Design Considerations and Evaluation of a Collaborative, Spatio-Temporal Decision Support System

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Abstract
Collaborative spatial decision support systems (C-SDSS) have been used to help groups of stakeholders understand data and search for opportunities at resolving local and regional decision problems in various domains including land use, transportation, and water resources. The key issue in designing an effective C-SDSS is the anticipation of user information needs. Knowledge of user information needs can guide system designers in achieving a C-SDSS that fits the decision process. In this paper we present a design approach that is informed by stakeholder concerns, as part of a user needs assessment. The approach is based on the premise that knowing stakeholders’ concerns can help anticipate user information needs and consequently lead to a more usable C-SDSS. We demonstrate the approach with the example of a spatio-temporal decision problem involving conjunctive water administration in the Boise River Basin in southwestern Idaho. The spatial dimension of the decision task involves delineating the areas of conjunctive water administration while the temporal dimension involves selecting the year in which a given area will start to be administered. We show how the elicitation of stakeholder concerns leads to functional specification of a collaborative spatio-temporal decision support system.

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1 Introduction

The concept of spatial decision support has featured prominently in the GIScience literature of the last two decades for a simple reason: much of geospatial data processing is done to obtain information for decision making. Since almost any spatial information system can be claimed to offer some form of decision support, an effort was made in the late 1980s and early 1990s to define a minimum set of functionalities required of spatial decision support systems (SDSS). SDSS were originally proposed to aid individual (Densham and Armstrong 1987) and group (Armstrong 1993) decision makers in solving spatial, semi-structured problems, in which location and spatial relationships of distance, direction, connectivity, and adjacency are an integral part of problem solution, and decision objective(s), decision alternatives and their outcomes, and evaluation criteria are not fully known. Accordingly, the original purpose of SDSS was to assist individuals and groups in articulating decision objectives and evaluation criteria, finding feasible decision alternatives, and identifying superior decision options. To achieve this purpose SDSS needed to integrate: (1) mathematical and logical formalisms (models) to process spatial data and information, (2) technical data (scientific measurements), and (3) perceptual data (estimates, probabilities, and human judgments). These requirements mirrored the requirements for decision support systems (DSS) formulated by Keen (1977) and Sprague and Watson (1986) in the field of management science. Similar to DSS, a blueprint for SDSS was based on the idea of providing an easy access to spatial data and decision models through the integration of spatial databases, analytical models, and visualization tools (Densham 1991).

The above notion of what constitutes decision support has not been uniformly shared. For some, any data processing activity resulting in information of direct or indirect value to problem solving and decision making is synonymous with decision support. This broad understanding of the meaning of decision support reflects the trend to treat almost any computerized data processing system as a “decision support system” (Keenan 1997). In the same vein, Geographic Information Systems (GIS) have been portrayed as SDSS on the grounds that a GIS provides spatial data access, analytical processing, and display capabilities (Cowen 1988). Arguably, the computational basis for spatial decision support was then and still is today some form of GIS technology. Just like early SDSS, today’s SDSS have at their core the basic decision aid(s) of GIS including data management to help extended human memory, graphic display to enhance visualization, and spatial analysis functions to extend human computing performance. Over the course of the 1990s and in recent years these common decision support functions have been expanded to include optimization (Aerts et al. 2003, Church et al. 2004), simulation (Wu 1998), expert systems (Leung 1997), multiple criteria evaluation methods (Malczewski 1999, Thill 1999, Feick and Hall 2004), on-line analysis of geographical data (Bedard et al. 2001), and visual-analytical data exploration (Andrienko et al. 2003) to generate, evaluate, and compute trade-offs among decision alternatives.

While much of the work on SDSS has been aimed at the design and development of software tools, another direction, started in the mid-1990s, has broadened the focus of research on SDSS by evaluating the usability and socio-behavioral consequences of decision support tools in the context of simulated (laboratory) and realistic (field experiment) decision situations (Reitsma 1996, Stasik 1999, Jankowski and Nyerges 2001a, Haklay and Tobón 2003). Some of this research was inspired by work in the field of
human-computer-interaction (HCI) centered on collecting empirical data about the use of software tools by humans in order to explain why some software systems and techniques are more usable than others (Nyerges 1993).

This paper builds on both directions of research on SDSS and presents the approach and the results of developing a prototype spatial decision support system for collaborative work within water resource administration called WaterGroup. In the paper we focus on the approach that may be re-used for other collaborative SDSS design efforts. The development of WaterGroup was undertaken in the context of a larger project, in which initially GeoChoicePerspectives software, developed for group-based site selection during the 1990s (Jankowski and Nyerges 2001b), was used to formulate year-to-year scenarios of wells, considering each well as a site. This software did not easily address the spatio-temporal problem at hand and the team set out to develop more robust software that was later called WaterGroup. The report on the decision process that transpired as the result of the interaction between stakeholders participating in the field experiment and the WaterGroup software is given elsewhere (Nyerges et al. 2006). In this paper we report on the design of WaterGroup. In section 2 we give an overview of the spatio-temporal decision situation, which motivated the development of WaterGroup. We then describe, in section 3, our approach to collaborative SDSS design using the example of WaterGroup. The overview of WaterGroup’s functional capabilities is presented in section 4 followed by the stakeholders’ evaluation of system usability in section 5. We conclude the paper in section 6 with lessons drawn from the design of WaterGroup, that may be beneficial to designers and developers of future collaborative SDSS and public participation GIS.

