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Abstract

The complexity of water resource issues, its interconnectedness to other systems, and the involvement of competing stakeholders often overwhelm decision-makers and inhibit the creation of clear management strategies. While a range of modeling tools and procedures exist to address these problems, they tend to be case specific and generally emphasize either a quantitative and overly analytic approach or present a qualitative dialogue-based approach lacking the ability to fully explore consequences of different policy decisions. The integration of these two approaches is needed to drive toward final decisions and engender effective outcomes.

Given these limitations, the Computer Assisted Dispute Resolution system (CADRe) was developed to aid in stakeholder inclusive resource planning. This modeling and negotiation system uniquely addresses resource concerns by developing a spatially varying system dynamics model as well as innovative global optimization search techniques to maximize outcomes from participatory dialogues. Ultimately, the core system architecture of CADRe also serves as the cornerstone upon which key scientific innovation and challenges can be addressed.

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1. Introduction: Solving multi-context problems

Traditional scientific inquiry uses a reductionist approach with a focus on specific details and, often, the minutia within a problem. Evaluations for policy, on the other hand, require representations of the causal relationships between key components and influences on the outcomes for a particular problem. In effect, the framing and approaches used to address these problems are different, but using a domain neutral approach the relevant portions of these models can bridge the gap.

Models are a key tool for both science and policy, yet the same models are rarely used to address both areas simultaneously. Scientific understanding can, and should, be incorporated into policymaking processes, but the elements that are important to a policy decision may be distinct from those that are critical to a scientific perspective. Enabling the movement between scientific knowledge and policy decisions is a complex challenge facing society whose resolution will, no doubt, engender improved understanding and management of natural resources. To address the disparity between scientific level models and models used within a decision making context, techniques for merging the processes together are needed.

This need to transition between multiple contexts, such as from science-based analyses to policy analyses, has led to the development of various modeling tools to help support the decision making process. These tools are often based on a system dynamics approach that brings together disparate yet connected systems, such as water resources and economics, by using a lumped-parameter 'commodity balance' approach. Stakeholder involvement is typically instigated through workshops where stakeholders and policy makers can use these models to examine the consequences of various decisions. While these approaches represent a significant advancement over past efforts, and current efforts are becoming increasingly comprehensive and useful, they are limited in two very important ways. First, there is no method of assessing spatially variable consequences of different policy decisions. Secondly, involvement of the stakeholders is facilitated through a trial-and-error approach, where agreements are met through manual calibration of the important parameters of a problem. In other words, no flexible, science-based method or tools exist whereby a suite of near optimal combinations can be generated to drive final decisions toward the best possible outcome for all involved parties.

The Computer Assisted Dispute Resolution system (CADRe) is a web-based software system that provides a platform to incorporate all elements common to an integrated assessment framework for the purpose of science-based decision support. The overriding premise guiding project development holds that while multiple contexts exist for every complex decision problem it may not be necessary for distinct models to be used to evaluate problems within both the policy realm and scientific domain. In fact, a primary advancement from the research is enabling technology to couple legacy models with causal relationships to other physical and social systems.

Research efforts to create CADRe addressed three main objectives: 1) the design and implementation of a system framework for policy-relevant modeling and negotiation interactions, 2) the development of Scale-Appropriate-Simulations (SAS) and 3) the integration of this framework into a process for community-mediated conflict resolution.

Completed as a collaborative effort between Sandia National Laboratories (SNL) and the University of Texas – Austin (UT) this project represents a clear advancement over other integrated modeling approaches. The Barton Springs segment of the Edwards Aquifer in Austin, Texas served as a testbed for the CADRe system due to its rich data-sets, the availability of existing groundwater flow and transport models, and existence of an active stakeholder process.

1.1.   Decision Support and Integrated Assessment

The process of melding scientific models with social, ecological, and economic effects is often referred to as Integrated Assessment Modeling (Jakeman and Letcher, 2003). Integrated Assessment Modeling (IAM) holds promise, both in terms of the benefits that can be realized from successful applications of IAM and the concomitant innovation that will result in improved technologies due to the demands of conducting evaluations in new ways. The majority of IAM software applications tend to be domain or problem specific (Sheppard et al., 2005; Mendoza and Martins, 2006; Acreman, 2005). Yet, generalized systems are beginning to appear (Rahman et al., 2004; Moore et al., 2004). The generalized IAM software provides the ability to either simulate across a set of scenarios or optimize a specific problem (Jakeman and Letcher, 2003).

CADRe provides a system framework that allows users to move between policy or science contexts, while also enabling users to evaluate problems using both scenario analysis and/or a flexible, rules-based optimization search engine. CADRe provides a cornerstone framework and application for IAM that is domain-neutral, capable of representing causal relationships within a problem, and can be scale independent. In addition, CADRe was constructed with consideration for linking the technical tools with interactive processes for planning and policy dialogues.

This linking of policy relevant elements with science-based modeling components is depicted by a conceptual framework (Figure 1) that was developed by the research group. The framework includes methods that are geared toward stakeholder engagement and elicitation of values and concerns. Using results of stakeholder interactions, a representative problem formulation can be created within CADRe and linked to pre-existing physical process models or a relational systems dynamics model. Once the problem formulation has been populated within CADRe's core system a set of scenario analyses, search techniques, and screening exercises can be completed. Output from CADRe can then be generated to guide a group dialogue about the case specific problem.

Figure 1 – Conceptual framework and workflow for linking dynamic modeling with rapid dispute prevention processes.

1.1.1. [1]*Background*

Research into the behavior of decision makers demonstrates that the complexity of many decision problems can outstrip a decision maker's unaided cognitive capacity (Gregory et al., 2005). The use of decision support systems (DSS) represents a systematic approach to often divisive and intractable issues, such as available groundwater yields. DSS is a broad ranging term that refers to the group of decision-analyses, most often computer generated tools, which assist decision-makers in the development and evaluation of alternative management strategies. A hybridized DSS loosely links together raw data, empirical calculations, numerical models, and other qualitative factors to analyze resource allocation problems. A DSS can help decision-makers conceptualize a problem in a new way, as well as allowing for the rapid conversion of the vast sets of data into formats that can provide guidance and insight (Kersten, 2000).

DSS's are the modeling and information system components of a larger process called integrated assessment (Jakeman and Letcher, 2003). Integrated assessment (IA) entails the inclusion of multi-disciplinary expert knowledge together with stakeholder advice and technical models in support of management decisions. The following research presents an overview of CADRe with specific application to a groundwater allocation problem. For this test case, CADRe couples a spatially explicit MODFLOW-based groundwater model and stakeholder values with the aim of providing insight into the calculations for available yield within an aquifer. While the test case has a specific domain of application, CADRe itself is applicable to any type of multi- resource decision problem.

Although the actual origin of the term DSS is blurred in the literature, many practitioners credit Simon (1960) with the presentation of basic management decision processes. One of the earliest definitions of DSS can be found in Little's (1970) seminal work on the concept of decision calculus. Early DSS development occurred in business schools, with the majority of publications appearing as dissertation documents. The first international conference on DSS was held in Atlanta, GA in 1981 (Power, 2003). DSS literature recognizes that DSS models are simplified representations of problems addressed within a society that assist with the development and evaluation of alternatives. They can utilize multi-objective planning to consider various aspects of the decision-making paradigm simultaneously (Haith, 1976), such as environmental quality, optimization, and economic cost-benefit analyses. A review of unstructured and strategic decision processes developed by Mintzberg et al. (1976) resulted in generalized phase model of decision processes. In the case of a groundwater decision the process is most similar to a dynamic decision situation identified by Mintzberg et.al. (1976). Two goals of implementing a DSS is to move the decision process beyond the iterative phases of identification and development into the selection phase for either a bargaining routine for an evaluative choice by stakeholders (consensus) and/or to aid development of alternatives that can be presented to an authority phase for a definitive policy outcome.
Development within the general decision support literature follows a trend of increasing complexity in terms of application and outcome goals for the processes. Figure 2 shows a

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[1] Portions of this document are excerpted directly from S.A. Pierce, 2006, Groundwater Decision Support: Linking causal narratives, numerical models, and combinatorial search techniques to determine available yield for an aquifer system, The University of Texas at Austin, Dissertation, p. 313.

conceptual timeline for the transition among model scopes and type (Pereira and Quintana, 2002). As research related to science-based decision making has evolved, increasing levels of insight and understanding are expected to be generated from the systems with the highest levels represented by knowledge generation, or the recently proposed Tool to Inform Debates, Dialogues and Deliberations (TIDDD) (Quintana et al., 2005). At present the highest reported implementations are integrated assessment models which include the basic features discussed in a review by Jakeman and Letcher (2003). Table 1 presents the features that are usually included in an integrated assessment study. The research completed for CADRe and its parallel rapid dispute prevention process (RDP) includes all of the features shown as part of a broad integrated assessment modeling effort. If real-time model mediated and optimization enhanced consensus sessions based on CADRe are successful this result may represent one of the earliest functional TIDDDs (Quintana et al., 2005).

Table 1: Features common to integrated assessment models.

