2002.

Common Name	A. Scientific Name	**Group**	**Status**	**Counties**
Northern Leopard Frog	*Rana Pipiens*	Amphibian	Species of Concern	Logan, Morgan, Phillips, Washington, Yuma
Common Garter Snake	*Thamnophis sirtalis parietis*	Reptile	Species of Concern	Logan, Phillips, Sedgewick, Washington, Yuma
American White Pelican	*Pelecanus erythrorhynchos*	Bird	Species of Concern	Logan, Morgan, Sedgewick, Washington
Barrow's Goldeneye*	*Bucephala islandica*	Bird	Species of Concern	Morgan
Bald Eagle	***Haliaeetus leucocephalus***	**Bird**	**Federal Threatened State Threatened**	**Logan, Morgan, Phillips, Sedgewick, Washington, Yuma**
Ferruginous Hawk	*Buteo regalis*	Bird	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Peregrin Falcon	*Falco peregrinus*	Bird	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Sharp-tailed Grouse	***Tympanuchus phasianellus***	**Bird**	**State Endangered**	**Logan, Morgan, Phillips, Sedgewick, Washington, Yuma**
Snowy Plover	*Charadrius alexandrinus*	Bird	Species of Concern	Logan, Morgan, Sedgewick, Washington, Yuma
Piping Plover	***Charadrius melodus***	**Bird**	**Federal Threatened State Threatened**	**Logan, Morgan, Sedgewick, Washington, Yuma**
Mountain Plover	*Charadrius montanus*	Bird	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Long-billed Curlew	*Numerius americanus*	Bird	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Least Tern	***Sterna antillarum***	**Bird**	**Federal Endangered State Endangered**	**Logan, Morgan, Phillips, Sedgewick, Washington, Yuma**
Burrowing Owl	***Athene cunicularia***	**Bird**	**State Threatened**	**Logan, Morgan, Phillips, Sedgewick, Washington, Yuma**
Black-tailed Prairie Dog	*Cynomys ludovicianus*	Mammal	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Swift Fox	*Vulpes velox*	Mammal	Species of Concern	Logan, Morgan, Phillips, Sedgewick, Washington, Yuma
Northern River Otter*	***Lutra canadensis***	**Mammal**	**State Endangered**	**Logan, Morgan, Sedgewick, Washington**
Brassy Minnow	***Hybognathus hankinsoni***	**Fish**	**State Threatened**	**Logan, Morgan, Sedgewick, Washington, Yuma**
Iowa Darter	*Etheostoma exile*	Fish	Species of Concern	Logan, Morgan, Washington
Organgethrat Darter	*Etheostoma spectabile*	Fish	Species of Concern	Yuma
Plains Minnow	***Hybognathus placitus***	**Fish**	**State Endangered**	**Logan, Morgan, Sedgewick, Washington, Yuma**
Plains Topminnow	*Fundulus sciadicus*	Fish	Species of Concern	Logan
Stonecat	*Noturus flavus*	Fish	Species of Concern	Yuma
Suckermouth Minnow	***Phenacobius mirabilis***	**Fish**	**State Endangered**	**Logan, Sedgewick**

* Documented in the South Platte Drainage but very rare.

APPENDIX C
RECHARGE AND COST KNOWLEDGE ACQUISITON METHODS

The formal knowledge acquisition process for the knowledge base was conducted first through interviews, and then through requests for reviews of the knowledge base and feedback from selected individuals, and through presentations to and discussions with local water user organization members. The knowledge acquisition procedures were adapted from those described by Mackinson and Newlands (1998). The selection of individuals included in the knowledge acquisition process was deliberately non-random, and included only those whose direct experience with the selection, development, and/or management of managed groundwater recharge sites and the recharge credits created at those sites was evident from their participation in local water user organizations.

