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Web-based Spatial Decision Support Systems (WebSDSS): Evolution, Architecture, Examples and Challenges

Vijayan Sugumaran
Oakland University, sugumara@oakland.edu

Ramanathan Sugumaran
University of Northern Iowa

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WEB-BASED SPATIAL DECISION SUPPORT SYSTEMS (WebSDSS): EVOLUTION, ARCHITECTURE, EXAMPLES AND CHALLENGES

Vijayan Sugumaran
Department of Decision and Information Sciences
School of Business Administration
Oakland University
Rochester, MI 48309
sugumara@oakland.edu

Ramanathan Sugumaran
205 ITTC, Department of Geography
University of Northern Iowa
Cedar Falls, IA 50614-0406

ABSTRACT

Spatial Decision Support Systems (SDSS), which support spatial analysis and decision making, are currently receiving much attention. Research on SDSS originated from two distinct sources, namely, the GIS community and the DSS community. The synergy between these two research groups has lead to the adoption of state of the art technical solutions and the development of sophisticated SDSS that satisfy the needs of geographers and top-level decision makers. Recently, the Web has added a new dimension to SDSS and Web-based SDSS (WebSDSS) are being developed in a number of application domains. This article provides an overview of the emergence of SDSS, its architecture and applications, and discusses some of the enabling technologies and research challenges for future SDSS development and deployment.

Keywords: Decision Support, Spatial Decision Support System (SDSS), Web-based SDSS, Geographic Information Systems (GIS), Internet GIS, GIS Web Services

I. INTRODUCTION

Decision Support Systems (DSS) have been an important area of information systems research [Eom 2003]. While many decision support systems have been used in managerial decision making, a major limitation of these systems has been their inability to exploit spatial and temporal data. Because much useful business data is spatially referenced, ignoring this additional information has limited the decision support analyses. Therefore, there is a growing interest in developing Spatial Decision Support Systems (SDSS) for managerial decision making [Sikder and Gangopadhyay 2002].

Spatial Decision Support Systems are designed to help decision makers solve complex problems such as site selection, urban planning, and routing, that have a strong spatial component. An SDSS incorporates both geographic information systems (GIS) functionalities such as spatial data management, cartographic display, as well as analytical modeling capabilities, a flexible user interface, and complex spatial data structures [Goodchild 2000]. Thus, SDSS provides a framework for integrating: 1) analytical and spatial modeling capabilities; 2) spatial and non-spatial data management; 3) domain knowledge; 4) spatial display capabilities; and 5) reporting capabilities [Armstrong and Densham 1990].

Traditional GIS-based SDSS are complex systems that require sophisticated hardware and infrastructure. They are capital intensive and most organizations cannot afford the resources needed to institutionalize such systems. Moreover, these systems are highly centralized and do not easily support group problem-solving activities. Even in a client-server configuration, an SDSS tends to use a thick client that requires high-end workstations and intricate user-interface. These limitations of traditional GIS greatly hindered the widespread adoption of SDSS technologies [Manson 2000]. However, Web-based SDSS (WebSDSS) are being developed to provide geographic information-centered decision support facilities to a larger audience through the Web [Jung and Sun 2006].

Effective use of SDSS in problem solving requires a tremendous amount of *a priori* knowledge about geo-spatial modeling and analysis. For example, users have to know which models are appropriate for what types of problems and the appropriate data to use. To minimize this cognitive burden, new capabilities are being developed such as intelligent agents that help the user in problem formulation and execution [Bui and Lee 1999; Sengupta and Bennett 2003; Sugumaran and Sugumaran 2003]. Similarly, the cumbersome and monolithic structures of SDSS are being transformed into user-friendly and less resource-intensive systems [Gregg et al. 2002; Gao and Sundaram 2007; Zhang and Goddard 2007]. In order to effectively make this transition, modularized and scalable architectures and a diverse set of technologies are needed. Thus, a good understanding of the different architectures and the appropriate enabling technologies is essential for developing sophisticated SDSS environments.

The objectives of this article are to: 1) review the evolution of spatial DSS; 2) explore the architecture and enabling technologies for WebSDSS design; and 3) identify challenges and future research directions. The main contribution of this article is the broad review of the spatial decision support technology and architecture, as well as its application in various domains.