- Problem- focused, needs driven; project-based

- Interactive, transparent framework; enhancing communication

- Process enriched by stakeholder involvement to facilitate adoption

- Links research to policy

- Connection of complexities between natural and human environment; spatial dependencies, feedbacks and impediments recognized

- Iterative, adaptive approach

- Focus on key elements, identifies missing knowledge/gaps for inclusion

- Team-shared objectives, norms and values; disciplinary equilibration

- Science not always new but intellectually challenging

- Characterization and reduction of uncertainty in predictions

Source: (Jakeman and Letcher, 2003)

The transition away from discipline or application specific DSS is not easy to delineate in the literature. In fact, the process of integrative modeling began at about the same time that DSS's were conceived. Early inception for modeling of the whole system, or complex systems, can be attributed to early global simulation models of the '70's and 80's (Rotmans and Van Asselt, 2001) and the systems dynamics modeling paradigm that emerged from the parallel work of Forrester and Churchman in the early '70's (Guhathakurta, 2002) who conceived the constructs of causality for driving model design.

Actual environmental modeling frameworks are developing rapidly, but little consensus on a generalized framework has been achieved in the current literature (van Evert et al., 2005; Mysiak et al., 2005). Various approaches and frameworks are presented in the literature (Villa, in press; Khaiter, 2005; Moore et al., 2004; Rhaman et al., 2004; Sydelko et al., 2001; Argent and Grayson, 2003; Segrera et al., 2003; Leavesley et al., 2002). These options range from generalized modeling frameworks that are more accessible to non-programmers, but that limit specific model implementation, and model specific frameworks or implementation-level frameworks, that require a higher level user group, usually with programming experience.

1.1.2. Decision support for groundwater resource systems

Water resource allocation is a challenging issue, particularly with regard to groundwater allocation. The CADRe system was tested for the calculation of sustainable yield for a groundwater system because these problems are often considered intractable. While quantifying the potential yield of an aquifer is a relatively straightforward problem, determining the sustainable yield of the same system entails the incorporation of both hydrogeologic and social issues. Domenico (1972) provided one of the most fundamental introductions to safe yield calculations, linear programming, and economic valuation for groundwater practices, but only touched on the implications for decision support and sustainability. An evaluation of decision-analysis with hydrogeological applications was put forth by Freeze et al. (1990) to be used for project evaluation. Freeze's paper was timely, preceding the development of a wide-array of DSS for applications to groundwater, particularly contamination and remediation problems (Camara et al., 1990; Xiang, 1993; Lovejoy et al., 1997). Little work can be found applying the same concepts to aquifer yield. A few lumped system approaches without spatial considerations are reported (Naik and Awahthi, 2003; Heath and Spruill, 2003; NRC, 1997; Mann, 1963), or dimensional approximation (Miles and Chambet, 1995), but these efforts lack the verity of a scientifically reviewed, distributed groundwater model.

Sophocleous and Ma (1998a) provide one of the few groundwater DSS that models the impact of salt water intrusion on aquifer yield. In 1997, the Journal of Hydrology printed a Special Issue on Decision-Support Systems (Jamieson, 1997) that noted the increasing interest in decision support applications. A non-exhaustive summary of the literature regarding decision support systems that are related to groundwater management or allocation is included in Table 2. Several of the DSS reported contain similarities with CADRE and merit differentiation in this report. These models include the WaDSS, Govuerne, Hydroanemas, GESMO, and MIKE-SHE systems discussed below.

The WaDSS addresses the problem of water resource distribution on a regional scale linking surface-water and groundwater through a nodal network (Letcher, 2005). The Govuerne system focuses strictly on policy questions to date and incorporates the media-based input from stakeholder participants, but does not clearly describe the groundwater component of the system

(Pereira and Quintana, 2002). Hydroanemas evaluates conjunctive use problems using MODFLOW as the groundwater module, but incorporates stochastic programming to address uncertainty (Nalbantis et al., 2002). GESMO incorporates a steady-state MODFLOW model to evaluate econometric problems for agricultural use on a regional scale (Belmonte et al., 1999). The MIKE-SHE system addresses the problem of sustainable groundwater management using scenario modeling, but does not incorporate optimization techniques (Demetriou and Punthakey, 1999).

Table 2: Review of water resource related decision support projects reported in recent literature.

Year	Authors	Problem	Scale	GW Simulation	Optimization or larger DSS	Objective	Decision Variables
2006	Carrerra-Hernandez and Gaskin	Spatially explicit groundwater modeling	Any	MODFLOW	Open source link to GRASS for geospatial groundwater modeling	Pure simulation capabilities at this point	NA
2005	Letcher, R.A.	Water allocation for a watershed basin	Regional to large: Namoi & Gwydir River Basins, Australia	Network- nodes linked with surface water sites	WaDSS based on ICMS	Max water allocation	Not clearly stated, but variable options
2005[2]	Recio et al.	Link hydrogeologic model with econometric for agricultural decisions	Regional: Eastern Mancha aquifer, Spain	MODFLOW, possibly 3-D (not clear) steady state	GESMO	Land allocation for crops Crop yield maximization	-pumping - head levels -electricity costs
2005	Mysiak et al.	Water resource management (general)	Local to regional	Not specified	MULINO	Multi-criteria weighting applications	Varies
2004	Lanini et al.	Participatory integrated model for basin study	Local to regional: Herault Middle Valley, France	Lumped parameter model of socio-hydrosystem	(no optimization) Matlab/Simulink	No clear description Stock and flow/steady state system	- Head - drawdown - humping - natural discharge
2005[1]	Quintana et al.	Groundwater governance	Local to regional: Herault Middle Valley, France	Not clear, but indicates that a groundwater module included	GOUVERNe or TIDDD (Tool to Inform Debates, Dialogues & Deliberations)	Exploratory decision support with stakeholder participants	Not clearly defined
2004	Fredrick et al.	Contaminant susceptibility	Local: Single aquifer, NY	2-D Steady state AEM	(no optimization) Spatial indexing Drastic method	Minimize pollution potential	Water table levels Drastic scores
2003	Aziz et al.	Optimization link for groundwater monitoring plans	Local: Contaminant plume various sites	Linear regression for plumes, empirical data, and simplified models	MAROS	Minimize the number of sampling sites and frequency	Monitoring location and time

Year	Authors	Problem	Scale	GW Simulation	Optimization or larger DSS	Objective	Decision Variables
2002	Fatta et al.	Landfill leachate impact	Local: Ano Liosia landfill, Greece	MODFLOW/MT 3D	ECOSIM : Pilot version / local client-server architecture	1st model links, confirms operability only parallelized, telemetrics, visualization, linked simulation models, GIS	No decision problem results reported, embedded expert system not discussed
2002	McKinney and Cai	GIS-based water management framework (prototype)	Local to regional: Kashkydarya River basin	Groundwater treated as source node	GIS and General Algebraic Modeling system (GAMs)	Maximize supply; downstream flow; Minimize salt concentrations; power; import sources	-water withdrawal -reservoir release -and others
2002[3]	Nalbantis et al.	Conjunctive use management	Regional: Athens, Greece	MODFLOW Multi-cell and Lumped parameter models	HYDRONOMEAS : Multi-reservoir system management	Stochastic optimization (limited solution algorithm description)	- pumping
2002	Oxley et al.	Land degradation in the Mediterranean	Regional: Argolida, Greece Marina Baixa, Spain	MODFLOW	MODULUS DSS: 9 sub-models for integrated assessment modeling	Solution algorithm and specific objectives not defined. General problem environmental problem scopes	Mentions as possible: - crop choice - subsidy change - water management and others
2000	Naveh and Shamir	Groundwater level management	Local: Hula Lake, Israel	MODFLOW with GMS	Spreadsheet model	Microsoft Excel solver optimization add-ins	- head levels - canal flow rates
1999	Demetriou and Punthakey	Sustainable groundwater management	Regional: Wakool, Murray Darling Basin Australia	MIKE SHE, 3-D flow	MIKE SHE	Scenario modeling (no optimization)	-mainly crop and vegetation related -defined with historic data for scenarios
1998a	Sophocleous and Ma	Saltwater intrusion (estimate parameters)	Local: Great Bend Prairie aquifer	3-D density dependent flow/solute transport (SWIFT II)	Linear regression (forward, backward, stepwise)	Minimize saline intrusion	-hydraulic conductivities -pumping rate -distance to saline interface layer thickness
1996	Latinopoulos et al.	Engineering supply & remediation	Small : Hypothetical case	2-D Method of Characteristics (1 yr)	(no optimization) Monte Carlo or Stochastic programming	sum of total costs + risk	Broken into costs, failure risks, tolerance
1996	Andreu et al.	River basin planning &	Local and Regional:	Eigen value aquifer response	AQUATOOL	Not clearly stated	Not clearly stated

Year	Authors	Problem	Scale	GW Simulation	Optimization or larger DSS	Objective	Decision Variables
		operational management	Segura & Tagus basins, Spain	flow module			
1986	Datta and Peralta	Alternative selection (Surrogate Worth Tradeoff)	Regional : Grand Prairie, AR	2-D Steady state Flow	Dynamic Multi-objective optimization (Quadratic & Linear)	Min cost of water and max total supply	-pump location & volume -head drawdown -vol. surface water diverted

Note: Projects that resemble the CADRe, with comments regarding differentiating features.
1-Very similar to CADRe, but does not include optimization search engine or scenario generation
2 – Focus on agricultural problems, uses non-compiled language (VB), No social values
3- Expert system only, no stakeholders, stochastic optimization, also a karst aquifer

Source: (modified from Pereira et al., 2002)

Figure 2: Evolution of decision support systems and the level of the current CADRe system.