The development of the initial knowledge base began with a formal 2-hour interview with Northern Colorado Water Conservancy District's (NCWCD's) Supervisory Water Resources Engineer, Jon Altenhofen, on October 15, 2001. Mr. Altenhofen has been the lead engineer for most of the recharge ponds developed on public and private lands in the Lower South Platte as part of Colorado's "Tamarack Plan" to re-time flows for an endangered species restoration program. With more than 15 years of experience with augmentation ponds in the Lower South Platte region and a background that includes the analysis and/or development of more than 50 recharge ponds in the Lower South Platte, Mr. Altenhofen has a solid understanding of the factors impacting the successful development of recharge facilities at a site. In addition, Mr. Altenhofen manages the Augmentation/Recharge Accounting (ARA) program offered by NCWCD to provide water accounting services for recharge facilities throughout NCWCD's service area (northeastern Colorado). Through his work with the ARA program and with the implementation of the Tamarack Plan, Mr. Altenhofen is familiar with other recharge facilities developed by individual landowners or with the support of groundwater user organizations (e.g. the Central Colorado Water Conservancy District Groundwater Subdistrict and Groundwater Appropriators of the South Platte (GASP)).

The interview with Mr. Altenhofen was somewhat structured, in that specific questions were asked and specific information was sought. As the interview progressed, however, there were opportunities for more "free range" or "adaptive" discussion of, for example, the ramifications of various legal and regulatory changes on recharge site development decisions. As noted in Mackinson and Newlands (1998), allowing for open discussion during the interviews provides "insight into many aspects which would have been overlooked by a simple questionnaire offering only a fixed set of responses." Interviews with other local experts were conducted in a similar manner, although those individuals typically had experience with fewer sites than Mr. Altenhofen, and their criteria tended to focus on considerations that had been particular concerns at the sites with which they had been directly involved.

During the interview, Mr. Altenhofen was asked to explain what he consider in evaluating a potential recharge site. Specifically, he was asked:

- what questions he asked a landowner who contacts him regarding the development of a new recharge site;
- what features he looks for during an initial site visit; and

- what data he reviews that would be available prior to conducting an in-depth field investigation at a site.

As each criterion was identified, Mr. Altenhofen was asked to provide specific threshold values or ranges of values for various attributes that would indicate better or worse recharge potential at a site. Such considerations included not only physical site characteristics, but also legal/institutional requirements and cost-related factors.

Mr. Altenhofen's responses were reviewed and three main categories of site considerations were identified, namely:

1) the physical characteristics of the site in terms of the ability to recharge the aquifer from the pond location;

2) the availability of source water to recharge the pond at that site; and

3) the physical characteristics of the site in terms of the recharge credits could be accrued at the times and location when and where the credits are needed.

Mr. Altenhofen's responses were analyzed, categorized and compiled into the initial, comprehensive knowledge base of site characteristics to be considered in selecting and evaluating potential recharge ponds, as described in more detail in the next subsection. The results were sent back to Mr. Altenhofen for review, and were also reviewed by Jack Odor, who is the Manager of the Ground Water Appropriators of the South Platte (GASP).

Mr. Odor is a Professional Engineer and Licensed Surveyor in Colorado with more than 30 years experience in Civil Engineering and water resources. For the past 30 years, Mr. Odor has been the Manager of GASP, which is an augmentation organization with members in the South Platte basin primarily from Denver to Julesburg on the main stem and also up the tributaries. GASP members own about 3000 wells used for agricultural irrigation, municipal and commercial purposes. GASP is the largest organization of its kind in Colorado. Currently, GASP is functioning with recharge waters from numerous ponds developed specifically for augmentation. In most cases, the recharge facilities have been privately developed and the use of these ponds for augmentation is coordinated for specific wells. If excesses occur, GASP leases additional credits from members for other member wells with recharge shortages, and for a broader spectrum of activities. GASP has been very active in the development of a reporting system to provide more specific end user information, as required under new state regulations. GASP has also led the development of recharge facilities as well as other augmentation arrangements, such as leases of municipal water, and has explored surface water storage options. Written feedback from Mr. Odor was incorporated into the knowledge base.

The initial knowledge base was also reviewed by the South Platte Division Engineer from the State Engineer's Office, Dick Stenzel, and Lower South Platte Water Conservancy District Manager Bob Schott. Recently retired, Mr. Stenzel was Division Engineer overseeing all activities for the Colorado Division of Water Resources in the South Platte Basin, and had been with the agency for 30 years. He began working for the State Engineer's Office in the South Platte Basin shortly after the passage of the legislation that originally required the development of augmentation plans for well users in the basin. Mr. Stenzel has been involved with the development and implementation of agency rules for augmentation plans in the South Platte. Mr. Schott, also recently retired, served as Manager of the Lower South Platte Water Conservancy District (LSPWCD), which includes the riparian areas of Sedgwick and Logan Counties. LSPWCD, like GASP, has developed contract agreements with water users within its service area to lease recharge credits, and has also been active in SPLRG activities with the Tamarack Plan. Mr. Stenzel and Mr. Schott both agreed with the content of the knowledge base, although neither contributed substantial new knowledge to the knowledge base.