II. EVOLUTION OF SPATIAL DSS

Although Geographic Information Systems (GIS) have been in existence for the past three decades, only recently have GIS technologies been incorporated into mainstream IT decision support solutions [Keenan 2005; Pick 2005]. While GIS has traditionally been used in areas such as utilities, environmental and urban planning, real estate, government, and natural resources management, there is a growing interest in the use of GIS technology for decision support within the business community because of analytical and visualization capabilities [Grupe 1990; Nasairin and Birks 2003]. Increasingly, organizations are adopting GIS-based solutions in a number of domains including customer-relationship management, vehicle routing, and healthcare management [Mennecke 1997; Tarantilis and Kirandoudis 2002; Pick 2007]. Spatial information supports specific business processes implemented in larger environments. This improves productivity and may help gain competitive advantage [Keenan 2006; Pick 2007]. For example, a company using geo-coded customer addresses can do direct marketing and potentially increase market share [Hess et al. 2004].

Research on SDSS originated from two different sources – decision support system and geographic information system [Jarupathirun and Zahedi 2005]. DSS has been an active area of research in Information Systems for many years [Sprague 1980; Holsapple and Whinston 1995; Bui 1997; Eom 2003]. However, DSS researchers have always acknowledged one of its major limitations - its inability to support spatial data [Keenan 1997a]. On the other hand, GIS is efficient in storing and managing spatial data, but has lagged behind in providing adequate tools to facilitate managerial decision making and cooperative problem solving [Ozernoy et al. 1981; Keenan 2003]. The integration of these two technologies has resulted in SDSS, which harnesses the decision analytic power of traditional DSS and the spatial capabilities of GIS. Thus, the two streams of research that lead to the development of spatial decision support systems can be characterized as geographic information based systems and decision support based systems. A schematic representation of the progression in SDSS development is shown in Figure 1.

The evolutionary path of the decision support technology from the information systems community contains four distinct stages (Figure 1-bottom): 1) Traditional Model-Based DSS; 2) Expert/Knowledge-Based DSS; 3) Web-Based DSS; and 4) Service-Based DSS. Similarly, GIS-based evolutionary path of decision support from the geosciences community contains (Figure 1-top): 1) Traditional GIS; 2) Spatial Decision Support System; 3) WebSDSS/Distributed SDSS; 4) Mobile SDSS; and 5) Service-based SDSS. These two parallel development paths and the major categories of systems within each path are briefly described as follows.

DSS-BASED DEVELOPMENT

Traditional decision support systems primarily consist of three major components: 1) data management; 2) model management; and 3) dialog/interface management [Keen 1987; Marakas 2002]. Early work on decision support focused on supporting individual decision makers [Alter 1980; Shim et al. 2002]. As group support software matured, the traditional DSS was augmented with communication capabilities to create group decision support systems, which enabled geographically dispersed group members to work on complex unstructured problems and evaluate different scenarios [Nunamaker 1989; Dickson et al. 1993]. These systems also facilitated brainstorming, idea evaluation and team problem-solving activities. The next phase in this progression of DSS development was influenced by advancements in artificial intelligence. Specifically, expert systems and knowledge-based systems added a new dimension to decision support systems [Holsapple and Whinston 1996; Klein and Methlie 1995]. They enhanced DSS development and usage by incorporating knowledge components specific to an application domain or the organization [Henrion et al. 1991]. These knowledge-based DSS enable users to analyze relatively complex problems and perform what-if analysis with the aid of organizational and domain knowledge [Courtney et al. 1987; Dutta 1996; Özbayrak and Bell 2003]. Developments in the knowledge-based DSS area were drawn upon in creating intelligent SDSS [Leung and Leung 1993; Gar-on and Qiao 1999; Leung 1997]. For example, Li et al. [2005] describe a knowledge-based SDSS that uses CLIPS (and expert system shell) for supporting fuzziness and uncertainty in evaluating risk and insurance pricing in typhoon-affected areas in China.

The Web has revolutionized application development. The ubiquitous nature of the Web and its intuitive user interface has facilitated the deployment of complex applications such as SDSS over the Web [Jeusfeld and Bui 1995; Cohen et al. 2001; Keenan 2006; Ray 2007]. Early work on Web-based decision support was carried out by Bhargava et al. [1995b]. They developed an electronic marketplace of Web-based decision support systems called DecisionNet [Bhargava et al. 1995a, 1997]. Several research and development efforts followed and a myriad of Web-based DSS have been developed over the next decade [Barlishen and Baetz 1996; Bertolotto et al., 2001; Zhu et al. 2001; Wild and Griggs 2004; Silva et al. 2006]. Thus, the next stage in the DSS progression is the Web-based DSS, which delivers appropriate data and models to a manager or a decision maker using a thin-client Web browser [Power and Kaparthi 2002; Liou et al. 2007]. Using Web-based DSS, organizations can provide DSS capability to managers over a proprietary intranet, to customers and suppliers over an extranet, or to any stakeholder over the Internet [Sikder and Gangopadhyay 2004; Delen and Sharda 2007]. Bhargava and Power [2001] provide a status report on how Web technologies are being used to provide decision-support services over the Internet. Similarly, Bhargava et al. [2007] provide an overview of the progress made in Web-based decision support technologies. Power [2002] provides examples of Web-based DSS development software and includes a long list of vendors that market Web-enabled decision-support products. Developments in the Web-based DSS arena have influenced the design and