2. System Framework and Design

CADRe serves as the core architecture to provide a stable transactional environment that mediates between human input, simulation queuing, search interactions, and results generation. CADRe supports multi-player style dialogues, such as those necessary in stakeholder negotiations and consensus building. At the same time, CADRe is flexible enough to support domain specific inquiry for improved scientific modeling in the areas of uncertainty analysis and multi-model comparison.

CADRe is a platform for rapid design of decision problems that uses an adaptable and generic DSS to streamline project definition and development for complex real-world problems.

The CADRe core provides a foundation within which management models (or decision models) can be linked to physical system models in a moderately generic environment. The core provides a system architecture that links to common elements for modeling at the two levels (lumped and explicit) that are needed to build out representations of decision problems. The systems architecture itself, as shown in Figure 3, includes implemented application program interfaces (api's), control, display, and data types, interfaces for modeling plugins and data access objects.

Figure 3: General system architecture diagram for CADRe.

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The overall design is a 3-tier web application architecture, which includes a data tier (back end), an application tier (middle), and a client tier (front end) that provides the interface from the application to the client.

The presentation and controlling logic are separated, but both reside in java server page (JSP) files. User functions and data submittals are handled through the presentation logic over the web. Once data has been submitted from the client tier, it is routed through the client tier to the applications controlling logic, or access layer. The middle tier enables access through data objects and the modeling logic. The middle tier is not web-specific and could be adapted to other application architectures such as a standard client-server. The back end is a transactional database, which is the authoritative data model assuring integrity of each implemented project. Some elements, such as data types and display types, do not separate neatly into a single tier because they are used for communication across all the tiers.

2.1.   Design and development of CADRe

The methods set out for this project are geared to achieve a usable computing environment and architecture to provide a logical, science-based sequence of socially integrated steps for addressing complex decision problems. CADRe has been designed to allow users to conduct the following tasks:

- Input basic simulation configurations via a GUI,
- Define and save simple scenarios
- Perform/run/execute simulation models at either a policy or spatially explicit scale,
- Perform simulation of a given realization using various decision variable and scenario settings
- Generate new management realizations and perform optimization iterations using a tabu search engine
- Create reports for sets of simulation runs using online graphical outputs, Microsoft Excel or XML reporting

2.1.1.   Programming language

Application programming interfaces (API's) for CADRE are written using Java (Gosling and McGilton, 1996). Eclipse (International Business Machines, 2006) is the recommended software development environment (SDE) but is not strictly required to develop for CADRe. Java was selected because it is a simple, distributed object oriented programming language that allows for robust, secure and portable code development, allowing for high performance computing and dynamic interactions. An interesting feature of Java is the architecture neutrality, as the code uses a "virtual machine" which acts as an interface between the code and the hardware so that Java code can be transferred directly from one operating system to another, such as Microsoft Windows to Mac to Unix (Gosling and McGilton, 1996). The current operating platform for CADRE is Microsoft Windows but only because the models created so far are Windows-specific. CADRe could easily be adapted to another operating system as long as the models worked with that system.

2.2.   Web Application Server

CADRe runs on the Apache Tomcat web application server. Tomcat was chosen for its robustness, simplicity, free open-source implementation, and ability to support quality, rapid web application development. Tomcat implements the basic Java Servlet Container definition, which means that code written for it is very portable to other web application platforms such as RedHat JBoss, IBM WebSphere, or BEA WebLogic. The web application platform provides CADRe with the ability to produce web content easily, manage user sessions and login, connect to a database, and in the future provide other non-HTML interfaces, such as web services or client-server interfaces.

2.2.1.   CADRe system implementation and functionality

The CADRe system can be broken down conceptually into three parts:

Authoring Components: These are the authoring tools that allow users to manipulate the important data in the system. Stakeholders edit dynamic input data, or scenario settings. Project Administrators edit constant input data and models.

Flexible Components: These are the pieces of the system that can be changed and updated either directly by users (in the case of input data and models) or by Customization Programmers (in the case of search algorithms and output formats). These correspond to domain-specific logic, or what in a commercial software application would be considered "business logic."

Execution Components: These handle the execution of models and final display of outputs. They provide frameworks common to all models, all searches, and all available display and comparison approaches. That way Project Administrators and Customization Programmers can concentrate on data, algorithms, and formatting and ignore implementation details such as web programming, user interaction, data persistence, data dependency resolution, and software performance characteristics.

Figure 4: Software modules by function.

Authoring components

Authoring components provide access, or expose functional components, within the underlying application for interactive customization by a user. Authoring access is presented to the user through graphical user interfaces (GUIs). The primary functions provided are for the manipulation of user data, which includes model interface definition. CADRe has a basic GUI with interactive components that include user data definitions, for use by stakeholders and decision makers, and model creation, for use by a science-advisor level user. Examples of implemented GUIs in CADRe are simple utility features, such as user log-ins (Figure 5), screens for defining simple scenarios (Figure 6), a set of dashboards for land use distribution and density assignments (Figure 7), interactive map panes for adjusting pumping rates (Figure 8), and real-time viewing of results (Figure 9). Login occurs whenever the user attempts to access a secure part of the CADRe application. Password login is used to authenticate the user and ensure that they have access to the system.

A stakeholder user is expected to access the stakeholder interface, which contains the scenario definition feature. This feature is for dynamic, or scenario data, that typically represents human choices or policy decisions that may be created, changed, tested and evaluated during a live negotiation.

A project administrator is able to edit static data that typically represents physical assumptions about the model. It is considered static in that it is not expected to change during a negotiation. Project administrators can also create model definitions in the system. This involves linking a model algorithm, implemented by a Java class, into the system by telling the system what the model's inputs and outputs are, and where the system should go to obtain the sources of the input data. Input data sources can be static or dynamic data.

Not shown in the components diagram is the fact that the case administrator also shapes all the data in the system using metadata authoring tools. Metadata describes the form of the actual data itself, including the data types. That way the data authoring processes for both the stakeholders and the project administrators can ignore the data formatting and focus on the data itself.

Figure 5: CADRe user login screen.

Scenario: Barton Springs Search: 2

Define Scenario

CADRe HOME
BACK

A scenario is any set of input parameters that are used to execute a model run. You can change input parameters within the same scenario between model runs, or save up to 7 different scenarios (e.g. high pumping rates vs. low pumping rates) at one time to compare them to each other. Scenario testing can be used as a starting point to gain insight into the system before setting up and executing an optimization run.

Open Scenario: [Barton Springs Search: 2 ▼] [Open]

New Scenario: [   ] [Create]

Change Model Settings

[Pumping]   Change the amount of pumping in each model zone
[Impervious Cover]   Change the % land covered by impervious cover
[Drought Cutbacks]   Set pumping reductions during drought

Model 1 results have **not** been stored.

Model 2 results have been stored.

[Model 1 Output]   [Model 2 Output]   [Optimization]   [Ranking]

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Figure 6: Scenario definition screen.

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Figure 7: CADRe land use distribution and density assignment screen for the Barton Spring project.

Figure 8: CADRe interactive map panes for viewing dynamic output.

Ranking

Top Candidates

Scenario	Rank	Total Pumping (cfs)	Average Springflow (cfs)	Average Sprawl (index)	Alarm (# months)	Critical (# months)	Select
Full Tilt	1	19.50	192.33	555.78	0	0	☑
IC-15 Pump-10 CZ	2	5.32	80.02	103.33	29	0	☑
Baseline	3	4.82	75.19	91.25	31	0	☑
Test	3	4.82	75.19	91.25	31	0	☑
IC-15 Pump-10 RZ	5	5.29	74.81	92.78	32	0	☑
Barton Springs Search: 11	6	6.82	73.45	91.25	31	1	☑
Barton Springs Search: 15	7	6.82	73.30	91.25	31	1	☑
Southern Exposure	8	12.53	76.25	113.95	29	4	☑
Growth	9	11.36	69.20	91.25	30	6	☑

Graph

Export Results

Figure 9 CADRe optimization results view.

Flexible components

The basic strategy for system implementation emphasized the creation of a flexible architecture that can be readily adapted as requirements change, by using open source tools. This approach allows compatibility with a variety of data formats, particularly GIS shapefiles, common spreadsheet formats, and text files. Important features of the system include the ability to represent a given project with different simulation models without the need to rebuild the overall system. CADRe allows users to interchange simulation model representations, adjust model queuing, and exchange model assumptions or scenario settings with ease.

