INFORMATION TECHNOLOGY IN WATERSHED MANAGEMENT DECISION MAKING[1]

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ABSTRACT: Watershed management decision making is a complex process. Cooperation and communication among federal, state, and local stakeholders is required while balancing biophysical and socioeconomic concerns. The public is taking part in environmental decisions, and the need for technology transfer from public agencies to stakeholders is increasing. Information technology has had a profound influence on watershed management over the past decade. Advances in data acquisition through remote sensing, data utilization through geographic information systems (GIS), and data sharing through the Internet have provided watershed managers access to more information for management decisions. In the future, applications incorporating hydrologic simulation models, GIS, and decision support systems will be deployed through the Internet. In addition to challenges in making complex modeling technology available to diverse audiences, new information technology issues, such as interoperability, Internet access, and security, are introduced when GIS, simulation models, and decision support systems are integrated in an Internet environment. This paper presents a review of current use of information technology in watershed management decision making and a discussion of issues created when developing Internet based, integrated watershed management decision support systems. A prototype spatial decision support system (SDSS) for rangeland watershed management was developed using web services, which are components that communicate using text based messages, thus eliminating proprietary protocols. This new framework provides an extensible, accessible, and interoperable approach for SDSS.
(KEY TERMS: watershed management; geographic information systems; information technology; Internet.)

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INTRODUCTION

Watershed management decision making is inherently complex. It requires cooperation with federal, state, and local stakeholders while incorporating biophysical and socioeconomic processes. Traditionally, transfer of information was unidirectional, typically from state or federal government agencies to landowners. In today's society, bidirectional communication is imperative, expanding the role of land management agencies in the decision making process. However, federal and state budgets are increasingly constrained, and new techniques for information transfer need to be employed. Watershed management decisions are further complicated by both the complexity of the issues and those processes creating the problems. The difficulties in spatially representing and quantifying biophysical and socioeconomic processes require that management decisions be based on imperfect information.

As with other disciplines, watershed management in the 21st Century is increasingly reliant on information technology (Guertin *et al.*, 2000). Recent advances in data acquisition through remote sensing, data utilization through geographic information systems (GIS), data sharing and communication through the Internet, and the use of models have provided watershed managers with access to more information for making management decisions. Not only is the quantity of data increasing, but the quality of data is also rapidly improving. New technologies such as interferometric synthetic aperture radar are providing data with greater spatial resolution, which

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increases the capability to analyze and predict water resource phenomena (Wilson *et al.*, 2000). However, the usefulness of this information is often limited because the information is not offered in suitable forms for many decision makers (NRC, 1999).

Watershed decision making lies between two conceptual extremes: top-down or bottom-up approaches. The top-down approach for decision making entails that planners, typically from outside agencies, prepare a plan and present it to stakeholders. The bottom-up approach involves local stakeholder input from the inception of planning. In a recent national survey, the vast majority (83 percent) of participants said they should have more influence on environmental management decisions and trusted the level of government closer to them (i.e., local more than federal) (Steel and Weber, 2001). Involving citizens in the planning process "insures that good plans remain intact over time, reduces the likelihood of contentious battles before councils and planning commissions, speeds the development process and reduces the cost of good projects, increases the quality of planning, and enhances the general sense of community and trust in government" (Moore and Davis, 1997, p. 3).

Effective watershed decision making requires the integration of knowledge, data, simulation models, and expert judgment to solve practical problems and provide a scientific basis for decision making at the watershed scale (NRC, 1999). A user friendly decision support system (DSS) is needed to help various stakeholder groups develop, understand, and evaluate alternative watershed management strategies. The DSS should integrate a set of components consisting of database management systems (DBMS), GIS, simulation models, decision models, and easy to understand user interfaces that could be available to different stakeholder groups.

The difficulty in developing the DSS is not a lack of available simulation models, but rather making these models available to decision makers. This was a key observation made by the National Research Council's Committee on Watershed Management (NRC, 1999). Over the past 40 years the federal government has spent millions of dollars on model development. While these simulation models are used extensively in research settings, they are infrequently incorporated into the decision making process. Among reasons for this exclusion are: that data requirements are usually only attained in a research setting, that models are complex and underlying assumptions are poorly understood by resource managers, that deriving model input parameters is extremely time consuming and difficult, and that the costs of maintaining and managing the necessary hardware and software systems are high. As hydrologic models continue to be integrated with other technologies, users will be required to have expertise in DBMS, GIS, computer operating systems, remote sensing, and Internet searching for data gathering, as well as watershed domain knowledge. Few seasoned professionals have all these skills, and the typical watershed stakeholder even less so.