Once the initial knowledge base was developed, the review, acquisition, and modification of the GIS coverages and other databases was begun, followed by the development of the MCDA and the prototype development and testing. Other local water managers and water users were consulted throughout the process, as is typical in the development of knowledge-based systems (Schmoldt and Rauscher 1996, Buchanan 1983). As discussed in Chapter VI, the final KBS was tested with both Mr. Altenhofen, who had participated in the development of the knowledge base, and with local experts who had not been part of the knowledge base development.

Table C-1 summarizes the key site characteristics identified during the interviews, which are explained in more detail below. Several of the physical aspects of a site are also tied to cost considerations. Costs alone are rarely considered prohibitive since there may be financial support available from water user organizations or habitat organizations, particularly if the site is also suitable for waterfowl habitat. The economic considerations are discussed in more detail below.

C-1. Recharge Pond Assessment Knowledge Acquisition Process and Results

Physical and related legal/institutional attributes cited by local experts as been important to determine in evaluating a potential recharge site include the following:

Question Line I. Physical Characteristics of the Site: Ability of Pond Site to Recharge Aquifer

One important consideration in selection of a recharge site is whether water placed into the pond will recharge an alluvial aquifer. Specific questions that need to be addressed include:

Ques. I.A. *Is there is an aquifer at the site?*

This can be determined to some extent by the presence of wells in the vicinity of the site.

Ques. I.B. *What is the depth to the aquifer water table at the site?*

Preferable sites have a depth to water table greater than 10 feet. Sites with shallower water tables can be used, but there might be standing water over a longer period of recharge at sites with lower seepage rates.

Ques. I.C. *Are there confining layers (tight clay soils through which water can not seep) at the site, and particularly within the first 3 feet?*

The presence of a clay lens will not necessarily make recharge facility development infeasible if the lens is small enough to be excavated, although that will increase the costs to develop the site.

Ques. I.D. *What is the depth to bedrock at the site?*

The preferred depth to bedrock is 50 to 150 feet. With a depth to water table greater than 10 feet, this leaves a saturated thickness of 40 to 140 feet through which recharged water can flow to the stream.

Ques. I.E. *What is the surface soil at the site?*

Local water managers suggested that the seepage rate of the surface soil was the most important site characteristic for the development of a successful recharge facility. For the purposes of an initial site screening, information on surface soil types and seepage rates can be determined from US Soil Survey soil maps. If a site is determined to be potentially suitable for recharge, soil characteristics and water table depth would be confirmed by on-site soil coring and water level measurements in nearby wells, as well as by review of well drilling logs from wells in the vicinity of the potential recharge site.

Question Line II. *Availability of a Water Source for the Recharge Facility*

Another important consideration for selection of potential recharge sites is whether there is water to fill the ponds, and how the water will be delivered to the ponds. Water availability concerns not only the physical aspects of whether the water comes from and how it gets to the pond, but also considerations of the legal and institutional complexity of providing water for the ponds at the site, and costs for water supply and delivery. Specific questions asked include:

Ques. II.A. *Is there a ditch in the vicinity of the recharge site? If a ditch cannot be used to supply water to the pond, is there a well available?*

In order to use water from a ditch to supply the recharge facility, the owner will need a recharge agreement with the ditch company. The recharge site landowner signs an agreement with the ditch company to deliver water to the recharge site. The ditch company typically acquires the recharge water right. The landowner and ditch company typically split the water credits developed from the recharge site. If there is no ditch water available to supply the pond, well withdrawals can be used from a well immediately next to the river (within 200 feet), in which case the withdrawals are considered a "direct diversion" from the river and are treated like a surface water right. Other considerations if using a well to supply the recharge pond include whether to use an existing well or a new well on the river, and whether an aquifer is available in which to install a well.

Ques. II.B. *Does the owner have a headgate from a ditch that can be used to supply water to the recharge pond? If not, can one be installed?*

A headgate from the ditch enables the landowner to access water from the ditch in the time and quantity allowed under the agreement with the ditch company. If there is not an existing headgate, then there would need to be a new agreement developed between the landowner and the ditch company allowing the landowner to install a headgate.