CADRe implements a spatially compatible database for Input data and Output Formats using MySQL to allow access to background data, scenario setups, simulation files, and tabu optimization search outputs. Storage formats for data within CADRE can be in text file, shapefile, numerical array, and binary file formats. The MySQL database stores relevant spatial data together with structured and unstructured data. The database architecture can support linked simulation-optimization techniques so that results can be accessed rapidly for use in stakeholder group dialogue. The MySQL database has been selected as the mechanism for storing all long-term user data. This is to maintain transactional integrity of user data during negotiation sessions. It also makes concurrent access safer and simpler to implement. Finally, selecting a non-proprietary database program aids with the interoperability of the overall system, because data exchange can be completed using standard formats and without requiring any special licensed access. In addition, the use of spatially referenced datasets within a water allocation decision support system provides an important means for integrating spatial data together with numerical models and empirical calculations.

Model adaptors have been created for the systems dynamics and groundwater simulation applications. For the Barton Springs project, the systems dynamics model uses the proprietary systems dynamics software package, Powersim (Powersim Software AS, 2005). This software package can be applied across typical disciplinary, or knowledge, domains (i.e. problems ranging from geologic applications to economic to medical, etc. can be addressed) and provides the ability to represent causal relationships with both physical and social systems. The groundwater model was built by the Barton Springs Water Conservation District using MODFLOW. MODFLOW is a freely available software program from the USGS. A tabu search algorithm, or metaheuristic search engine, was developed as part of parallel research by Michael Ciarleglio (Ciarleglio and Barnes, in preparation) and provides the underlying mechanism for conducting searches for management alternatives in CADRe. This component of CADRe provides a rules-based optimization method that is tightly coupled into the overall decision support system.

The search algorithm can be used to generate suites of alternatives as well as conduct parameter estimation for model calibration if needed. This flexibility makes comparing multiple versions of conceptual models or evaluating uncertainty much simpler. The

system architecture of CADRe means that multi-model comparison doesn't require rebuilding of the input files since they are interchangeable within the CADRe system. A combinatorial search algorithm is linked to CADRe by an API. Combinatorial searches are computer algorithms that evaluate numerous combinations of input parameters and decision variables for a problem, assess the performance of outputs, and systematically seek improving results. This allows for iterative searches and optimization routines.

Within the resource modeling field, optimization methods are generally based on the classic gradient, or descent, method. The process starts by calculating an objective function that represents the quality of the match between the simulated results and the calibration values. After calculating the Jacobian matrix, the process incrementally changes each parameter to reduce the value of the objective function. The model is run again with the new set of parameters and the process is repeated until further adjustments in the parameter values no longer reduce the objective function. The limitation of this approach is that many times, the solution surface does not monotonically approach the global minimum, meaning the optimization process can 'finish' at a local minimum. Thus, for our automated optimization procedures within CADRe we implemented the MASTs meta-heuristic tabu search approach. MASTs is a tabu search engine (Ciarleglio and Barnes, in prep.) that enables deterministic search through linked simulation-optimization.

The roots of tabu search go back to the 70's, with the classic form first presented by Glover [*1986*]. The basis of the tabu search algorithm is that it allows the search to explore solutions that are not 'forbidden' (i.e. tabu), or deemed reasonable, even if it means no reduction in the objective function. This is done by keeping track of the previous solutions in terms of the actions used to transform one solution to the next. This tracking provides a means whereby similar actions become forbidden (e.g. actions that resulted in cris-crossing a local minimum), which can move the solution in a different direction. This, in turn, can help progress the optimization process past local minimum and greatly speed up solution convergence.

Execution components
The execution components include software systems that must interact with the middle tier, but remain external to the database functions. The interface between external models and the system is handled through adaptors which implement application protocol interfaces (APIs). An API provides a structured mechanism for communicating between different software programs with the goal of transferring output from one program into another. Graphical user interfaces (GUIs) provide access for human-computer interaction.
Dynamic links are established via the APIs to the different software programs: MODFLOW, (Harbaugh and McDonald, 1996), Powersim (Powersim Software AS, 2005), and a tabu search engine (Ciarleglio and Barnes, in preparation). Dynamic data transfer is managed within CADRe by both the model and search execution frameworks. These execution frameworks are fairly central to CADRe. Execution components facilitate communication between programs and transfers of both input and output files for the various software packages that are linked to the system. Results from CADRe are

stored in a database with the ability to export simple reports using Extensible Markup Language (xml), which is a markup language with a structure specifically designed to support transfer of data across programs.

The model execution framework is the piece that allows multiple models to be connected, properly serializes concurrent model execution requests, and actually connects the input data to the model being run. It also fits inside the search execution framework. It reports output back into GUI displays for the user to analyze.

The search execution framework connects the selected search algorithm with the search parameters (such as objectives, decision variables, and number of iterations), runs the algorithm, and stores the resulting solution scenarios. It informs the user of the new scenarios created, which can then be accessed from the scenario editing tools. Alternatively, the output can be examined using the results display and comparison component.

The results display and comparison component connects display formats with the actual model output data and generates displays in real time. It is integrated with the GUI and also provides the user some opportunity for display customization.

3. Management and model scales

Traditional scientific inquiry uses a reductionist approach with a focus on specific details and, often, the minutia within a problem. Evaluations for policy, on the other hand, require representations of the causal relationships between key components and influences on the outcomes for a particular problem. In effect, the framing and approaches used to address aspects of the same problem are different, depending upon the analytic perspective (i.e. scientific inquiry or policy driven evaluation). CADRe offers an approach capable of bridging the gap by coupling access to models that provide scientific fidelity and policy-relevancy from within the same software application.

While many efforts have been made to create single, comprehensive models that can meet the needs of multiple circumstances, a tractable approach can be achieved immediately by creating a single system that can interact with and implement multiple models. Using the strategy of multi-model access, the CADRe application environment establishes two options of information for model interactions: implementation and scoping.

Implementation level information for operations and management of physical systems usually begins with a spatially explicit model and the description of the physical system. This is the information that can be used to develop minimum spring flow policies, pumping restrictions, drought definitions, and other policy level decisions that are appropriate for a science-driven management agency. Typically, the considerations within this implementation level are limited to the domain of physical system behavior and can be adequately modeled using existing domain-specific models. CADRe is capable of adding new API's for domain specific models, such that existing or legacy models can be incorporated into the overall decision system.

Scoping level models reflect interactions that include changes in the physical system, as well as components with causal relationships to those physical systems. Implementation level models do not lend themselves well to planning processes, because they do not represent a problem in a meaningful way for decision makers. Scoping models emphasize the key decision variables and attributes with import in a social or policy context, but representations of the physical systems are typically simplified, or lumped, representations that may miss important behavior. Scoping models also reflect the preferences and vision that a community, or stakeholder group, may share for a region. The implementation level model may demonstrate sensitivities to the scoping level elements, but the role of defining social elements is outside the traditional realm of physical system models. Thus, a systems dynamics (SD) model can be used to relate socio-economic influences with the physical system, to define possible community growth scenarios, and to constrain the policies implemented to control the physical system.

3.1. A multi-model system for scale appropriate simulation

CADRe has been designed with the concept of enabling easy use of multiple APIs for simulation, together with rapid interchange between particular model representations for a specific problem, or case. The development of a multi-model system was initially conceived as a dual model system, with the goal of linking spatially distributed components of a physical system (e.g. a hydrogeologic system), with the qualitative components (e.g. urban growth preferences) that can be better represented with a lumped parameter model. To that end the CADRe architecture enables the use of multiple models, via cross-application API's, that enable interoperability for simulating across and within different spatial and temporal scales. The result is an ability to conduct cross-platform comparisons for the same decision problem, execute rapid assessment of projected policy outcomes, and provide a means to double check results from the scoping level output against implementation level detail.

Every model represents a hypothesis about the way a system or aspect of the world works. To build any hypothesis, observed facts or data, must be collected and evaluated. The conversion of factual components into related information provides the beginnings of conceptual understanding. In 1970, E. F. Codd, introduced data modeling techniques (Allen, 2003). The process of relational data modeling supports our ability to derive, map, prioritize, and logically interact with data. A data model provides data structure to support different kinds of functionality (Allen, 2003) and provides a means to store otherwise disparate data in one location.

To build CADRe, a prototype data model was constructed and a preliminary schema for implementation was applied to a MySQL database (see Figure 10). MySQL was selected because the program has spatial extensions and it is a freely available and stable database program with functionality to support geographic information. A spatially indexed database provides the storage capacity for both structured and unstructured data attributes, while the schema define principle relationship classes within an urban groundwater context.

Figure 10: Preliminary CADRe data model and functional categories.

When a spatially detailed simulation model is run under various management scenarios, output files may be linked back to the spatially referenced database by its grid cell address. Grid-based computing enables spatially detailed analyses, such as the creation of either raster or vector-based files that represent temporally varying potentiometric surfaces, or visual presentation of ranked results. Iterative model runs and analyses may be also be collected and directly compared.