2 Decision Situation Background

Throughout the western U.S. there is a growing tendency to recognize the interconnection between ground water and surface water systems. However, administration of water resources based on this recognition – termed conjunctive administration – is difficult to implement in a river basin in which ground water pumping has occurred for decades without regard to impacts on surface water systems. One such basin is the Boise River Basin in the State of Idaho (Figure 1).

The appropriation doctrine of “first in time is first in right” has provided a consistent basis for distributing limited supplies of surface water in Idaho. Water rights have been decreed in the basin since 1907, and since that time a water master has been distributing the flows in the river, because flows during the summer are insufficient to satisfy all water rights. Priority dates for surface water rights (dates of acquiring rights to divert water from a surface water body) are typically in the range from 1864 through 1910, and each year water rights with priorities as early as the 1880s are curtailed due to low water flows in the Boise River. Priority dates for ground water rights are seldom older than 1940, so in general water users diverting from ground water are junior to those diverting from surface water. However, the impacts of ground water pumping on these surface water supplies have often been ignored because of the legal and technical difficulties that they invoke. Many states have dealt with these “conjunctive” impacts by ceasing to issue new permits for the pumpage of ground water. However, when there has been an attempt to incorporate the impacts of existing ground water pumping systems on streams, western states have witnessed conflict and struggle.
Improved modeling in recent years has enabled better characterization of the impact of ground water withdrawal on surface water supplies (Cosgrove 2001). However, the characteristics of the aquifers in the Boise River Basin make it difficult to model this system with a high degree of accuracy. The aquifers that underlie the basin include a shallow aquifer in the alluvium to a depth of about 30 m; a partially confined intermediate aquifer in the range of 30–100 m, and a deep, confined aquifer. The confined aquifers have been found to be leaky due to discontinuities of confining layers and multiple perforations caused by unsealed boreholes. The aquifers are anisotropic and heterogeneous, so impacts on the river due to well pumpage cannot be accurately predicted using equations that assume homogeneity and isotropicity.

2.1 Decision Problem

Creation of conjunctive administration rules in Idaho, and a growing awareness of the relationship between surface and ground water systems, has led regulators to consider the impacts of the diversion of ground water that is tributary to the Boise River upstream from and within the regulated reaches of the river. The complexity of the situation is symptomatic to a semi-structured decision problem that is only partially understood. The geohydrology of the aquifer and the hydrologic data support (in part) the position of the decision maker authority – the Idaho Department of Water Resources.
Spatio-Temporal Decision Support Systems

(IDWR), which maintains that the interception of surface water by ground water users does take place, and thus the pumpage of ground water should be regulated. Yet, the hydrologic impacts of ground water pumping cannot be computed for specific wells and river reaches due the lack of location-specific data and the hydrogeologic complexity of the basin. Amidst the uncertainty about specific impacts of ground water pumping on surface water flows the decision making authority wants to develop the administrative policy of regulating ground water pumping beginning in 2007 and continuing into the future. The decision making authority has come to realize that the analysis procedure and logic used in developing such a policy must be transparent to all interested parties (stakeholders) and be defensible in administrative and judicial venues today and into the next decades. The latter is dictated by the strong desire, on the part of the decision making authority, to avoid lengthy and costly litigation that has characterized the disputes between surface water users and ground water users in southern Idaho in the past 20 years. Hence the decision making authority has been interested in fostering a collaborative stakeholder interaction resulting in developing broadly shared policy recommendations.

2.2 Collaborative Process

The collaborative process, envisioned by the decision maker and the paper authors who were both the researchers and advisors to the decision maker, had stakeholders, including one or more representatives from the following groups: water master, surface water users, ground water users, potable water provider, municipality and the general public, working towards shared policy recommendations on conjunctive water management in the Boise River Basin. The collaborative process was structured using an experimental design, in which two similarly-constituted groups of stakeholders faced the same task of developing a policy recommendation. These groups were called the control group and the treatment group. Members of the treatment group were provided with individual computers to enable exploration of the data. They were aided by one chauffeur for every two stakeholders, to assist in the use of (i.e. navigate and drive) the computer software. Members of the control group did not have individual computers with which to further analyze data, instead utilizing one information display for the group. The experimental design with two groups was used to compare whether or not the (individual versus group) access to SDSS software would result in a different decision process and produce different results. The process design had each group participating for a full day in a meeting. The agenda for the morning consisted of a series of presentations intended to familiarize the stakeholders with legal and technical issues related to the implementation of conjunctive administration in the basin. Conjunctive administration is a policy process resulting in designating specific management areas for ground water users, who are junior to surface water users, and determining time and hydrologic conditions under which water pumpage may be curtailed. During the afternoon the stakeholders were requested to develop group solutions for the following questions: (1) should the water district proceed toward implementation of conjunctive administration; (2) when should implementation begin; and (3) which wells should be added each year after conjunctive administration has been initiated? The stakeholders were provided a collaborative spatial decision support system to help them develop solutions to the above three questions. In the next section we describe our approach to system design.
3 Analysis of User Information Needs