Because successful bottom-up decision making hinges on educating stakeholders, new methods should be used for disseminating applications that provide information to stakeholders. Information technology in the form of hydrologic simulation models, GIS, and DSS can represent an understanding of the environment, but it is often unavailable to stakeholders. The Internet provides a great opportunity for sharing information and applications with decision makers. However, limitations in availability, architectures, bandwidth, and security present challenges for using this medium. Advances in communication of information through Internet GIS, simulation models, and integration of these technologies in SDSS provide opportunities for improving the transfer of information and knowledge from watershed scientists and managers to decision makers.

The objective of this paper is to review and discuss the use of information technology in support of watershed management decision making and integrating these technologies in an Internet framework. Hydrologic simulation models, GIS, and DSS are evolving to web-based applications in watershed management. A case study is presented to describe a prototype Internet-based SDSS and to illustrate problems that arise in creating these applications.

USE OF INFORMATION TECHNOLOGY IN WATERSHED MANAGEMENT

Information technology is currently integrated into watershed management in various forms. New hydrologic models are developed using geospatial technology to distribute equations describing biophysical processes over a watershed. The integration of hydrologic models with GIS is simplifying data management and improving visualization. The cost of GIS technology, however, could deter some stakeholder groups from using it. As more digital data are made available, GIS applications are created, allowing users to view these data through the Internet or with free software, and stakeholders to incorporate this information into the decision and education process (Peng and Tsou, 2003). These advances and issues related to using technology are discussed in greater detail in the subsequent sections.

Hydrologic Models

Hydrologic simulation models have been used in watershed management since their inception in the latter half of the 19th Century. They provide an important resource for evaluating and assessing hydrologic systems, and managers increasingly rely on this technology to support decision making. The classification, application, and development of available models have been reviewed in great detail by others (for synopses see Singh, 1995; and Maidment, 1993). The majority of models applied today perform simulations using methods derived in the early 20th Century. These methods are implemented with today's technology, which raises questions regarding the applicability of these tools. For example, Green-Ampt's infiltration equation was developed as a point model to estimate infiltration under saturated conditions and is now commonly applied over large landscapes using distributed hydrologic simulation models. Simulating watershed scale processes continues to be an extremely challenging activity, in spite of recent advances in data quantity and quality and in technologies used to manage the spatial attributes of watersheds. The National Research Council (1999, p. 135) recommends that tools be developed to facilitate the transfer of simulation modeling technology to provide modeling results to managers for decision making "even if they are based on imperfect information."

Recently, a number of Internet-based hydrologic applications have been realized. These applications offer several advantages over traditional single computer applications. A typical Internet application offers a centralized simulation model that does not require installation on local computers and provides access to the latest version of the software at all times. Internet applications do not require advanced software or hardware for the end user, since these applications operate through a web browser with most of the processing conducted on the server.

Two examples of web-based hydrologic applications are the work of Dr. Leonard Lane and other scientists at the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center in Tucson, Arizona, and the effort of scientists at the USDA Forest Service (FS) Rocky Mountain Research Station in Moscow, Idaho. The Southwest Watershed Research Center developed an Internet-based Hillslope Erosion and Sediment Yield Model (HEM) (USDA-ARS, 2003). The model predicts runoff volume, sediment yield, interrill and rill detachment, rill deposition, and mean concentration of sediment for hillslope segments. The model estimates output using hillslope segment lengths, slopes, percent canopy, and surface ground cover for each hillslope segment along with runoff volume and a soil erodibility value for the entire hillslope. HEM produces graphs depicting the input hillslope profile and distribution of cover on the hillslope and output for sediment discharge, detachment and deposition, and mean sediment concentration along the hillslope profile.

The Rocky Mountain Research Station developed the Forest Service Water Erosion Prediction Project (FSWEPP) interfaces (Elliot *et al.,* 1999), which provide the capability to evaluate erosion and sediment delivery from forest roads. The application uses the Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995) to estimate erosion rates and sediment delivered using input values developed at the Rocky Mountain Research Station (Elliot *et al.,* 1999). The interface provides links to models capable of simulating sediment yield from a road segment across a buffer and soil erosion from forest roads, rangeland, forestland, and forest skid trails.