Using a grid based system, features for spatially referenced calculations can be generated to correspond to the hydrologic simulation model grid. This delineation of spatial features within the MySQL database is the property that makes spatial decision tools unique because the physical system can be modeled while retaining data in its relevant spatial layout.

Selecting the smallest element of scale for the system, or the atomic unit, has important implications for the ability to translate information within the modeling components. If the atomic unit is too large there is a risk of missing important behavioral or spatial complexity. If a unit is too small, then the system may be burdensome to run or become too difficult to implement. In the case of CADRE, a decision was made to create one "Master Table" that assigns a consecutive integer ID to each cell and its 4 attributes (Zone, Layer, Row, and Column). In this way each piece of information used to populate the database is linked back to at least one cell. The inclusion of a 'Zone' attribute for each cell provides the transitional component between spatially explicit physical process models and systems level models. In the case of the groundwater models developed for this project,, zones were based on zones of hydraulic conductivity within the spatially explicit model (zones as defined for this project are discussed in more detail below). This feature provides a means of scaling between two levels of detail; a scoping and policy level model that is useful for broad policy evaluations and a detailed aquifer level model, used in the development of operational rules.

Efforts to scale between different levels of model detail must balance with interactivity and breadth of the instantiated model versions. Components that play important roles in the development of scoping level models capable of emulating implementation level models may include temporal elements such as, timestep and planning horizons, as well as spatial elements, such as hydraulic conductivity or impervious cover parameters, that can be adjusted or aggregated to match the physics and behavior of the physical systems while also meeting the needs for computational performance and complexity. Figure 11 shows a conceptual representation of scales and potential resolutions across fine, medium, and coarse level models.

Figure 11: Conceptual representation of scales and potential resolutions across fine, medium and coarse level models.

3.2. Modeling Barton Springs: An example of scaling

Physical process models that are at the heart of CADRe are usually built as high-resolution models in space and/or time. In practice, models of different scales and that emphasize different processes and/or outputs are needed to address distinct but related questions. Model development for CADRe is focused on creating, calibrating, interrelating, and optimizing the computational models to support policy dialogue. To do this, the research team selected the Barton Springs segment of the Edwards Aquifer as a test case. The objective of model development was the construction of a systems dynamics to emulate a spatially explicit numerical model for the test case groundwater system.

A pre-existing spatially distributed groundwater model (MODFLOW) for the Barton Springs segment was adopted along with the development of several interacting sub-process models (i.e., drought detection/land use models). Additionally, a systems dynamics model of the same region, but at lower spatial resolution, was constructed for rapid analysis purposes. It is necessary for these models to yield compatible results, thus requiring calibration to a common 'base case'. For Barton Springs, the model calibration was completed by the modeling team using the parameter estimation code PEST (Doherty, 2003). Future research that automates this process of scaling implementation level models for scoping level within CADRe would be worthwhile from both a theoretical and applied standpoint.

For this study, we developed a scoping level groundwater model using a lumped parameter, systems dynamics (SD) approach that maintains important spatial relationships within the broader context of socio-economic conditions. An implementation level Groundwater Availability Model (GAM) that had already been developed by the Barton Springs Edwards Aquifer Conservation District (District) was used as the template for designing the lumped-parameter, systems dynamics model.

Pumping and drought restrictions are determined by the District, which began a recent initiative to evaluate sustainable yield using the GAM developed with MODFLOW as a science-based planning tool (District, 2004). The GAM represents the results of an effort to systematically model Texas aquifers with a standardized, technically rigorous process. The resultant models are approved by the Texas Water Development Board for use as an allocation and planning tool and identified by the Texas State Legislature as the mechanism for determining the available yield for communities throughout the state.

The Barton Springs GAM is a two dimensional MODFLOW model that demonstrates a high sensitivity to recharge, limited response to changes in pumping, and two drains that represent drought sensitive springs. The model is constructed on a 120x120 grid with cell sizes of 1000 and 500 feet in the *x* and *y* directions, respectively (Figure 12). While the model assumes a continuous, porous media to represent the aquifers' karst system, the calibration results indicate adequate performance for use in management analyses (Scanlon et. al., 2001). In addition, other studies by Scanlon et al. (2003) have shown that the Barton Springs segment of the Edwards aquifer can be successfully modeled using either equivalent porous media models or lumped parameter models. Lumped parameter models are used to aid the negotiation process by providing a means for

linking disparate systems to provide real-time feedback for scenario and hypothesis testing. While the lumped parameter model for Scanlon et al. (2003) considered 5 hydraulic conductivity zones, calibration and testing during the early design phases for this project determined that effective replication of the spatially explicit GAM was best achieved using 11 zones, with each lumped-parameter zone corresponding to one of the 11, irregularly shaped, multi-celled zones of hydraulic conductivity within the GAM (Figure 12).

Figure 12: Top figure shows discretization of the GAM, which consists of 7036 active cells. The bottom figure illustrates the 11 zones used in the SD model.

Within the SD model, each hydraulic conductivity zone is represented as a single, homogeneous, isotropic volume of the aquifer where a 'communication matrix' is used to indicate what zones are capable of communication with each other. Inter-zonal flows, spatially-averaged heads in each hydraulic conductivity zone, and conductance of the two drains (representing Barton and Cold Springs) as simulated by the GAM were used in a two-step process to calibrate the SD model. The first step set the drains to a known-flux boundary condition to match actual springflow data. Hydraulic conductivity and storativity in each of the 11 zones where then changed to match the inter-zonal flows and

averaged heads calculated by the GAMS. Once the inter-zonal flows and averaged heads matched those from the GAMS, the drains were changed to a head-dependent flux boundary and the conductance of each drain was changed to match the springflow data. The calibration for each step was done using the parameter estimation code PEST. Figure 13.0 illustrates that the transient discharge rates for Barton Springs in the MODFLOW model are successfully reproduced by the systems dynamics model. Initial inter-model calibration was completed using a steady state version of the GAM allowing for minimal adjustments to fit the transient model flows.

Figure 13: Barton Springs discharge inter-model calibration showing that the systems dynamics model emulates the discretized model behavior.

With an adequate groundwater component for the systems dynamics model, non-hydrogeologic influences and relationships may be readily incorporated into the model. Thus, the scoping level SD model also includes several sub-models to calculate recharge rates to the aquifer, relative property values, and a 'sprawl index' as a function of land-use distributions. Development of the systems dynamics component represents a critical feature in the overall CADRe case representation for Barton Springs, because it allows for simplified hypothesis testing and rapid scenario building.

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4. Participatory Methods & Decision Science

One rationale for community stakeholder processes is that incorporating human preferences into natural resource management and planning through the use of models that represent links to non-physical system factors and community preferences may facilitate consensus building and the calculation of a scientifically defensible management strategy. One purpose of this research is to develop participatory modeling processes consistent with CADRe, such that a set of efficient, systematic, and repeatable procedures are developed for incorporating stakeholder concerns into scoping level models. The ultimate goal is to develop methods and procedures that move complex decision problems towards resolution rapidly.

CADRe participatory methods discussed here include elicitation, narrative development, and value focused thinking. Research steps for the development of the stakeholder component included: 1) Pre-modeling interview sessions, 2) Value-focused thinking attribute assignment, and 3) Conceptual model design and review focus sessions. These initial steps represent methods to elicit attributes from stakeholders that can inform scoping level modeling. Later stages are parts of model-mediated negotiation or dialogue to actively resolve conflicts.

4.1.   Pre-modeling interview sessions (Step1)

Interviews and narrative analysis were selected as a systematic procedure for collecting stakeholder positions, concerns, and measurable indicators that relate physical, or natural, system performance to community concerns. The determination to use this combination of methodologies is based on a series of studies that show: 1) surveys and questionnaires can quantify people's attitudes towards water allocation (Syme and Nancarrow, 1996); 2) informal elicitation techniques have similar results when compared with hardcopy surveys and improved participation (Willis et. al, 2005); and 3) non-market valuation may be more effective when completed as an open-ended elicitation (Satterfield, 2001; Satterfield et al., 2000) .

Face-to-face elicitive interviews are conducted using informal verbal dialogues that are loosely guided using open-ended questions sequenced in a traditional narrative style and recorded on video tapes. Narrative analysis, or narrative valuation, is an approach to elicitation that is sensitive to the contextual perceptions of an interviewee at a particular point in time, as well as, the temporal sequence of events. The 6 elements that comprise a narrative (Elliot, 2005; Satterfield et al., 2000) include:
- Abstract (summary);
- Orientation (time, place, situation, participants);
- Complicating action (what actually happened);
- Evaluation (the meaning and significance of an action);
- Resolution (what finally happened); and
- Coda (return perspective to the present).

Table 3 lists a general outline of interview topics and questions from stakeholder interviews. The photos presented in Figure 14 are examples of pre-modeling interview sessions in progress.

The purpose of elicitation is to identify the key motivation and stance of an individual prior to negotiation (ie. pre-negotiation position) and to define relevant value attributes, scenario conditions, and fundamental model inputs to link with a scoping level simulation model. Early stage elicitation provides disaggregate information with regard to the dependent variables of the problem, which may subsequently be aggregated into an overall ranking hierarchy for decision support (Willis et. al, 2005). Stakeholder responses during elicitation are used to identify measurable attributes for modeling with key metrics.