Keeney (1992) argued that the anticipation of user information needs during a decision process requires the knowledge of user values understood as deeply held beliefs and moral convictions affecting the user behavior in a decision situation. Keeney’s work and the earlier work by Edwards and von Winterfeldt (1987) suggest that user information needs during a decision process derive from deeply held user values. The practical problem, however, is how to elicit user values. We suggest that good proxies for values relevant to a given decision problem are user concerns. We use the term “concern” as the everyday proxy word (concept) to engage people in unpacking their values, which otherwise might be difficult to elicit. The difference between values and concerns is that the former represent a fundamental basis for judging whether something is good or bad or neutral, and hence making choices and the latter are their manifestations in reaction to a specific problem situation. Values derive from cultural traditions and social norms but are rarely invoked during a deliberative discourse being a part of the decision making process. Instead, people commonly voice their concerns, which derive from values. For example, in developing a conjunctive water administration plan stakeholders are unlikely to state their positions in terms of value-laden phrases such as “preservation of one’s livelihood” or “equal access to water for everyone”. Instead, they are more likely to state their positions in terms of value-derived concerns such as “costs and benefits to water users”, “surface water availability”, or “ground water availability”. In order to elicit the stakeholder concerns related to the Boise River Basin decision situation we organized two facilitated meetings, one for each group of stakeholders, led by a staff member of IDWR. During the meetings conducted in May of 2001, participants were asked to identify their concerns regarding conjunctive administration of surface and ground water resources in the Boise River Basin. These concerns were synthesized and organized by research team members into three groups: administrative, environmental, and water user impacts, as depicted in Figure 2. The concerns were not ranked, and hence the order, in which they are listed in Figure 2 does not represent a priority order.

All of these concerns have some relevance to the decision situation in the mind of one or more of the stakeholder participants. In order to support their fully informed participation in the decision process, information relevant to each of these concerns must be provided that allows the participants to evaluate the potential impacts of alternative decision outcomes. However, the agency with jurisdiction over this decision problem, IDWR, only has a legal mandate to manage the distribution of water resources. It does not have a mandate to consider certain kinds of impacts, such as those to fish and wildlife habitat or water quality. Therefore consideration of these concerns was left out during the design of WaterGroup. Furthermore, some of the concerns focus on administrative and legal aspects of the decision situation. These are also important and legitimate concerns, and efforts were made to respond to these concerns with the best available information at each of the stakeholder decision workshops. However, given our focus on supporting stakeholders in the spatio-temporal dimensions of the decision problem, administrative and legal concerns were also not considered during the system design. Table 1 lists the remaining concerns as well as the specific information needs that motivated the development of WaterGroup. There were no spatial data or other information available for many of these information categories. Information categories we incorporated into WaterGroup are listed in bold. An expert on the hydrology of the Boise River Basin and a staff member at IDWR were both available at each stakeholder
workshop to discuss the best available science relevant to stakeholder information needs, as well as to answer other questions about impacts to water users.

The information categories listed in bold in Table 1 guided the database design for the decision problem and the development of the WaterGroup software. Furthermore, they pointed to the data items needed during the decision making process including the flow capacity of wells, response ratios of wells, cumulative impact of wells, flows in the Boise River, and the impact of ground water pumping on surface water flows.

The user information needs identified in Table 1 are an important component of user need analysis guiding the development of C-SDSS. The other components are task description and user characteristics. The user characteristics include their background and familiarity with a problem domain, the institutions they represent, and their familiarity with computer technology. The decision task assigned to the Boise River Basin stakeholders was challenging in terms of addressing both spatial and temporal dimensions of the problem. The stakeholders were tasked with recommending to the decision maker the start year of conjunctive administration, and which wells should be added each year after the conjunctive administration has been initiated. The stakeholders were experienced water users strongly interested in the Boise River Basin water issues (see Table 2). Among the stakeholders there were representatives of local and state government, water and irrigation districts, municipal water providers, and members of the public that use ground water. There were eight stakeholders in the control group and nine in the treatment group.