Both the HEM and FSWEPP applications perform simulations at the hillslope scale and can incorporate field observations. They do not provide the capability to estimate the cumulative response for several adjacent hillslopes nor address watershed scale responses. Most watershed problems must be addressed at the watershed scale and therefore require the application of a watershed scale model. This increases the complexity required of Internet applications. Users must be provided with the capability to identify and delineate watersheds using site specific data and to summarize watershed characteristics for specific model applications.

Geographic Information Systems

The use of GIS as a management tool has grown since the late 20th Century, and GIS technology, with roots in cartography, continues to evolve. GIS technology provides an infrastructure for managing, analyzing, and visualizing information, thus allowing the integration of spatial relationships in watershed scale applications. Linking this technology with existing applications simplifies data management for watershed scale simulation models. GIS has been successfully linked to various distributed watershed scale simulation models, including CASC2D, SWAT, HEC-RAS, HEC-HMS (Ogden *et al.,* 2001) and KINEROS (Miller *et al.,* 2002c). Geospatial tools and digital datasets have eased previously laborious procedures. Delineating watersheds and stream networks has been simplified and the difficulty of conducting spatial data management and model parameterization reduced.

Of concern to managers is the perception, in many cases justified, that GIS is an elitist technology (Pickles, 1995) and only available to institutions capable of absorbing the expense of developing, managing, and maintaining required software components. If bottom up decision making is to succeed, all stakeholders must have access to this technology in various forms. GIS advocates have noted that robust citizen participation in ongoing policy decisions will be limited because many groups lack access to today's GIS environment (Obermeyer, 1998). The new challenge is to provide individuals with applications using GIS technology that until recently were only available to professionals (Carver and Peckham, 1999).

Free GIS software has recently become available that provides users with the capability of viewing spatial data (Peng and Tsou, 2003). Government agencies are mandated by the Freedom of Information Act (1965) to provide access to data at no or minimal charge, and many agencies are leveraging the Internet to distribute this information (Plew, 1997). Thus, users can download free data and GIS data viewers to explore available information for their areas of interest. Hydrological and meteorological data can be downloaded from web sites maintained by the U.S. Geological Survey (USGS), the National Weather Service, and the Natural Resource Conservation Service (NRCS). These sources provide data for watershed management decision making that include digital elevation models (USGS, 2003), soils (USDA-NRCS, 2003), and land use (USGS, 2003). For stakeholders who do not have GIS software, data and remote sensing images are made available for viewing by Environmental Systems Research Institute, Inc. (ESRI, 2003a), and watershed specific information is provided by the U.S. Environmental Protection Agency (USEPA) Surf Your Watershed site (USEPA, 2003). However, although these applications allow users to view watershed based information, they do not provide the capability to synthesize the data or assist in its interpretation.

A few web sites have been developed to provide access to watershed assessment tools and models, such as USEPA's Better Assessment Science Integration Point and Nonpoint Sources (BASINS) (USEPA, 2002) and U.S. Army Corps of Engineers' Hydrologic Engineering Center (USACE, 2003). These web sites allow users to download data, individual models, and support information, but users are still expected to maintain and support their applications. This continues to place the burden of computer expertise on users. The necessary computer hardware and software capabilities and expert knowledge in multiple domains may exceed the abilities of many watershed managers as well as many stakeholder groups. The advantage of a fully functional Internet DSS is that users are not required to maintain local computer resources, including software licenses, to utilize modeling tools. Furthermore, users do not need extensive knowledge in periphery domains such as DBMS or GIS.

INFORMATION TECHNOLOGY ISSUES IN WATERSHED MANAGEMENT DECISION MAKING

As watershed management applications are developed that integrate hydrologic models, GIS, DSS, and the Internet, new issues are introduced that should be recognized. These problems range from incompatibilities of technologies used for integrating disparate applications to security in Internet environments These issues will be discussed below.