The intent of completing narrative assessments with individual participants was to achieve a second-order narrative (Elliot, 2005) that can reflect the social category of the stakeholder, shedding light on how a particular individual, or category of individuals, makes sense of events. In other words, the stakeholder representing environmental interests provides insight and value attributes that are expected to be consistent for individuals with similar perceptions and beliefs. The plot reflects the causal relationships by linking prior choices to subsequent events. The results of interviews can be considered representative of current stakeholder views for the test case community. Decisions made at any given time reflect a perception of a situation at a given time and the outcome depends upon how we judge or value various elements of the "story" up to that point.

The results of pre-modeling interviews are presented to stakeholders in order to facilitate the emergence of a common understanding of the problem and to aid with the formulation of representative values, or objectives, for modeling the system.

Table 3: Example questions used in CADRe process for stakeholder narrative elicitation.

Questions discussed with stakeholders	General content analysis to define attributes
History	
- Tell me about yourself, what is your stakeholder group - How did you come to Austin - What is it like to be a _____ (stakeholder category) - What led to your interest in water resource issues	Responses aid in defining a decision context and the orientation of each stakeholder.
Knowledge	
Please describe your understanding of: - Issues . . . - Activities . . . - Elements . . . . . Of the problem as it affects you. Beliefs about human activities: - How should things be (best management practices, regulations, etc.) - What has greatest impact on the Barton Springs case and what are key elements controlling those impacts	These questions provide an abstract summary from each stakeholder describing the decision problem.
Perceptions	
Can you describe the conditions, problem, and cause for: - Why Austin is a good place to live - Development, growth, economy, land values, & water - Environmental regulations and development - Water supply and quality: risks to the future and scarcity - Barton Springs What are your main concerns (factors, variables, etc.): - What can affect them or is affecting those concerns - What does a graph of those components look like - What can we change to affect it (need more of) - Where are we today in comparison to the past - What are the dynamics of the linkages Idealized world (place) - What would you like the future to be - Why is that good to you - Characteristics and consequences Anti-world (place) - What do you want to avoid in the future - Why is that bad to you - Characteristics and consequences The challenge - Sacrifice, transition, heroic change to allow us to go on the path to the ideal - What (analog value) puts us on the path to an idealized world - What must we achieve or become (the universal) - Causal link from good to bad - What must we do to change the situation Tasks, deeds, work, feats - Details of how to successfully take on the challenge - What do we need to do to get there	Questions in this group help clarify a stakeholder's orientation and view of the complicating actions for the decision problem. Some of the questions elicit responses that evaluate the value of an element within the decision problem. These questions help to: - identify alternatives - consider problems and shortcomings - predict consequences - identify goals, constraints, guidelines - determine strategic objectives The final set of questions focus on defining a possible path to resolution through feasible actions.

Figure 14: Photographs of elicitive interviews with stakeholder participants (A) Property rights stakeholder, J.T.Stewart, policy researcher, Marcel Dulay, and cameraman, Scott Perez, (B) Environmental concerns stakeholder, Jon Beall, and policy researcher, Marcel Dulay.

4.2. Valuation and value-focused thinking (Step 2)

Problem formulation is one of the most difficult aspects of a decision analytic process and can significantly affect the subsequent stages of a process. Problem formulation, identifying the symptoms, causes, and opportunities can require almost half the total time of modeling, (Dyer and Lasdon, 2006; Keeney 1992; Volkema, 1995).

The formulation of a problem statement will determine what alternative solutions can be generated; therefore it is worthwhile to identify methods that help lead to creative and tractable solutions. In this research, scoping level simulation models are connected to stakeholder concerns through interviews and participatory focus sessions that apply value-focused thinking (VFT) techniques. VFT is an iterative process of formulating a problem statement with measurable components and within a structured format that includes defining the decision context, identifying values, specifying the elements of a decision problem, and defining stakeholder interests and metrics (Keeney, 1992; Clemen and Reilly, 2001; Merrick, 2004) that allows for interactive model sessions at a later date. Decision analysis is a field of study that is concerned with aiding improved decision making through the development of tools to define and structure problems, as well as analytical techniques to evaluate a decision problem. Figure 15 presents a flowchart showing the steps in structuring a value, or decision, model. Clemen and Reilly (2001) state that, "a person's values are the reason for making decisions . . . and without objectives we would not be able to choose from among different alternatives." VFT helps to distinguish objectives and measurable attributes for a decision problem. One of the advantages of using VFT is the ability to represent the multiple objectives and criteria of stakeholders for both monetary and non-monetary values, as well as providing a mechanism for maintaining a disaggregate tally for alternatives scores (Gregory, 2000). It is the distinction between objective values and subjective values that is critical in a systematic evaluation of a decision problem. Certainly, decision problems contain subjective components, but the process of systematically evaluating the problem is scientific in nature (Keeney, 1992). Therefore, an early step in any decision analysis requires the definition of stakeholder concerns, values, objectives, and metrics. This is an important mechanism for separating the influential components that are either factual from those that may not be based in observable fact, but rather human judgment.

One way to represent the decision, or value model, is to depict it as an objectives, or goals, hierarchy. Objectives hierarchies are two graphical tools for displaying the basic structure of a decision problem, they aid with structuring a multi-objective decision model. Goals hierarchies can help distill the list of important objectives for a problem, assuring that only those sub-objectives which are indispensable to the final outcome are included (Clemen and Reilly, 2001; Keeney, 1992).

Fundamental objectives and model elements for this research are represented through the use of a goals hierarchy. Objectives should reflect why a stakeholder is interested in the decision (why do they care?) and give an indication of how alternative decision options can be evaluated. Figure 16 shows a goals hierarchy with fundamental and means-ends objectives for an example groundwater allocation problem. By linking the fundamental and means-ends objectives via goals hierarchy the subjective values and weighting factors can be determined as a link to community values and science-based

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                      │ Define decision │
                      │    context      │
                      └────────┬────────┘
                               │
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                      │and candidate    │   ┌───►│natural attributes │   │
                      │objectives       │   │    └────────┬─────────┘   │
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                               │            │    ┌────────▼────────┐  ┌──────────┐
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                      │Structure        │   │    └────────┬────────┘  │into      │
                      │objectives       │   │             │          │component  │
                      │Fundamental/Means├───┘    ┌────────▼────────┐  │objectives │
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  └─┬──────┬──────┬──────┬─────┬┘                 │Identify possible│
    │      │      │      │     │                  │proxy attributes │
    ▼      ▼      ▼      ▼     ▼                   └────────┬────────┘
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| Decisions | Scenarios | Uncertain events | Consequences | Outcomes |

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                      │Influence diagram│        │hierarchy        │
                      └────────┬────────┘        └────────┬────────┘
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Structuring
Problem:
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work
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                      └────────┬────────┘        │(values to       │
                               │                 │objectives)      │
                               │                 └────────┬────────┘
                               └──────────┬───────────────┘
                                 ┌────────▼────────┐
                                 │Evaluate         │
                                 │alternatives     │
                                 └─────────────────┘
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Source: (modified from Keeney and Gregory, 2005; Merrick, 2004; Clemen, 2001; Keeney, 1992).

Figure 15: Flowchart for setting up a decision or value model.

Figure 16: Goals and objectives hierarchy example for a groundwater allocation case, Barton Springs segment, Austin, TX.

analysis. This step in analysis of the decision problem effectively separates subjective values and observable facts in a complex decision problem.

Attributes are the measurable components within a decision model that measure how well an objective is achieved. A decision problem defines attributes so the attainment of objectives among a set of alternatives can be determined or measured. Attribute selection, as recommended by Keeney (1992), considers how well strategic objectives achieve performance levels of an individual alternative. Results from stakeholder interviews, and the narratives developed through that process, are used to focus and delimit fundamental and means objectives with measurable attributes. Stakeholder aided development of a set of attributes linking social concerns (fundamental objectives) and aquifer elements (means-ends objectives) provide the ultimate measure for multi-criteria ranking of generated solution sets that are presented during negotiation dialogues.

4.3. Conceptual model design and review (Step 3)

Upon completion of pre-interviews and value-focused thinking attribute assignment, initial build out of a case can begin. This phase of the process includes the compilation of a datawarehouse and design of a database structure to house historic data and simulation results in an accessible format. In addition, confirmation through participatory modeling work sessions that a "requisite model" has been completed, or that the value model includes all of the necessary components necessary for stakeholders to make the decision(s) at hand is also needed at this stage. Through mediated dialogue participants evaluate whether the relationship between measurable attributes and primary concerns has been captured.

Problem representation within CADRe can include multiple objective functions for a case. In the Barton Springs test case the decision problem is defined by an objective of maximizing available yield, subject to 6 fundamental objectives that reflect an aspect of community concerns; 1) maximize total storage, 2) minimize the number of dry wells, 3) minimize impervious cover, 4) minimize recharge from infrastructure leakage, 5) minimize impacts of drought, and 6) maximize spring flow. Objectives serve as the transfer functions between community preferences and physical system behavior. The relative performance of attributes describes the physical system response to various management plans, while each fundamental objective is the mechanism for assigning a preference weighting such that sets of alternatives may be ordinally ranked. Figure 16 provides a graphic presentation of these relationships.