Several observations about the stakeholders can be deduced from Table 2. First, the stakeholders in both groups had extensive experience in the water community. While the average for the Control Group was higher than that of the Treatment Group, both groups had significant water experience. Second, personal interest in water was
Table 1  Stakeholder information needs

<table>
<thead>
<tr>
<th>Stakeholder concern</th>
<th>Information/data need</th>
</tr>
</thead>
</table>
| Ground water availability                               | o  Changes in ground water availability (e.g. height of water table) during recent years and expected changes if no decision regarding conjunctive administration is made  
|                                                          | o  Predicted impacts on ground water availability by alternative decision outcomes  
|                                                          | o  Variations in these changes and impacts over space and time                                                                                          |
| Impacts of ground water wells on other ground water wells| o  Estimated spatial impacts on ground water availability based on the operation of a selected well                                                                                                                       |
| Total cumulative impact of de minimis* wells on Boise River| o  Estimation of total wellhead flow of de minimis wells* (i.e. how much they are pumping from the ground)  
|                                                          | o  Estimated response ratio of de minimis wells (i.e. the ratio of water pumped to reduction in flow of the Boise River)  
|                                                          | o  Total cumulative impacts of de minimis wells                                                                                                              |
| Surface water availability                               | o  Current flow rates on stretches of the Boise River  
|                                                          | o  Predicted flow rates along the Boise River if conjunctive administration is not initiated  
|                                                          | o  Predicted flow rates along the Boise River based on alternative decision outcomes  |
| Benefits of dams                                         | o  Current estimated impacts of dams on the surface and ground water system  
|                                                          | o  Predicted impacts of additional dams on the surface and ground water system  |
| Impacts on senior ground water rights                    | o  Current availability of water to senior water rights (i.e. are any senior water rights not being fulfilled, or at risk of not being fulfilled)  
|                                                          | o  Predicted impacts on senior water rights of alternative decision outcomes  |
| Costs and benefits to ground water users                 | o  Predicted monetary costs to ground water users if no decision regarding conjunctive administration is made (e.g. from declining water table)  
|                                                          | o  Predicted monetary costs/benefits to ground water users who will be regulated if/when conjunctive administration is initiated  |
| Hydraulic connection between ground and surface water    | o  Summaries of the best available science about the Boise River Basin hydrology  
|                                                          | o  Estimated response ratio of individual ground water wells (i.e. the ratio of water pumped to reduction in flow if the Boise River)  |
Table 1  Continued

<table>
<thead>
<tr>
<th>Stakeholder concern</th>
<th>Information/data need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated cumulative impacts of ground water use on</td>
<td>surface water flows based on criteria such as well depth, response ratio, and/or</td>
</tr>
<tr>
<td></td>
<td>distance from the Boise River</td>
</tr>
<tr>
<td>Data quality and currency</td>
<td>o Accurate, complete, and easy to interpret metadata for all data in WaterGroup</td>
</tr>
<tr>
<td>Comprehensiveness of examined impacts to ground water</td>
<td>o Accurate assessment regarding how comprehensively the impacts to ground water users</td>
</tr>
<tr>
<td>users</td>
<td>were examined</td>
</tr>
<tr>
<td>Effects of groundwater recharge</td>
<td>o Explanation of the process of groundwater recharge</td>
</tr>
<tr>
<td></td>
<td>o Estimations of the rate of the current groundwater recharge</td>
</tr>
<tr>
<td></td>
<td>o Information about projects to expedite groundwater recharge</td>
</tr>
<tr>
<td></td>
<td>(and the legality of initiating new projects)</td>
</tr>
<tr>
<td>Costs and benefits to surface water users</td>
<td>o Predicted costs to surface water users if conjunctive administration is not initiated</td>
</tr>
<tr>
<td></td>
<td>(e.g. from predicted shortfalls in surface water availability)</td>
</tr>
<tr>
<td></td>
<td>o Predicted flow rates and shortfalls along the Boise River if conjunctive administration is not initiated</td>
</tr>
<tr>
<td></td>
<td>o Predicted flow rates and shortfalls along the Boise River based on alternative decision outcomes</td>
</tr>
</tbody>
</table>

* De minimis wells are very small in water pumping capacity – 0.1 cubic foot per second or less. More than three quarters of the wells in the Boise River Basin are de minimis. These wells are generally used for domestic water consumption and small-scale irrigation.

Table 2  The Boise River Basin stakeholder characteristics

<table>
<thead>
<tr>
<th>Stakeholder Characteristics</th>
<th>Control Group (Control)</th>
<th>Test Group (Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of years personally involved with the acquisition, diversion or regulation of water within the State of Idaho.</td>
<td>27.5 years</td>
<td>17.4 years</td>
</tr>
<tr>
<td>2. Personal interest in the administration of ground water as related to surface water.*</td>
<td>83</td>
<td>95</td>
</tr>
<tr>
<td>3. Anticipation that the information to be discussed will be useful.*</td>
<td>81</td>
<td>89</td>
</tr>
<tr>
<td>4. Experience in working with groups.*</td>
<td>85</td>
<td>77</td>
</tr>
<tr>
<td>5. Experience in making business decisions.*</td>
<td>79</td>
<td>67</td>
</tr>
</tbody>
</table>

* Note: Characteristics 2–5 are scaled from 0 to a 100 point maximum. Source: Tuthill 2002.
high for both groups. Finally, experience in making business decisions received the lowest score for each group. This appears to have been caused by government employees in the groups rating themselves lower in this category, stating that they were not experienced business people. The familiarity of stakeholders with computer technology and common software productivity tools varied from almost non-existent to high.