Ques. II.C. *Is the ditch that will supply the pond uphill or downhill from the recharge pond?*

An uphill ditch is preferable in that water can be gravity-fed to the pond, reducing costs and construction requirements. A downhill ditch will require a pump and piping to transport water from the ditch. The owner would also need to obtain an agreement with the ditch company to install a pump at the headgate.

Ques. II.D. *Does the landowner own the land between the ditch and the pond?*

If not, the owner would need to negotiate an easement with the neighboring property owner to transport the water from the ditch to the pond site.

Ques. II.E. *Does the landowner have water rights for source water from the ditch or well to supply the pond?*

If not, the owner would need to purchase water rights or otherwise arrange to acquire rights (e.g. split recharge credits with ditch company in exchange for rights).

Question Line III. *Physical Characteristics of the Site: Recharge Credits Can Be Accrued from the Site at Times When Needed.*

The main physical characteristic associated with a potential recharge site that determines when recharge credits can be accrued is the stream depletion factor (SDF), which is the time it take for water from the pond to reach the stream, in units of days, as determined by the aquifer properties (as discussed earlier in this publication). Another consideration in selecting sites for recharge ponds, however, is the need for the recharge credits that can be accrued at that site. Possible needs include recharge to cover wells on the landowner's property (i.e. the landowner intends to cover his or her own wells with the credits from the pond); leasing to groundwater user organizations that can, in turn, lease credits to other landowners without sufficient recharge to cover their well withdrawals; and the State of Colorado if a market develops for recharge credits to increase flows in accordance with the Tamarack Plan. In some cases, the recharge facility will provide recharge credits for several of these needs, with different needs met at different times of the year. The combination of the SDF, the potential needs for recharge credits, and the availability of water to fill the pond will govern the operation of the recharge facility. Specific questions include the following:

Ques. III.A. *What is the stream depletion factor (SDF) at the site?*

There is not a specific SDF value or range of SDF values required for recharge pond development, although the operation of the pond and market for the credits will vary depending upon the SDF. Generally, the primary market for recharge credits is during the irrigation season, with some future demand possible during February and March if required under the Cooperative Agreement. Thus, if the pond has an SDF of less than 100 days, recharge during the spring is preferred to produce credits during the irrigation season, or during the fall if needed for Cooperative Agreement winter flows. Ponds with an SDF greater than 150 days can be filled year-round, and credits are issued in 1/12 increments each month.

Higher SDF ponds (e.g. 600-700 day SDF) can be used to provide recharge credits for future years when water to supply ponds may not be available.

Ques. III.B. *At what time of year is water available for recharge?*

If water is not available at the time recharge credits are needed with the SDF of the site under consideration, then water will need to be acquired from nearby water sources.

Ques. III.C. *Does the landowner own the land between the pond and the river?*

If not, the landowner may need to work with his or her neighbor(s) to ensure that the recharge water is not intercepted prior to reaching the stream, as well as to arrange any easements if the water source for the pond is downgradient.

Ques. III.D. *Does the source water come from the same stream that is being augmented?*

Legally, in order to receive credits for stream augmentation, the source water must come from the stream being augmented. In this case study, however, all source water can be assumed to be from the South Platte River and its tributaries, and all return flows from recharge is assumed to return to the same stream.

Ques. III.E. *To which river reach are the return flows credited?*

Division One (Platte River Basin) of the Colorado State Engineer's Office administers water rights in the basin by dividing the division into districts, and by dividing each district into river segments or "reaches" between surface water diversions. For example, District 64 (the lowest portion of the South Platte River basin, covering the region from Balzac to the Nebraska state line) is divided into 30 reaches. Because groundwater flows in a direction normal to the gradient of the aquifer, rather than to the surface topography, water that is recharged in a pond on land will seep into the aquifer and intersect the river at a point downgradient and downstream from the point in the river that is adjacent to the recharge pond. The recharge credits are provided to the recharge facility owner at the location where the return flows are expected to intersect the stream. If a surface diversion from a senior water right is upstream from the point where the recharge return flows are credited, then those recharge credits cannot be used to compensate for impacts to the surface water rights holder. Any well withdrawals creating impacts upstream from the surface water diversion would need to have another recharge facility to cover their impacts, or would need to cease pumping. In addition, since the augmentation ponds would be administered according to river segment, the feasibility and use of recharge at a site would be tied to the location of the return flows, the location of the well or wells for which impacts to which the recharge would be credited and location of the impacts of those wells, and the location of other water rights, and the river segments in which those locations would be found.