Interoperability

Since watershed management decision making requires a coordinated effort between stakeholders representing different groups and levels of government, integrated DSS should facilitate interaction and communication among agencies' information systems to make the group decision making process more efficient. However, competing application programming platforms (i.e., Java, Visual Basic, FORTRAN, etc.), operating systems (i.e., Window, Unix, Linux, etc.), and DSS (i.e., Oracle 9i, MS SQL Server, MySQL, etc.) make communication difficult or impossible. Standardizing programming languages, operating systems, and DSS for watershed management stakeholders is impractical because different groups have distinct budgets, legacy systems, and requirements for their information technology (IT) infrastructure. Creating a centralized database repository containing watershed management data for decision making is a possibility, but this leads to logistical issues such as what data should be contained in the database, who administers the database, how often the database is updated, and who pays for infrastructure. Component based frameworks have been adopted such as Microsoft's Component Object Model (COM), but they lack the inclusion of all programming languages and all operating systems. A standardized interface that functions independently of both programming language and platform should be used when developing integrated watershed DSS because it allows the different management IT systems to interoperate.

Years have been spent on research and development of simulation models that encapsulate the understanding of environmental processes. These applications represent the current state of knowledge and should be leveraged in the decision making process. However, these models are often developed using technologies that make interaction with today's object oriented, web-based technologies cumbersome at best. Because different programming languages are developed for different purposes, languages that are computationally efficient are often not compatible with languages that have extensive libraries for Internet development, and no single language is ideal for all applications. Therefore, an integrated DSS must be capable of incorporating legacy applications that are built with technologies that do not communicate with Internet capable programming languages.

Accessibility

While deploying watershed management applications via the Internet greatly increases availability to users, in August 2000, an estimated 61.6 million, or 41.5 percent of, all American households lacked access to the Internet (NTIA and ESA, 2000). Moreover, Internet access is unequally distributed across the United States – access in rural areas is lower than in urban areas. Therefore, rural stakeholders must find alternatives such as public libraries to get access to Internet applications. However, the digital divide between the "haves" and the "have nots" is narrowing. More importantly for watershed management, the gap between households with Internet access in rural areas and the nationwide average has narrowed from 4.0 percentage points in 1998 to 2.6 percentage points in 2000 (NTIA and ESA, 2000). In 2000, 38.9 percent of households in rural areas had Internet access, compared to 22.2 percent in December 1998 – this represents a 75 percent increase.

The Internet-GIS architecture determines the complexity and efficiency provided by the application. Currently, there are two types of Internet-GIS applications: client side and server side. Client side strategies require that the client conduct most of the processing. This requires the web browser to load a program (such as an applet or plug-in) when users request to view spatial data for the first time. This "thick client" architecture has the advantage of more functionality for users, and it requires fewer interactions with the server. However, applets are not persistent and must be downloaded at the inception of the application. Plug-ins need to be downloaded and installed like traditional applications (Plew, 1997). This type of architecture is typically best for applications with GIS literate users because users are required to have knowledge of handling and manipulating GIS data.

Server side strategies perform all processing on the server, relying on the spatial server to conduct the analysis and generate output (Peng, 1997). These "thin client" applications require a high performance server due to the computation intensity. They have higher network congestion because each operation performed by users must communicate with the server. While users have access to large and complex datasets, users do not need sophisticated computers since client machines perform minimal processing (Foote and Kirvan, 1997). Because tradeoffs exist among functionality, efficiency, and required knowledge, integrated DSS should support multiple weight clients, providing access to users with different backgrounds, experience, and network connection speeds.

A limitation in creating richer applications is the lack of bandwidth. Bandwidth is the rate at which information can be transferred on a given transmission path. As Internet-based applications become larger and provide more features, the need for high speed Internet access will increase. In August 2000, only 10.7 percent of households with Internet access had high speed connections; in rural areas 7.3 percent of the households with Internet connections had high speed access (NTIA and ESA, 2000). While high speed access is increasing, current applications should target users with traditional "dial-up" services. Thus, challenges exist for increasing application functionality while keeping applications available to the majority of Internet users.

Security

Security is always a concern for Internet users. Reports of security breaches in Internet environments are frequently documented (Palmer and Helen, 2001). If web-based applications are going to be integrated into the decision making process, precautions need to taken to assure application security. Data ownership questions also arise when data used in Internet applications are stored by government agencies in central data warehouses. For example, when data are placed in a government data warehouse by a watershed group composed of private citizens, does it belong to the private citizens or does it become public property? These issues can be argued and must be recognized when using information technology in watershed management.

CASE STUDY: INTERNET-BASED SPATIAL DECISION SUPPORT SYSTEM

A prototype Internet-based SDSS for rangeland watershed management is under development at the University of Arizona in conjunction with the USDA-ARS Southwest Watershed Research Center in Tucson. The goal of the SDSS development project is to provide an integrated watershed scale application that can be used to educate stakeholder groups and assist in the decision making process. The application provides users with access to GIS tools and hydrologic models. The project also contains a research component for examining uncertainty and error propagation in DSS and is developing methods for providing advanced modeling and visualization technology for an array of stakeholders with different computer skills and capabilities.