The user needs analysis can guide the functional specification of C-SDSS. In the Boise River Basin decision situation the stakeholders needed tools to support the formulation of conjunctive administration options where an option would detail locations of ground water wells and timing of their administration. The conjunctive administration in this case means the curtailment (or alternative mitigation) of ground water pumping in wells identified by their distance from the river, depth to water, consumptiveness – where the consumptive use of water means that no water is returned to the water source from which it was withdrawn, pumping rate simplified to de minimis (≤ 0.1 cubic foot per second) and non-de minimis (> 0.1 cubic foot per second), low river water flows, and the timing of administration. For example, an administrative option could be comprised of a spatio-temporal regime as presented in Table 3.

Since multiple conjunctive administration options could be proposed by the stakeholders there was a need for a software function to resolve the differences between the options and to order them from most to least attractive. In total there were six categories of software tools (functions) identified as a result of user needs analysis:

1. Tools to query and visualize the decision space.
2. Tools to construct conjunctive administration options.
4. Tools for submitting new options to the facilitator.
5. Facilitator tools to organize, transmit, and display options.
6. Tools to vote on conjunctive administrative options, analyze, and display voting results.

We describe the design and implementations of these decision support tools in Water-Group in the following section.

Table 3 An example option for conjunctive administration of water in the Boise River Basin

<table>
<thead>
<tr>
<th>Distance from river (miles)</th>
<th>Depth (feet)</th>
<th>Consumptiveness (yes or no)*</th>
<th>De minimis or Non-de minimis**</th>
<th>Timing (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>100</td>
<td>Yes</td>
<td>Non-de minimis</td>
<td>2008</td>
</tr>
<tr>
<td>0.3</td>
<td>150</td>
<td>Yes</td>
<td>Non-de minimis</td>
<td>2008</td>
</tr>
<tr>
<td>0.4</td>
<td>200</td>
<td>Yes</td>
<td>Non-de minimis</td>
<td>2009</td>
</tr>
<tr>
<td>0.5</td>
<td>200</td>
<td>Yes</td>
<td>Non-de minimis</td>
<td>2010</td>
</tr>
</tbody>
</table>

* Water use that is consumptive effectively eliminates the water from the water system (e.g. irrigating crops). Water use that is non-consumptive returns the water to the water system (e.g. a decorative fountain which draws water from a river then returns it directly to the river).
** Non-de minimis wells are all wells which are not de minimis.
Development of a collaborative spatial decision support system can be described as the process of creating, within the constraints imposed by the development environment, a system providing end-users with maximum functionality that can be effectively applied to a decision task. Constraints in developing C-SDSS derive from the nature of the decision processes in which the system would be utilized, type of physical platform(s) hosting C-SDSS, developer resources, access to end-users, and the training of chauffeurs.

4.1 Constraints

The process agenda for the Boise River Basin problem included the following activities: define the meeting objectives, explore the available data and nature of the problem, create conjunctive administration options, review option impacts, and vote for preferred options. Although the process could conceivably be navigated sequentially, the possibility existed that end-users would want to skip certain steps, revisit activities, or even iterate through multiple process steps. In order to avoid over-defining the process flow, the prototype would need to be flexible enough to allow the stakeholders the ability to create their own preferred process sequence.

The hardware platform selected for WaterGroup was made up of laptop notebook computers running Windows 2000 connected through a wireless local area network (LAN). The decision to use the wireless laptop network was dictated by the afforded flexibility in deploying C-SDSS at almost any location as opposed to being confined to a fixed meeting facility equipped with desktop computers. Due to limited project funds the decision was made to build WaterGroup from existing commercial software components rather then writing the code from scratch. In order to make the prototype as up-to-date as possible, provide a stable integration environment, and possibly enable its use further into the future, it was decided that the GIS application that would be used as the software development platform should have an open architecture and be based on the component object model (COM). ArcGIS Version 8 was selected for the GIS development platform. In addition, the prototype would be restricted, beside the custom code, to the use of functionality contained within the Environmental Systems Research Institute (ESRI) products, the Microsoft Office suite, and Windows 2000.

Developer resource constraints also played a role. Development efforts would need to be accomplished from a two station wired network setup in the developer’s home (Robischon 2002). In addition, a single developer would be responsible for all of the prototype development, and that developer’s programming expertise was much higher with Visual Basic than other high level languages.

For this project, end-user (stakeholder) access was not available beyond the data collected about stakeholder concerns described previously; therefore researchers would need to act in the role of proxy stakeholders. Although the researchers were all very familiar with the problem domain and process considerations, their life experiences and levels of domain knowledge and computer expertise were quite different from those of the end-users.