C-2. Cost Considerations and Cost-Related Knowledge Acquisition Results

The criteria included in the above knowledge base all involved physical or hydrological aspects of the site, although legal and economic subcriteria may also be an important considerations related to these physical site characteristics. For example, a water source such as a ditch might lie close to the site, but the landowner may not have the right to divert water from that ditch. In that case, an agreement between the landowner developing the recharge pond and the ditch company might be required before that water can be considered "available" for use as a source for the recharge pond.

Many of the contributing factors to the overall cost of a pond are tied to design parameters and agreements between the landowner and various water user organizations or habitat programs, and cannot readily be represented in GIS or other database format. Calculation of an estimated development cost would also require extensive inputs by the landowner and pond developer. Consequently, the cost calculations were not included in the MCDA, which was restricted to physical criteria that could be addressed through data available in GIS coverages and databases, with minimal landowner or pond developer input. Instead, a separate Cost Estimate Parameter Knowledge Base was developed identifying multipliers or other costs that could be assigned to various site attributes if future research supported the development of a model with more extensive user inputs. This Cost Estimate Parameter Knowledge Base is summarized in Table III-2. Table III-2 also identifies the data that would be needed to calculate estimated site costs and possible sources of that data.

The Cost Estimate Parameter Knowledge Base currently considers only development costs. Major site factors identified by local experts as driving the costs of pond development included:

1) water source and delivery factors; and

2) pond excavation factors.

Water Source and Delivery Cost Factors: The location and type of water source impact costs, as does any requirements for installation of new equipment to enable water to be delivered to the site from the water source. The most expensive water source would be a new well, at an estimated cost of $25,000. The well would need to be installed within 100 feet of the river to be legally considered a "direct diversion;" otherwise, augmentation credits would be needed to cover a water source intended for use to provide augmentation credits for other water uses. The well would need sufficient pumping capabilities to bring water not only to the ground surface, but also to pump the water uphill to the pond site. If the water source is a ditch that is downgradient from the pond site, a life station with headgate and flume/recorder will probably need to be installed, at an estimated cost of $10,000.

Whether the water source is a pond or a ditch, if the water source is downgradient from the pond, the water will need to be transported through a system of pipes, which can be installed for $5-10 per foot. The total costs for the pipes would depend upon the distance from the water source to the pond.

The least expensive water source is from a ditch that is upgradient from the pond site. In this case, water can be "gravity fed" (allowed to run downhill) from the ditch to the pond, and pipes are usually not installed between the ditch and the pond. If there is no headgate and flume/recorder, however, those items will need to be installed, at a cost of $2,000 for the headgate and $3,000 for the flume/recorder. First, however, the landowner will need to have an agreement with the ditch company allowing him or her to use the water. The feasibility of developing an agreement between the landowner and the ditch company is tied to a complex array of issues that are not typically available in databases or easily portrayed in GIS coverages.

Generally speaking, the development costs for a downhill ditch would be less than that for a well, but more than that for an uphill ditch. As of October 2001, the "rule of thumb" used by local experts to estimate the development cost for a recharge pond ranged from $5-10 per acre-foot if the water source was an uphill ditch which could reach the pond by gravity, to $25-30 per acre-foot if a well and piping needed to be installed.

Pond Excavation Cost Factors: The cost for pond excavation is dependent upon the pond area and upon whether or not there is a clay lens within the top 4 feet of ground surface. If there is a clay lens which cannot be excavated, the pond development may be infeasible. Excavation costs for a site without a clay lens range from $200 to $500 per acre. Excavation costs for a site with a clay lens range from $1000 to $1500 per acre.

Other cost factors: In addition to costs to develop a pond, other factors that may be part of an economic evaluation of a potential recharge site include the potential benefits of leasing any excess recharge credits produced by the pond; the costs to operate and maintain the pond; the potential benefits from receiving payments or tax benefits for conservation easements; and other factors related to partnerships between the owner of the recharge site and ditch companies or habitat programs, as discussed further below.