The starting point for the SDSS is the Automated Geospatial Watershed Assessment (AGWA) (Miller *et al.*, 2002b,c) application, which was developed by the University of Arizona and USDA-ARS Southwest Watershed Research Center in a collaborative effort with the USEPA's National Exposure Research Laboratory. AGWA uses ESRI's ArcView (ESRI, 2000) GIS and performs hydrologic model parameterization and results visualization for the Kinematic Runoff and Erosion Model (KINEROS) (Smith *et al.*, 1995) and the widely used Soil Water Assessment Tool (SWAT) (Arnold *et al.*, 1994) watershed scale hydrologic simulation models. The application derives hydrologic model parameters from readily available digital elevation models, soils, and land cover datasets, and it allows users to spatially visualize changes in hydrologic response through the use of remotely sensed land cover scenes from different time periods. The primary purpose of AGWA is to evaluate the hydrologic response of land cover change (Hernandez *et al.*, 2000; Kepner *et al.*, 2002; Miller *et al.*, 2002a,b). This project converted AGWA's KINEROS component to a web-based application using ESRI's ArcGIS 8.3 (ESRI, 2003b).

The Internet-based SDSS provides core functionality required for rangeland watershed management education and decision making. Users have the capability to dynamically delineate watersheds by clicking on a map to locate a watershed outlet (Figure 1). Using this boundary, users can perform simulations