5. Barton Springs Test Bed

The CADRe software application and participatory modeling process was tested for a groundwater allocation problem located in the Barton Springs segment of the Edwards aquifer. The Barton Springs segment of the Edwards aquifer in Austin, Texas served as a testbed for the CADRe system due to its rich data-sets, the availability of existing groundwater flow models, and existence of an active stakeholder process. An existing distributed parameter model (e.g., a calibrated MODFLOW model) was used to define the initial hydrogeologic characteristics and numerically simulate aquifer conditions in a spatially explicit manner under various scenarios. This research presents results from using the CADRe methodology and software system to accommodate the demands of a hybridized calculation for sustainable yield that includes the interests of a community.

5.1. Case study background

The Barton Springs segment of the Edwards aquifer is located in central Texas (see Figure 17). A recharge zone of approximately 229.32 km^2 is overlain by a rapidly urbanizing section of the city of Austin. Primary hydrostratigraphic units are karstified limestone with discrete sinkholes and fracture-based conduits forming the significant recharge features (Sharp and Garcia-Fresca, 2000).

In Texas, stakeholder participation has been mandated into their groundwater management procedures through HB 1763 that enforces the use of stakeholder defined "desired future conditions" to guide the calculation of available yield for aquifers.

This research project was completed in collaboration with the Barton Springs/Edwards Aquifer Groundwater Conservation District and representatives from an ongoing Regional Water Quality Planning Group and other stakeholders with the goal of designing a flexible DSS to forecast the amount of groundwater available within the Barton Springs segment of the Edwards aquifer. A group of 8 community stakeholders volunteered to participate on the CADRe research project and collaboratively build the community values portion of the systems dynamics model. Stakeholders participated in the CADRe research project from June 2005 to November 2006. Actual participants in the CADRe process include members from 7 interest groups. Three members of the management and assessment staff for the Barton Springs Edwards Aquifer Conservation District represent governing entities. Representative interest groups, included Concerned citizens, Governmental entities, Neighborhood interests, Local environmental preservation/Good governance, Development interests, Economic interests, and Property owners/Agricultural interests
While previous work by research teams have applied value-focused thinking style approaches to varying degrees (Kodikara et al., 2005; Maguire, 2003: Borsuk et al., 2001; Messner et al., 2006; Merrick et al., 2005: Merrick and Garcia, 2004), the research presented here includes a groundwater resource to a degree of detail not addressed

elsewhere and, unlike many other studies, stakeholder participants that are actual citizens involved in an ongoing conflict resolution process.

Legend
Hydraulic Zones of the Barton Springs segment

- Contributing Zone
- Recharge Zone
- Artesian Zone

- Negley Well
- Lovelady Well
- Cold Springs
- Barton Springs and Barton Well

0 5 10 15 20 25 km

Figure 17: General location of the Barton Springs segment of the Edwards aquifer, Austin, TX.

5.2. The Problem

Groundwater allocation that adheres to the doctrine of sustainable yield involves complex concerns of both a non-scientific (social conflict) and scientific (available yield) nature. Water resource conflicts arise in society when the quantity of a shared water resource does not meet expectations of user groups or when an opposing party's use affects another's interests. From a hydrogeological perspective, the yield of an aquifer is limited by the relationship between recharge and storage for a given aquifer. From a regional planning perspective, the determination of allocation is dependent upon how water is viewed by a community.

The concept of sustainable yield has been present in the hydrologic literature since the mid-1950's with even earlier descriptions of safe yield appearing in 1915 (Lee, 1915). The definition typically contains the caveats for not exceeding annual average recharge, extraction rates that are economically feasible, not violating previously existing legal limitations, avoiding water quality degradation, and meeting the needs for ecosystem flows. In spite of the long-lived existence of the concept, implementation of allocation rates that consider the diverse aspects of the term remains largely elusive. The development of a bi-model system for CADRe was initially conceived with the goal of linking both the quantifiable hydrogeologic components of sustainable yield with the typically qualitative extraction limiting aspects that originate from stakeholder concerns.

Some traditional hydrogeological methods for estimating the parameters include: water budgeting, numerical modeling, optimization simulation, chemical tracing, chemical mixing models, flow-net construction, pump testing, slug testing, and geophysical methods (Weight and Sonderegger, 2001). With the ability to link the model results to a spatially indexed database water budget estimates may now be completed via CADRe applications. This approach is similar to the Urban Value Quality (UVQ) approach defined by Eisworth (2001) with the added ability to evaluate other performance metrics for the aquifer system simultaneously.

Consensus yield is a set of limitations placed on a groundwater resource management problem by community preferences. The limitations of defined preferences provide a feasibility region within which operational guidelines for aquifer management can be developed. CADRe incorporates management objectives, such as maximizing total pumping, and stakeholder preference sets, such as a preferred minimum spring flow rate, into the evaluation, so that multiple objectives may be evaluated. CADRe evaluates alternatives against one objective, but subsequent ranking or ordering of the top alternatives is completed with consideration of additional objectives. Groundwater resource management that addresses sustainability should not optimize a single indicator to define a long-term groundwater management regime, but rather should take into account the various hydrogeologic, economic, legal, environmental, and other factors to estimate the most appropriate yield for all parties concerned. Currently observed general practice continues to result in the implementation of some version of safe yield (Mace et

al., 2001). The CADRe system provides an alternative means for approaching water resource management operations.

5.2.1.   Building a science-based case

The representation of hydrogeologic components within a systems dynamics framework provided the opportunity to link science information with stakeholder values. At the same time, CADRe preserved the necessary link with the spatially explicit GAM model, making it a simple task to verify the simplified model results against the real-world tool that will be used to determine the final policy outcome. In addition, switching between the two models can be completed entirely through the CADRe interface.
Building a project requires data identification and collection, preliminary data organization, and identification of useful (off the shelf) software packages. The effort to complete this portion of the research was substantial and benefited from a thoughtful approach because key decisions regarding how the system was to be represented were made, which had a significant impact on both how the natural system was represented as well as on the flexibility of the programmed components.

Constructing the model for the Barton Springs test project, a lumped parameter systems dynamics model was developed to mimic the original GAM behavior In addition, the scoping level SD model include additional processes (e.g. urban growth models, pipe leakage model, etc.) and functionality (e.g. optimize across user-defined performance metrics) that are not possible with the GAM. Through discussion with the stakeholders, the SD model was iteratively modified to accommodate their comments as they used and interacted with the CADRe system. The necessity of the SD model is due to its additional functionality, as well as the fact that it can completes simulation runs relatively quickly in comparison to the GAM (less then 30 seconds versus 5 minutes). This quick execution provides a means to support real-time group mediation and decision making.

5.2.2.   Selecting measurable attributes for Barton Springs

Stakeholder involvement in defining the Barton Springs case resulted in development of an overall decision model, together with identification of decision elements, sub-objectives, and metrics. Through a series of interviews and work sessions that were conducted between June 2005 and November 2006 (Table 4), recommendations and requests were documented and were used to modify the CADRe system development and design.
In structuring objectives for the Barton Springs test case, content and narratives gathered during stakeholder interviews, together with inclusion of relevant results of the Regional Water Quality Plan (Naismith Engineering, 2005) were evaluated for potential attributes and metrics; providing a link between the social concerns and the aquifer system. Figure 16 shows the hierarchal goals/objective diagram with "Calculating Available Yield" as the dominant objective, complementary indicators of the social feasibility for alternatives are sub-objectives. In addition, Figure 16 shows the list of attributes and decision

variables identified for stakeholders. From this initial list, a total of 9 basic attributes were selected as criteria for the Barton Springs test case for CADRe (Table 5). Analysis of interviews provided detailed information about the complexities of the ongoing land use conflict in the Barton Springs region as it relates to water allocation. In the Barton Springs case, the stakeholder interviews revealed six fundamental objectives, or areas of concern, that were linked with the groundwater system model. All of the stakeholders shared a concern for policies regarding impervious cover. Stakeholders perceived urban growth and population expansion as a primary cause of risks posed to the aquifer. The perception in the region of rapid urban sprawl is supported by a sub-process module in the SD model that calculates a sprawl factor for various land use settings. Presenting attributes and concerns separately provided an opportunity for the group to develop a common understanding and vocabulary for the decision problem under scrutiny. This process of aiding dialogue, rather than argument, is one benefit of the decision analysis process and methodology. The stakeholders noted, both during the interview process and group sessions, that the combination of narrative and value-based discussion leads to a more open process for brainstorming and problem-solving together, versus their prior experiences with "public comment" stakeholder events that could result in rhetoric- ridden arguments.

Table 4: Summary of stakeholder related events for Barton Springs test case.