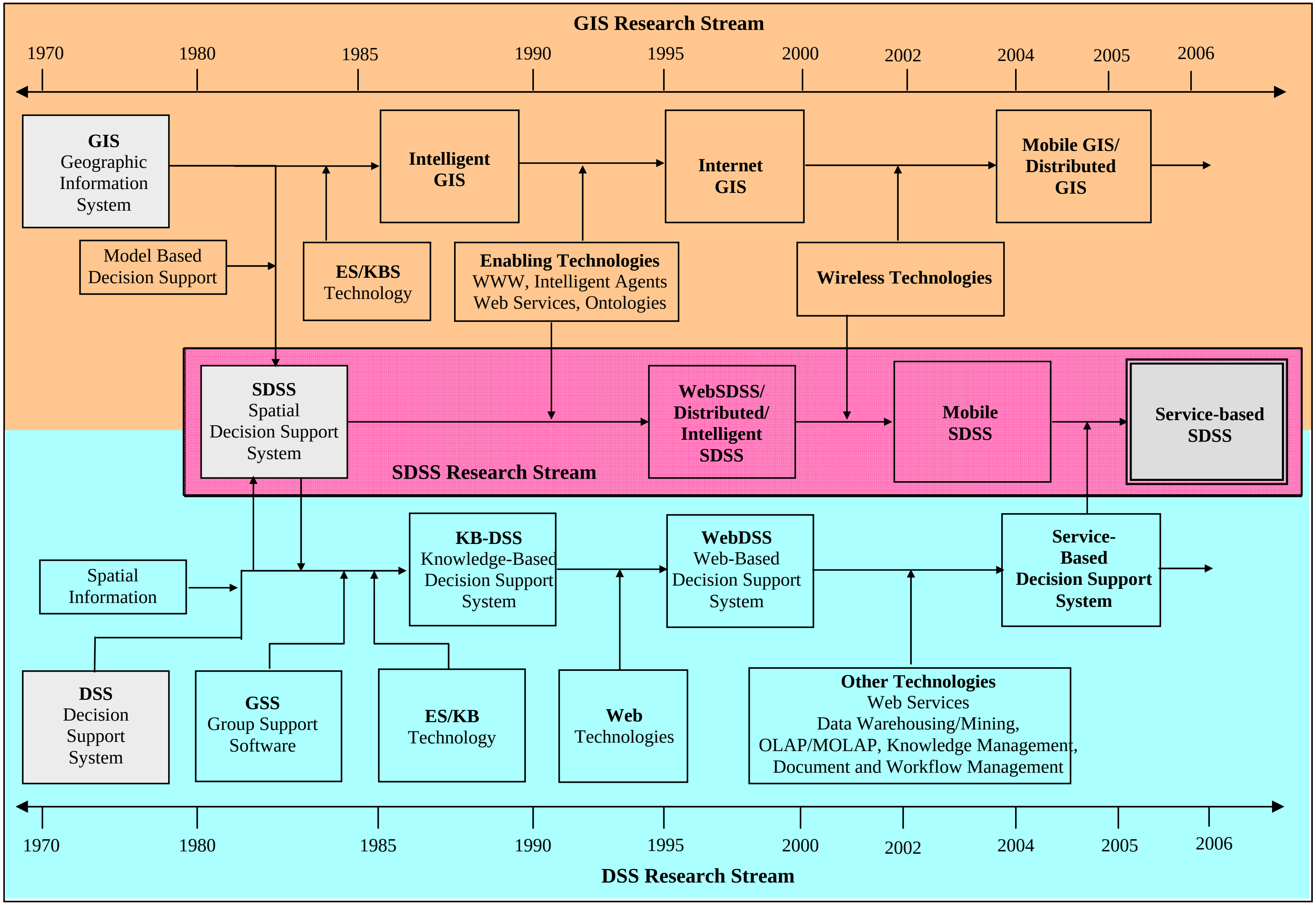

Figure 1. Progression of Spatial Decision Support Systems Development

implementation of SDSS to a large extent. For example, the open-DSS protocol suite proposed by Goul et al. [1995] could be used for deploying SDSS on the Web. Sikder and Gangopadhyay [2002] discuss the design and implementation of a Web-based SDSS that parallels the collaborative decision-making process typically supported by group support software discussed in the DSS literature.