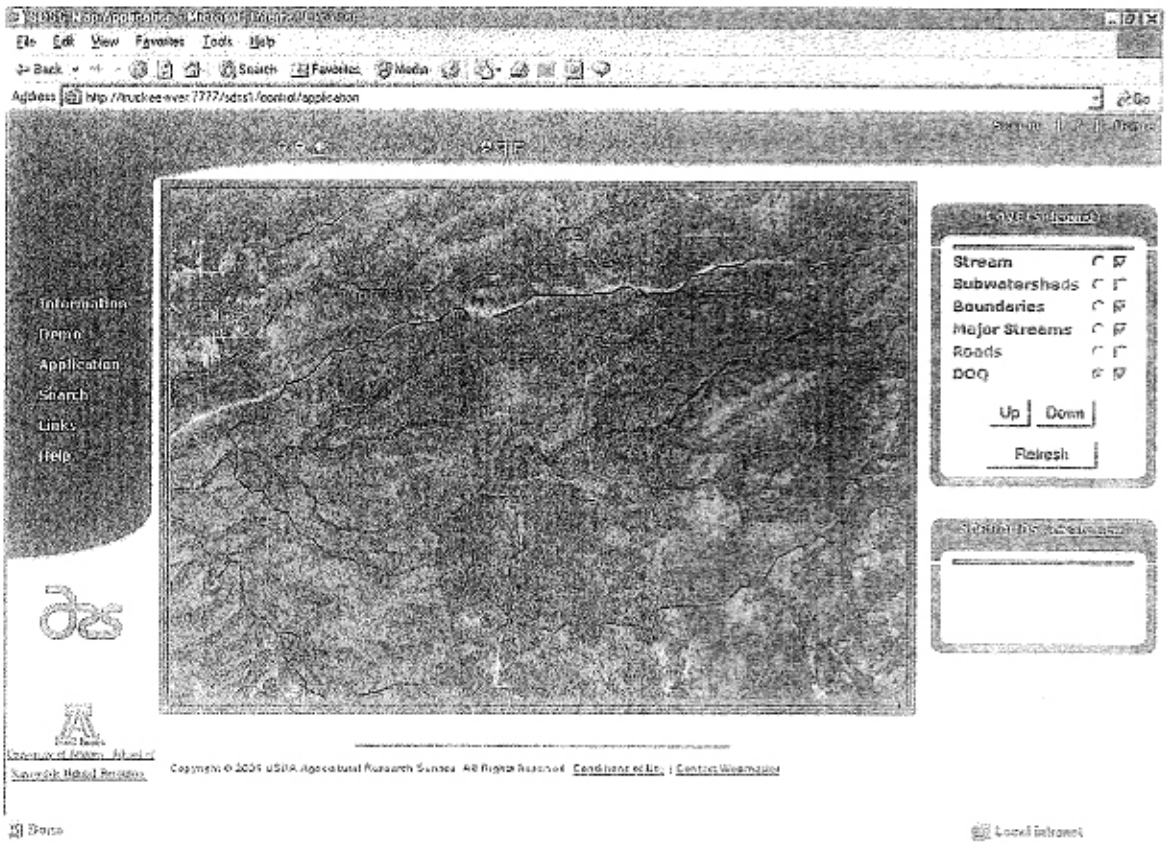

Figure 1. The Internet-Based SDSS for Rangeland Watershed Management Provides Users With the Functionality to Delineate Watersheds by "Clicking" on the Map Locating the Watershed Outlet.

using hydrologic models with parameter sets derived from soils and land cover GIS data layers and can spatially visualize results. The application provides a "thicker" client to create rangeland management systems that consist of pasture boundaries, water points, and sediment detention structures (e.g., stock ponds) by allowing the user to enter these features online. Each management practice may contain user defined attributes that are incorporated into the modeling process. Once users have created their management system, the application simulates the distribution of grazing impacts (Figure 2), hydrologic and economic simulations are performed, and the results are presented in a spatial, graphical, and tabular format. Users can create "what if" scenarios such as locating water sources at different locations within a pasture or change the location of pasture boundaries and compare the runoff, sediment yield, and cost impact of different scenarios.

The Internet-based SDSS can help users evaluate effects of common best management practices (BMPs) related to livestock management. Currently, the application can assess the impacts of fence locations, water source locations, stock ponds, and changing vegetation cover and type. Vegetation management is modeled using the NRCS Ecological Sites Guides. When using the parameters of vegetation information (herbaceous canopy cover, herbaceous basal cover, shrub basal cover, rock cover, etc.) for an ecological site, the application changes hydrologic parameters for KINEROS. Users have the option to delineate an area for improvement such as shrub removal and