Date Range	Activity	Participants	Purpose
June 8th, 2005	Project kick-off meetings	Technical team Stakeholder group	• Project overview and participation requirements laid out. • Stakeholders acknowledged the scientific aspirations for research and committed to participate in elicitive interviews.
June 8, 2005 to November 15, 2006	Stakeholder interviews and focus sessions	Stakeholders	• Established attributes • Attained consensus for the decision model.
October 12, 2005	Work session	Technical team Stakeholder group	•review video clips of interview sessions •highlight the attribute selection
November 9, 2005	Work session	Technical team Stakeholder group	•Review and discuss the conceptual model •present lumped model components
January 2006	Conceptual model technical review session	Technical team Stakeholder group (District personnel)	•identified operational objective functions, •decision variables, and •scenarios of specific interest to the District for policy questions.
June and	Preliminary working model debut	Technical team Stakeholder group (District personnel)	• June meeting reported early results from CADRe modeling
August 27, 2006		Technical team Stakeholder group	• update and presentation of preliminary model results • presented outcomes and functional alpha version of the CADRe.
September 2006	Transfer alpha version of working model	Technical team District personnel	• Provided working version of CADRe to District for testing efforts and drought conservation policy development
November 15, 2006	work session	Technical team Stakeholders	•Identify priority preferences, initial alternative ranking, and full working model debut.
January 2007	Porting application online	Technical team	•Desktop application ported to web-enabled version

Table 5: GWDSS decision model attributes for Barton Springs.

Attribute name	Measure
Total storage	Average annual storage in aquifer storage for 10 year transient period in m^3 (ft^3)
Water level change	Average water level change across recharge zone in meters (feet)
Saturated thickness	Sum of the number of wells that fall below a set saturated thickness (calculated as cells in model)
Impervious cover	Aggregate amount of impervious cover over recharge zone (percentage)
Infrastructure losses	Annual leakage estimate for water mains and sewage lines in m^3/s (cfs)
Drought policy – Alarm	Total reduction in pumping volume for alarm stage drought during 10 year transient period in m^3/s (cfs) and as a count of the number of months in stage
Drought policy – Critical	Total reduction in pumping volume for critical stage drought during 10 year transient period in m^3/s (cfs) and as a count of the number of months in stage
Spring flow – Minimum	Minimum monthly springflow for 10 year transient period in m^3/s (cfs)
Spring flow – Maximum	Maximum average monthly springflow for 10 year transient period in m^3/s (cfs)

5.3. Test Case Results

After the elicitation and model building sessions with the stakeholders, a set of scenario settings and model outputs were identified. These model elements link measurable hydrogeologic parameters to key issues of concern and preferences stated by the stakeholder participants. Specific scenario generation elements include options for setting the land use distribution, or impervious cover levels (% by watershed zone), urban expansion rates (as a function of aerial extent), and demand projections (pumping rates).

Examples of measurable natural attributes include; spring flow performance, water budget parameters, saturated thickness, change in recharge, drought trigger frequency, the effect of conservation measures, and infrastructure leakage rates. Model runs indicate that water quantity would increase with impervious cover due to the recharge dynamics from urban infrastructure. However, these results do not yet address another principle element of stakeholder concerns; degrading water quality, which should be addressed in future studies.

The SD model is well suited for real-time discussions over consensus yield. The detailed model (i.e. the GAM) can be used to determine effective yield for the aquifer system. Combined, the two models can be used to evaluate a comprehensive available yield for the aquifer that is both scientifically credible and sustainable within the context of the community that depends upon the aquifer as a resource.

The integrated model was developed with the intent to use it in support of live, rapid dispute prevention/resolution sessions. Model sessions can be used for either community consensus or for setting policy strategies within the feasible ranges of social preference sets. The results represent a first approximation of model parameters that can be refined with time. CADRe may be used as a platform to test a series of multi-disciplinary hypotheses and method comparisons, within areas of inquiry ranging from hydrogeology, economics, operational research, decision analysis, behavioral psychology, and public affairs. In addition, CADRe is an aid to the consensus building process by engaging stakeholders in meaningful, science-based dialogue.

CADRE provided an interactive tool for strategic planning and modeling for the Barton Springs/Edwards Aquifer Conservation District, as well as a platform upon which the components for a real-time rapid dispute prevention process can be based. The capabilities of the Barton Springs test case within CADRe were used to:
- evaluate operational rules by the groundwater conservation district;
- rank alternative management plans;
- facilitate consensus building sessions with stakeholder groups;
- conduct multi-model and method comparisons; and
- identify general behavior trends or aquifer response to management related stresses.

6. Discussion

The objectives for this LDRD projectincluded development of a software system to aid with problem scoping, scientific gap identification, long-term strategic planning for policy-making and model mediated consensus session support. The resulting product is a **C**omputer **A**ssisted **D**ispute **Re**solution (CADRe) system. CADRe is a flexible modeling and decision support system that provides a platform for rapid coupling of science-based simulation models, relational data, and global optimization algorithms for decision analysis and real-time, model-supported group dialogue. The core software system has been developed to achieve real-time support for model-mediated negotiation and group consensus sessions.

Development of CADRe involved three technical areas of effort: software engineering, modeling, and decision science. Development and refinement in each of these thrust areas was necessary to advance this project beyond the proto-type stage and to develop a generic framework and process that can be applied to different types of problems (e.g. water quality, surface water, water-energy, trans-boundary issues, water marketing, and other resource allocation or management problems).

A major outcome of this research is an emergent computing environment that provides a technological base from which the feedback process between science and policy can be addressed. CADRe is a foundation upon which the conceptual link between the two realms of policy and science can be evaluated and the remaining theoretical and practical obstacles for complex decision making can be addressed

The scientific advancement and innovation of this project lies in developing new methods that merge spatially variable results under a systems dynamics framework that is web-enabled and linked to a powerful global optimization search tool. In addition, the integration of technological tools within a conflict resolution process required the development of approaches that can take advantage of the new tool in a structured environment for negotiation.

CADRe addresses problems that involve both complex scientific topics and contentious public policy issues. The CADRe architecture is a means of accommodating complex problems common to a wide-range of resource allocation issues. In effect, the architecture provides a platform that supports the application of both hard and soft science methodologies. The CADRe architecture includes both detailed and simplified simulation models. It stores disparate datasets, links multiple model types, such as numerical groundwater models (MODFLOW) and systems dynamics models (Powersim), and can search for alternative scenarios efficiently using a tabu search algorithm (MAST's). The architecture permits interchangeable applications to ease policy implementation.

The software system provides a structural bridge for iteration between discipline specific models, decision science applications, and social values. Using the CADRe architecture an innovative new process and approach can be used to bridge the gap between current

modeling abilities and the needed management science applications. CADRe provides an avenue for implementing an adaptive management process for water resources. Using the system design, it is possible to convert information into knowledge in a format that is accessible for both strategic planning and rapid dispute prevention of water resource conflicts.

This project achieved the following objectives:

- Development of new methods that integrate spatially distributed physical models (e.g. groundwater and land surface processes) under a systems dynamics framework

- Development of new methods by which these simulation and visualization tools can be used in a structured environment to support conflict resolution processes

- Created a method for identifying optimal solutions for complex water resource management problems

- Built collaborative relationship between UT-Austin and SNL researchers by combining efforts that are complimentary and parallel, and leveraged the strengths of each organization's ongoing research programs

In addition this research diversifies the portfolio of the SNL Corporate Water Initiative with tools that directly support the Energy and Critical Infrastructure investment area; especially the Water Initiative, by contributing to the following objectives (from the SNL Fiscal Year 2004-2009 Institutional Plan):

- Allow quantifiable optimization of infrastructure and response options

- Provide assurance information for public policy decisions

- Provide means for increasing the safety, security, and reliability of water resources and other critical infrastructure

- Provide the ability to test and implement technologies and systems for the United States and, other nations

- Allow SNL to become better recognized as leading water research and problem-solving institutions in the United States and the world

The transfer of both the CADRe software environment and the participatory modeling process methods is already occurring in a number of ways. The initial CADRe system is already in use by the Barton Springs/Edwards Aquifer Conservation District to evaluate drought policies, and may augment habitat conservation planning. Work on this research project has resulted in completion of 3 doctoral level dissertations in the disciplines of hydrogeology, mathematics, and public affairs. Follow-on research is being conducted on the topic of Real-time Water Markets for the Mimbres Basin, Mimbres, NM. A derivative or sister application has been applied to a regional groundwater management application for the Central Texas Groundwater Management Area (GMA-9) as a beta test site for the CADRe methodology. The GMA-9 work has resulted in the first recorded

completion and submittal of a regional consensus yield policy under new legislation for the state of Texas. To date, no other regional groundwater planning group has completed the same process. The GMA-9 process was an exemplary use of participatory modeling activities using CADRe as an underlying basis.

We also anticipate CADRe serving as the foundation to expand SNL's capability in systems level modeling and assessment. Through the use of both the modeling interface, as well as the participatory modeling process, new and additional problem sets can be addressed that prior to this project, would have been difficult to address. These include problems in energy use, land-use planning, cross-border resource issues, and integrated problems such as water and energy.

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