The researchers planned to enlist volunteer chauffeurs to help the stakeholders use the system. Although the chauffeurs had considerable problem domain expertise, they would need to be trained in the operation of the software. Logistical constraints limited the training opportunities to teleconferenced walkthroughs of system functionality.
4.2 System Architecture

Although the needs analysis had identified high-level functionality required in the prototype, it was also necessary to consider the level of integration that would be included in the system. Three common approaches to integrating various software components into SDSS include loose-coupling where the components retain their separate user interfaces and exchange data through a file-sharing mechanism invoked by the user (Jankowski 1995), tight-coupling where the components share a common user interface and the data exchange is automated (Bennett and Vitale 2001), and embedded systems in which the components share a common user interface, data structure, and storage (Fedra 1996). A loosely-coupled system would be able to make use of functionality contained in different applications (e.g. ArcGIS and Excel), but might require that the stakeholders act as data transmission conduits, accepting outputs from one application and transferring them to another application for additional processing. This approach, although efficient from a developer perspective, would almost certainly impose excessive cognitive process load on the decision-making effort. An embedded system would select a single application (likely ArcGIS) and modify the application, utilizing custom code, to accomplish the required functionality. This approach, although appearing attractive from the stakeholder perspective, would require significant effort in developing the custom code required and would likely result in functionality less effective than that that could be provided by multiple, special purpose applications.

A third approach would involve the creation of a tightly-coupled system that would access functionality from multiple applications while still presenting a single, integrated user interface to the stakeholders. This approach would represent a compromise between the loosely coupled and embedded approaches. Although it would introduce additional (computer) processing overhead to the system, its implementation would involve significantly less developer resource and minimize the (decision making) process distractions associated with shuffling data between applications. This is the approach that was chosen for development of the prototype.

As a first step in identifying the sequence in which the development would occur, it was recognized that most, if not all of the functionality identified in the needs analysis might require that the system be capable of communicating between multiple applications and laptop machines, so a seventh function (in addition to the six functions listed at the end of section 3), interprocess communication (IPC) was added to the list. Several IPC methods are available within the recent versions of Windows operating systems; both 2000 and SP Professional. Dynamic data exchange (DDE) is similar to an extension of the clipboard where single cut and paste operations are enhanced by the ability to repeatedly update the data. File mapping is a technique whereby multiple applications are mapped to a shared memory location. Mailslots are one-way communication devices in which client processes can send messages to mailslots created by server processes. Named pipes involve the creation (by a server process or pipe server) of a section of memory that can be accessed by multiple client (pipe client) processes (Robischon 2002). Since WaterGroup would be used by stakeholders accessing several laptops linked by a wireless network the approach utilized for transmitting message type data between processes was the named pipe approach. This approach is well suited to areas where communications can involve both intra- and inter-machine transmissions. Because the system would be installed on a known collection of (10) machines, large datasets and processing intensive applications could be stored and accessed locally, and
the relatively low bandwidth available to the wireless network could be reserved for stakeholder and facilitator communications and small dataset transfers. In addition, the implementation of named pipes was less complex than some of the other available methods. Communications could be accomplished using calls to operating system functions made available through the Windows application programmer interface (API).

4.3 Graphical User Interface

The graphical user interface (GUI) design was intended to integrate functionality from different applications into a coherent, easy-to-use set of display windows. In order to accomplish this goal, the Windows 32 bit application programmer interface (API) was utilized to coordinate the display of in-process as well as out-of-process servers with the main WaterGroup prototype module.

Overall functionality of the prototype was controlled by a Visual Basic program that provided a single main toolbar window to the end-user (Figure 3). This toolbar contained 11 different command buttons, each of which provided access to different prototype functionality. After a successful login and prototype launch, this main toolbar window was always displayed on top of all other windows, enabling stakeholders to switch between functions or applications by choosing a command button from the window.
Integration between applications was accomplished using a client-server approach. The main program (and its main toolbar window) was essentially the client for services provided by several other applications. Both in-process and out-of-process servers provided the services. In-process servers are those that access the same memory space as the client. To accomplish charting and database query functions, the main program accessed objects from Microsoft Excel and Access without explicitly creating instances of (i.e. running) the programs. The objects were accessed from within the process of the main program, and were acting as in-process servers.

Out-of-process servers access separate memory space from the client. In WaterGroup these services were provided by ArcMap and ArcScene as well as the image exploration VB program. The main program contained code that launched instances (and displays) of these applications and then used named pipes to accomplish data transfer when necessary.