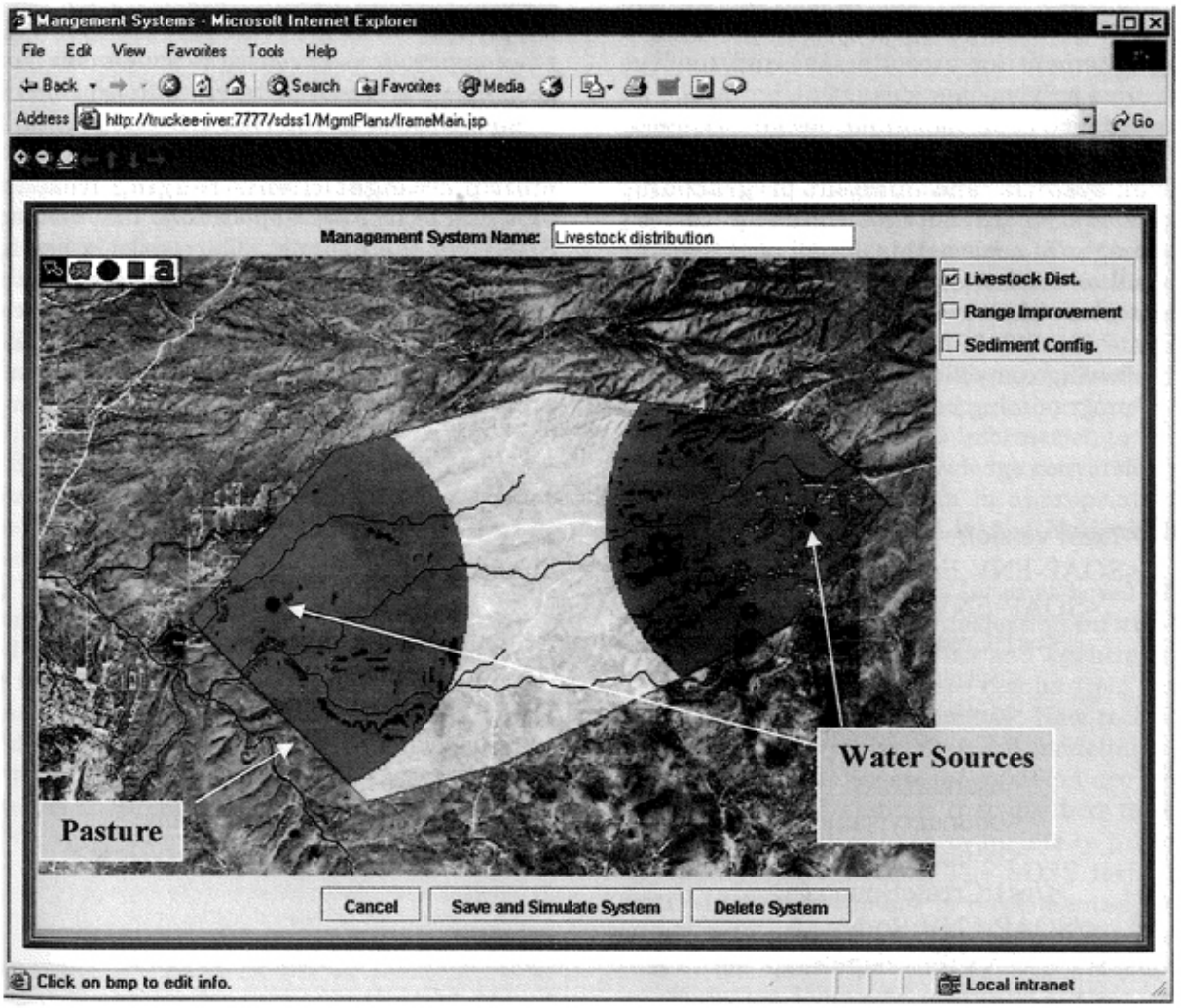

Figure 2. The SDSS for Rangeland Watershed Management Allows Users to Simulate Livestock Distribution Based on Delineated Pasture Boundaries and Water Sources. The most intensively grazed areas are near the water resources in dark gray and the least intensively grazed areas are in the lighter gray. Livestock distribution is predicted using relationships developed by Gdertin *et al.*, 1998.

indicate the future vegetation cover. Users can also use either average vegetation condition or simulate the response for low precipitation or high precipitation years. The fence and water locations are used to model the level of forage utilization across a pasture.

As discussed previously, integrating hydrologic simulation models, GIS, and DSS in an Internet environment creates new challenges related to interoperability, access to the application, architectures for Internet GIS, and security. While increasing access to the Internet and bandwidth are beyond the scope of this project, the prototype SDSS is designed to provide a solution for problems related to linking these technologies. The design is interoperable, which allows application components to communicate independent of programming language, operating system, or hardware configuration. In addition, the application supports multiple weight clients, allowing functionality to change as user requirements change, and it contains a user authentication system, providing a secure environment for users to save and retrieve their data from previous sessions.

Interoperability is an important design consideration, as various management groups have different information systems, and different programming environments have advantages that applications should leverage. To achieve this design objective, the SDSS is built on a relatively new web services component architecture that uses text-based messages to communicate (Stal, 2002). The text format is standardized, allowing components to communicate independent of programming language, operating system, and hardware configuration (for a more technical description of web services see Stal, 2002). An example of the use of web services in the SDSS can be illustrated by discussing the geoprocessing components in the SDSS. The SDSS is developed with Sun's Java enterprise technology, while the GIS geoprocessing components use Microsoft's COM interfaces and are incompatible with Java. However, Java components needing a delineated watershed send a text message (Figure 3) to the watershed delineation web service, which is a component written in Microsoft's Visual Basic requiring x and y coordinates of the watershed outlet. The watershed delineation web service creates the watershed and returns the result to the Java component in a text-based response. Legacy applications are also incorporated into the SDSS as web services. Hydrologic simulation models written in FORTRAN receive input parameters and return simulation results via text-based messages. This distributed, loosely coupled architecture provides the flexibility for other applications to reuse the simulation models and geoprocessing components, regardless of location.

Since different Internet GIS architectures serve different purposes, the SDSS is designed to support multiple weight clients ranging from thin web browsers to desktop applications that connect to the SDSS via the network. Currently, users have the capability of using a thin web browser client to delineate watersheds, parameterize hydrologic simulations, and spatially view results. With a thicker client, users can delineate, attribute, and perform simulations for different BMPs contained in management

```
<?xml version="1.0" encoding="UTF-8" ?>
<SOAP-ENV:Envelope xmlns:SOAP-ENV="http://schemas.xmlsoap.org/soap .... >
   <SOAP-ENV:Body>
      <ns1:CreateBoundary xmlns:ns1="http://tempuri.org/message/" ... >
         <outnumber xsi:type="xsd:string">1311</outnumber>
         <outletX xsi:type="xsd:double">581716.091</outletX>
         <outletY xsi:type="xsd:double">3511404.965</outletY>
         <username xsi:type="xsd:string">SDSSUSER2</username>
         <boundaryName xsi:type="xsd:string">Watershed 1</boundaryName>
         <boundaryDesc xsi:type="xsd:string">Watershed 1 Desc</boundaryDesc>
      </ns1:CreateBoundary>
   </SOAP-ENV:Body>
</SOAP-ENV:Envelope>
```