If the pumping and irrigation records are provided for a property, the user can calculate the depletions per month using a consumptive use model and stream depletion model that are already included as part of the South Platte Mapping and Analysis Program (SPMAP). The stream depletion model can also be used to calculate the net return flows per month, so that the net streamflow depletions can be calculated. The total streamflow that must be augmented by the landowner is dependent upon the time of year and timing of more senior surface water rights downstream. These downstream demands include the requirements of the interstate compact with Nebraska, which typically calls for 100% replacement of depletions by wells (all of which are junior to the 1897 date specified in the compact) in the Lower South Platte from April 1 through October 15. The estimated value of recharge credits in 2003 was $25 per acre-foot during the "compact call" (between April 1 and October 15). If replacement of winter depletions were required (e.g. to allow refill of downstream reservoirs), the estimated value of recharge credits in 2003 was $12 per acre-foot. The same rates apply whether the landowner has a shortage of credits (and must lease the difference from a water user organization) or creates an excess of credits through development of a recharge pond (and can lease the difference to a water user organization).

Several water user organizations have developed in the Lower South Platte that lease recharge credits from members with excess credits to members with no credits or a shortage of credits. These water user organizations may charge landowners a fee for their brokerage services. In addition to leasing credits between members, these organizations may arrange to lease credits from the South Platte Lower River Group (SPLRG), which has developed a recharge facility at the Tamarack Ranch State Wildlife Area as part of the Tamarack Plan, an effort to provide water for a multi-state species recovery effort. The largest such organization in the Lower South Platte is the Groundwater Appropriators of the South Platte (GASP), whose highest membership has included more than 3000 wells. In addition to leasing credits between members, GASP receives excess Tamarack Ranch credits from SPLRG in exchange for payment of electricity costs at that site. The Lower South Platte Water Conservancy District (LSPWCD) also leases recharge credits among its members and with SPLRG. In 2003, new water user organizations have developed, including the Lower Logan Water Users and the Logan County Water Users. These organizations have also begun to make arrangements to lease water credits between members and from SPLRG. The ability of these water user organizations to arrange recharge credit leases within and outside of their memberships may be impacted by new regulations under Senate Bill 73, passed by the state legislature in 2003, but the economic impacts of this legal change is not yet fully understood by local water managers.

The potential availability of financial support from habitat organizations and wildlife agency programs, including lease payments and tax benefits, was another potential consideration that could impact both the development and operational costs if the recharge site to be developed was determined to provide habitat benefits, particularly for waterfowl. Several programs exist through which private landowners can develop partnerships with public and private organizations in which the partner organization pays all or part of the costs of development, maintenance, and operation of the recharge pond. Organizations with habitat partnership programs in the target region include Ducks Unlimited, the Natural Resources Conservation Service habitat programs, the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program, and the Colorado Division of Wildlife.

In many cases, the partner organization will alter the design and operational requirements of the recharge ponds to increase the habitat benefits. These changes in design and operations may increase the cost of the pond, but those increased costs are typically offset by payments and services provided by the habitat programs. The type and amount of financial benefits provided to the landowners vary widely from program to program and from site to site. Typically, the landowners benefit from the recharge credits developed from the pond as well as from other payments and tax benefits from participation in these programs. Further discussion of the financial benefits of partnership in habitat programs by landowners developing recharge ponds is provided in Appendix A.

Operational costs can be driven by several factors, which are less often considered in the selection and development of a recharge site. As more sites are being developed, however, the awareness of the importance of the eventual operational costs is increasing. Electricity is a major operational cost for sites that draw from downgradient wells or ditches, from which water must be pumped to reach the pond. Julesburg Irrigation District Manager Larry Frame has also suggested that the distance from the diversion source to the pond is becoming a major factor. The longer the connecting ditch between the water source and the pond is, the more maintenance will be required, with the connecting ditch often being clogged by tumbleweeds. Recharge operations can also be interrupted by freezing, particularly with connecting ditches and smaller reaches of irrigation ditches. Ice removal is thus an operations and maintenance cost to consider. Finally, the efficiency of a recharge pond can be improved by draining and dredging the pond on a regular basis. Although farmers can benefit from participation in waterfowl habitat programs if their ponds prove to be good waterfowl habitat, the presence of waterfowl can also increase the frequency with which the pond bottom will need to be dredged to maintain recharge efficiency. Because this knowledge base has been focused on site selection, operations and maintenance (O&M) considerations were not explicitly addressed during knowledge acquisition, other than as these considerations were raised by local experts as they pertain to their site selection decision making.