The main toolbar window was oriented vertically on the screen, with the first eight of 11 buttons appearing in assumed order of process flow. Three buttons at the bottom of the window invoked utility functions (Message, Exit, and Connect) that could be invoked at any point during the stakeholder decision-making process. In (top down) order of presentation, the process-related command buttons were as follows: Images, 2D View, 3D View, Flow Details, Well Details, Create Option, Impacts, and Vote. The Images button produced a watershed level map that allowed the stakeholder to switch between 5 m and 1 m imagery. By selecting the 2D View or 3D View buttons, the stakeholder was presented with full screen windows displaying the ArcMap (Figure 3) and ArcScene applications, respectively. The displays included a 5 m resolution aerial photo raster and the wells covering the study area. By selecting the Flow Details (Figure 4) button the stakeholder could view a full screen window containing a chart of flow details (time series flow rate line charts) for either the upstream or downstream point in the Boise River. The Well Details button produced charts with hydrologic characteristics of ground water wells in the study area. The Define Option button resulted in the presentation of a series of windows where stakeholders would loop through the process of building a query for a specific year within the conjunctive administration period, submitting the query, visualizing the wells bounded by the query definition, and proceeding to subsequent years. When selecting the Impacts button the stakeholder was presented with a full screen thumbnail window displaying 26 impact charts for a given conjunctive administration option as well as a timeline detailing the queries applied to individual administration years. Selection of the Vote button initialized a check for whether voting had been enabled by the facilitator. If the vote concerned selection of preferred options, the voting window contained three dropdown boxes from which the stakeholder could choose their first, second, and third choices. Votes were tabulated automatically and the results were visualized for all stakeholders to see. The Message button enabled stakeholders to submit private or public messages directed either to another stakeholder or the facilitator, or to the entire group.

4.4 System Evaluation

Four sessions aimed at the development of conjunctive administration recommendations were conducted with the Boise River Basin stakeholders during 2001 and 2002. The initial two sessions, conducted on 16–17 May 2001 at Boise State University utilized GeoChoicePerspectives software (Jankowski and Nyerges 2001b) as a generic C-SDSS.
GeoChoicePerspectives (GCP) was originally developed in the late 1990s to support group decision making in spatial problems involving data visualization, multiple criteria evaluation of decision options, and voting. For the stakeholder sessions in 2001 the GCP was used as “off the shelf” software and not as a custom-built C-SDSS for the conjunctive administration decision problem. WaterGroup was used during two stakeholder meetings on 19–20 September 2002 at the Idaho Department of Parks and Recreation in Boise, Idaho. The 2001 and 2002 meetings utilized the same experimental design comprised of two sessions: the control group session where only the facilitator had access to the software, and the treatment group session where in addition to the facilitator the stakeholders also had access to the software. The make up of both groups in each year was similar – of 10 stakeholders comprising the control group in 2001 eight returned to participate in the 2002 session, and of 10 stakeholders comprising the treatment group in 2001 nine returned to participate in the 2002 session.

At the beginning of each workshop, stakeholders were given a one-hour presentation by an IDWR hydrologist about the state of knowledge of the groundwater flow within the stretch of the Boise River under consideration for the conjunctive administration process. Stakeholders were free to ask questions at any time of the hydrologist, whereby the hydrologist responded making sure that stakeholders were satisfied that their questions were answered within the limits of knowledge available.
At each workshop, the stakeholders were asked to create and select a water resource management plan for the Boise River Basin as a recommendation to the Department. During the 2001 workshop the control group, which interacted with the software (Geo-ChoicePerspectives) exclusively through a facilitator, created two options of water management plans whereby all 10 years and all wells were considered for administration. The treatment group, in which the stakeholders used the software individually, spent most of their time bogged down in the technicalities of using the software and did not come up with a management plan. During the 2002 workshop, in which the WaterGroup software was used, the control group generated two options whereas the treatment group generated five options. There were clear differences between the control and the treatment groups in terms of the decision process dynamics. The control group spent more time on deliberating water management issues than on analyzing data and had a stronger majority vote than the treatment group. The treatment group conversely spent more time on analyzing water resource data and less on deliberation; however, its work was characterized by less agreement than the control group. More details about the dynamics and outcomes of the decision process are presented in Nyerges et al. (2006).

Both in 2001 and 2002 at the end of each meeting the stakeholders completed a 38-question exit survey. Each question utilized a five-point Likert scale. Four of the questions were specific to the software. The responses were standardized to fit a scale ranging from 0 to 100 and averaged. The average score was used as a measure of software usability. The questions are repeated below:

- How much did the software help you to understand the data?
- How much did the software help you to understand the consequences of implementation of conjunctive administration for you and your constituents?
- How much did the software help you to understand the consequences of implementation of conjunctive administration for other parties in the meeting?
- How much did the software help you in communicating the consequences of implementation of conjunctive administration for you and your constituents to other parties in the meeting?

The comparison of the results between the 2001 and 2002 sessions is presented in Figure 5. Three observations can be quickly discerned from the data. First, the usability of GCP software used in 2001 was rated an average 13% lower than the usability of the WaterGroup software used in the 2002 sessions. Second, the standard deviation of the ratings for both treatment groups (using the GCP and WaterGroup software) was on average 14% higher than the average standard deviation of both control groups (using GCP and WaterGroup software). Third, in both experiments the respective control groups rated the software’s support functionality higher than the treatment groups.