Figure 3. The SDSS for Rangeland Watershed Management Uses Geoprocessing Web Services, Which are Components That Communicate Through Text Messages. This text message is sent the watershed delineation component and includes a unique number, outlet location, name, and description. The web services perform the watershed delineation and return the boundary to the client.

system scenarios. This flexible architecture is developed using Sun's Enterprise JavaBeans component framework, which encapsulates the application logic on the server. Centralizing the application logic simplifies maintenance and distribution of the application. Future SDSS clients will support additional functionality such as the inclusion of data stored on client machines in the modeling process.

Users will have different objectives for using the SDSS. Some will use the SDSS for management decision making, while others may only use a subset of the application's functionality, such as delineating watersheds. As a result, a security framework is implemented to allow users developing management systems to access their data without hindering the experience for users exploring the capabilities of the SDSS who do not require user specific data to be stored and retrieved. To accomplish this goal, the SDSS uses a form based authentication approach requiring that users sign in to save simulation data for the current session and retrieve management scenarios from a previous session. Users not signed in are provided with the same functionality for a session. Form based authentication is commonly used in electronic commerce sites such as Amazon.com, where users can browse and retrieve information on books but are required to sign in for purchases.

Providing access to applications such as the SDSS opens doors for future research to evaluate the role of technology in bottom-up decision making with watershed management. Through this project, additional research questions will be addressed. Impact of error and spatial resolution of GIS datasets on output from the SDSS will provide insight into the data requirements for the system. Once this application is made available to the public, the application will also be monitored to determine and evaluate user needs and how the system is used providing insight into the future modification of the SDSS. The SDSS is designed to be independent of simulation models, allowing for new models to be included. However, different models have separate assumptions and are developed for varying purposes. Research will be conducted on developing heuristics for constraining the application of these models in a spatial/temporal context and for specific environmental problems.

CONCLUSIONS

Information technology has drastically changed watershed management in the past few decades. Advances in technologies such as the Internet, GIS, remote sensing, and spatial databases have improved the manner in which people communicate and exchange information as well as collect, process, visualize, and store spatial phenomena. Information technology allows watershed managers to be more efficient. Procedures that took weeks when conducted manually, such as hydrologic model parameterization, can now be conducted in minutes.

While information technology has profoundly impacted watershed management, opportunities for further improvement continue to arise as technology changes. As management decisions move toward a bottom-up approach, information technology can provide communication and education for those involved. The Internet offers an efficient medium for transferring and sharing information among decision makers. The availability of and access to data allow local stakeholders to use current information, perform analyses, and educate themselves on the complexities of the issues. Moreover, empowering local stakeholders results in a bidirectional communication and increases chances for consensus among stakeholders.

The success of bottom-up decision making depends on educating stakeholders about the issues and processes related to the problems. Providing access and training to decision support technology offers the opportunity to integrate the social, economic, and biophysical processes into a framework accessible to local stakeholders. These applications can integrate three domains that provide access to information: (1) simulation models that describe the physical processes; (2) GIS that captures the spatial nature of the information; and (3) the Internet. When combined with other technologies, decision support systems offer the potential to convert data to information to knowledge. This data information knowledge conversion provides decision makers with data in appropriate formats, which is a need identified by the National Research Council (1999).

Applications such as the Internet-based SDSS presented in this paper are transferring information and technology from universities and agencies to stakeholders who can incorporate results from simulation models into the decision process. New techniques for integrating GIS, environmental modeling software, and database management systems are producing component based systems that use text to communicate and thus eliminate proprietary protocols for application integration. The SDSS for rangeland watershed management is implemented using web services to provide an open component framework that future applications can leverage independently of programming language, operating system, and hardware configuration. The application supports multiple clients, providing varying users with different application functionality based on their background, experience, and network connection speeds. Using information technology to create and deploy

watershed based educational tools provides stakeholders with additional resources to incorporate into the bottom-up decision making process.

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