APPENDIX D
SYSTEM ANALYSIS TEST SITE FOR SCENARIO ANALYSIS

The 9 test sites selected for inclusion within the scenario analysis for system evaluation in this research are profiled below:

Site C: This operational site has a relatively high SDF value, with recharge credits accruing in the river nearly one year after placing water in the pond (331 days). The KBS data indicates that this site was developed on low-rated silt loam soil in an area with no wells within a ½-mile radius of the site, although there is another operational recharge pond within that radius. This site was selected as an example of sites with one high-rated criterion value (for the SDF value) and two low-rated criterion values (for the soil type and number of wells), using the KBS scaling functions.

Site D: This operational site was developed by a municipality, and is frequently mentioned by local experts as a model recharge site. Site D has a very high SDF value, with recharge credits accruing over a period of several years (1415 days). The site is located on fine sand, and there are four wells within a ½-mile radius of the site. This site was selected as an example of a site with high-rated scaled criterion values for all three criteria when using the KBS scaling functions.

Site F: This operational site was developed by a landowner whose property is close to the river, who had limited options for sites at which to develop a recharge pond. The site accrues recharge credits less than one month from the time the pond is filled (21 days). The site was developed in loamy sand, and there are 3 wells within a ½-mile radius of the site. This site was selected as an example of a site with two high-rated scaled criterion values (for soil type and well density), using the KBS scaling functions, but an extremely low-rated value for the third criterion.

Site L: This operational site also has a low SDF value of less than 2 months (56 days), as well as a low well density (1 well within a ½-mile radius) and low-ranked surface soil (loam). This site was selected as an example of a site with low-rated criterion values for all three criteria when using the KBS scaling functions

Site R: This operational site has a moderately-rated SDF value, with recharge credits accruing in about 4 months (132 days), and has a high-rated well density (5 wells within a ½-mile radius) and fairly low-rated surface soil type (loam). This site was selected as representative of one of those most commonly occurring combination of criteria ratings (using the KBS scaling functions). Of the 34 sites in the pool of potential test sites, 4 sites (two operating sites, one rejected site, and one site under development) had similar combinations of soil type, well density, and SDF value.

Site W: This operational site accrues recharge credits in about 15 months (456 days), has a high-rated well density (4 wells within a ½-mile radius) and fairly high-rated surface soil type (sandy loam). This site was selected as representative of one of those most commonly occurring combination of criteria ratings (using the KBS scaling functions). Of the 34 sites in the pool of potential test sites, 4 operating sites had similar combinations of soil type, well density, and SDF value.

Site FF: This site is one that had been rejected for a more favorable location on the landowner's property. Site FF is similar to Site C, with recharge credits accruing in the river almost exactly one year after placing water in the pond (366 days), loam surface soil, and no wells within a ½-mile radius of the site, although the operational recharge pond for this landowner is located within that radius. This site was selected as an example of sites with one high-rated criterion value (for the SDF value) and two low-rated criterion values (for the soil type and number of wells), using the KBS scaling functions. Site FF was included as one of two sites (out of the 9 test sites) that had been rejected by local experts in their real-world site selection activities.

Site HH: This site was under development at the time of the demonstration KBS testing. Site HH was being developed jointly by an irrigation district and a habitat organization to provide both recharge credits and waterfowl habitat. This site has a moderately high SDF value, with recharge credits accruing in the river nearly 4 months after placing water in the pond (115 days). The KBS data indicates that this site was developed on loam soil in an area with 5 wells within a ½-mile radius of the site. This site is similar to Site R in combination of criteria ratings (using the KBS scaling functions) and values, with the difference between the sites being that Site R is operational and Site HH is still under development.

Site II: This site had been rejected and a more favorable location was being sought on the landowner's property at the time of testing. Site II is an example of a site in an area with an extremely high well density (12 wells within a ½-mile radius), indicating a very good aquifer, as well as a very high SDF value, with recharge credits accruing in nearly 20 months (652 days). The surface soil type for this site, however, is a fairly low-rated loam. This site was selected as an example of a site with two very high-rated criterion value (for the well density and SDF value) and one low-rated criterion values (for the soil type), using the KBS scaling functions. Site II was included as one of two sites (out of the 9 test sites) that had been rejected by local experts in their real-world site selection activities.