The higher average rating of the WaterGroup software supports the premise that a customized SDSS that takes into account requirements and constraints of a specific decision problem is likely to result in more usable decision support software than a generic SDSS. Decision support tools, in order to be perceived as useful by its users, invariably require a direct relevance to the steps of the decision process. The spatio-temporal character of the conjunctive administration problem required defining the areas of administration, selecting the starting year of administration, and computing the impacts. These functions, available in WaterGroup, were not available in the GCP software, which afforded primarily data exploration and option voting.
The higher standard deviation of the mean ratings for the treatment groups reflects the high heterogeneity of groups in respect to computer skills, which is to be expected in any participatory decision making situation involving a representative sample of diverse constituencies. This fact needs a careful consideration during the design of C-SDSS.

The higher rating given by the control groups, regardless of the software used, underscores an important constraint of using groupware tools known from other studies with group decision support systems (Jankowski and Nyerges 2001a). Heterogeneous groups of stakeholders prefer facilitated decision processes, in which a facilitator relieves them of the burden of operating the software. This was the case with both control groups. The facilitator was leading the process and simultaneously chauffeuring the software on behalf of stakeholders, who felt freed of technical tasks and could concentrate on a creative part of solving the decision task.

5 Conclusions

Central to the approach utilized for the creation of the WaterGroup prototype was the elicitation of stakeholder values. Values, approximated by people’s concerns about the decision situation, can be the indicators of user information needs. In the decision making debates involving the affected parties, stakeholders are naturally interested in information about issues and problems that are concerns to them. These concerns result from values understood as deeply held beliefs and moral convictions affecting the user behavior in a decision situation of GI technology-supported public participation. Although in the herein reported research only a limited subset of stakeholder concerns was used in guiding the development of WaterGroup functional capabilities, the
software’s usability increased as compared with its predecessor – GeoChoicePerspectives, which was used during the first workshop in 2001.

Some aspects of the overall project structure might be modified to improve the effectiveness of future development efforts. In addition, if efforts similar to those described herein are to be undertaken in other real world decision-making environments, additional cognitive, social, and economic considerations could perhaps produce alternative approaches better suited to the problem at hand. We outline below steps that might be taken towards these ends.

One of the most difficult things for the C-SDSS developer to do is to place him or herself in the shoes of the end-users. Frequently, the developer’s life experiences are far removed from those of the users, and interfaces that appear clean, friendly and straightforward to the developer often appear cluttered, unfriendly and complicated to the user. For this reason whenever possible it is wise for developers to solicit feedback from end-users both when defining system requirements and testing the usability of the software they develop. For this project (using the spiral approach) this would have entailed sitting down with stakeholders at the beginning and end of each spiral cycle, once to validate the functional requirement for that cycle and later to verify its usability. However, since the stakeholders in this project were busy individuals holding full-time jobs there was no opportunity for pre-experiment interaction with end-users. From reviewing the exit surveys completed by the stakeholders, it appears the final prototype interface provided during the experiment worked well for some of the group, but others were not satisfied. Personal observations made during the experiment indicated that there were few difficulties with the data exploration functions, but significant difficulties with the management option creation function. If end-users had been available during the cycle that created the option creation function, either the requirements or implementation interface might have been modified to produce a prototype that was more helpful to the stakeholders.

In lieu of using the actual end-users for usability testing, developers frequently enlist the assistance of proxy end-users who assume end-user roles and attempt to identify areas where the interface might be improved. Although not the ideal approach, this method often is the only one available when logistical constraints prevent having access to those who will use the software. If proxy end-users and their roles are defined properly, many of the faulty assumptions made by the developer can be identified and corrected prior to launching the final product.

A key consideration in embarking upon the design and implementation of a collaborative spatial decision support system is the value of the system relative to the development cost. Since SDSS, unlike generic information systems such as GIS, are usually designed for a specific task at hand and thus unlikely to fit a different decision task, one should consider whether the costs of developing a system are warranted by the expected benefits. If the utilization of custom developed participatory spatial decision support software is to become mainstream, it must demonstrate its value not only in terms of decision quality and satisfaction, but also cost effectiveness. For problem domains in which the consequences of poor decision quality are high, cost effectiveness should be relatively simple to demonstrate. But in areas where the consequences are low, or where the precise nature of the contribution of the decision support software is difficult to quantify, cost effectiveness may be questioned. One approach to lowering the cost of future systems might involve the development of customizable modular systems that could, with minimal development effort, be tailored to suit a multitude of problem domains. WaterGroup is an attempt at such a modularized design taking advantage of
component object model (COM) architecture and a library of commercially available GIS objects (ArcObjects). Extending this approach, generic modules could be created that would enable data exploration, solution option generation, option analyses, group communication, and voting. If the interoperable modules were created to facilitate the processing of data in various formats in a fashion that would allow the import of data in standard formats, decision-making groups could “plug” domain specific data into the modules and choose from a shopping list of available functionality. Groups would not need to expend the significant resources required to develop the major functionality of the system from scratch. In addition, such systems could be continually improved as needs for additional functionality are identified by field use of the software.

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