The next phase in the DSS progression is the service-based DSS, which primarily utilizes business and spatial components (objects) as well as Web services. Component-based software development and Web-services-based application development are maturing and researchers are exploring ways to incorporate them into DSS and SDSS architecture and design [Lepreux et al. 2003; Di 2005; Wang and Cheng 2006; Zhao et al. 2007; Wu et al. 2004; Ray 2007]. Component-based DSS development is based on existing code rather than development from scratch. Lepreux et al. [2003] discuss a phased approach for developing a component-based DSS. It integrates the development and use of business components and the DSS components in collaboration with the users of the DSS. This method has been applied to design a DSS for investments in the French railway infrastructure [Lepreux et al. 2003].

Wang and Cheng [2006] discuss a standardized framework for Web-based collaborative decision-support services, which facilitates information exchange and sharing of knowledge and models between various entities within an organization or across organizations. This framework provides metadata services, geodata services and geoprocessing services to help collaborative decision making. Advances in this phase of DSS progression have been incorporated into SDSS development as well. For example, Ray [2007] discusses the development of a spatial Web-services based SDSS at the Delaware Department of Transportation. This system manages the movement of oversized vehicles and integrates several components and services such as analyzing vehicle characteristics, location management, route management, and spatial map server.

Recently, several researchers [Bhargava et al. 2007; Power and Sharda 2007; Carlsson and Turban 2002; Alter 2004] have suggested that the domain of discourse of DSS has proliferated to such an extent that the traditional boundary of DSS has become quite fuzzy and is blending with related technologies such as business intelligence, OLAP, data warehousing, knowledge management, and Web services [Dong et al. 2004]. In fact, Power [2003] argues that there is a great need for reclassifying DSS because they have evolved to become "more specialized and generic at the same time." Power [2004] provides the following classification scheme for DSS: 1) data-driven DSS; 2) model-driven DSS; 3) knowledge-driven DSS; 4) document-driven DSS; and 5) communication-driven DSS. A detailed description of these categories and examples is provided in Power [2005]. The next generation of decision-support systems are primarily service-based and are classified based on the type of the core technology that drives them.

GIS-BASED DEVELOPMENT

Early GIS primarily focused on assembling, storing, manipulating, and displaying geographically referenced information [Dueker 1987]. Geographical information consists of both textual data ("attribute" or "aspatial" data) as well as spatial data (data which includes cartographic coordinates). While the first generation of GIS provided some modeling capability, they were inadequate for supporting any type of business decision making [Ozernoy et al., 1981; Pittman 1990]. During this time, considerable strides were made in designing and developing DSS by the information systems community and the model-based and knowledge-based approaches for building decision-support systems were adopted by the GIS community [Grupe 1990]. This marked the next phase in GIS-based evolution path and spatial decision-support systems were created.

SDSS development entailed integrating analytical/decision models with GIS to produce systems capable of solving spatial problems [Densham 1991; Crossland et al. 1995]. These systems assist users in exploring, structuring, and generating solutions for complex spatial problems such as site selection, evacuation, routing, etc. [Mennecke, 1997]. They support problem-solving and decision-making activities by employing quantitative approaches with the use of geographic information that is stored in the GIS. This provides the capability to display the results of the analysis (including non-spatial aspects) on maps or satellite images or digital terrains [Mennecke et al. 2000]. Such GIS applications for decision support have been used in a number of domains such as marketing, legal and government agencies, strategic planning, environmental management, healthcare, etc. [Murphy, 1995; Jarupathirun and Zahedi 2005; Heurta et al. 2005; Sugumaran and Bakker 2007; Zhang et al. 2007]. In fact, Jarupathirun and Zahedi [2005] provide an excellent summary of the application of GIS-based decision-support systems in different areas. Similarly, Huerta et al. [2005] provide a review of the use of GIS for decision making within the business domain.

In the next phase, in order to deal with complex decision situations, intelligent systems such as Expert Systems (ES) or knowledge-based systems were integrated into GIS. This integration resulted in environments commonly known as “Intelligent GIS.” Several applications have been developed utilizing intelligent GIS, for example, to identify and manage dryland salinization [Kirkby 1996], classify urban land cover [Moller-Jensen 1997], implement state transition model of oak woodlands [Plant and Vayssieres 2000], and identify different plant species [Sugumaran et al. 1999]. Similar to Intelligent GIS, few Intelligent SDSS have also been created [Gar-On, and Qiao 1999; Sengupta and Bennett 2003; Sugumaran et al. 2007].

The next phase in the GIS-based development has been shaped by the tremendous growth of the Web. Internet-based technologies have been assimilated into GIS leading to a variety of Web-enabled GIS applications. Several researchers have demonstrated the use of Internet and GIS for application development to improve decision making [Dragicevic et al. 2000; Rinner and Jankowski 2002; Sugumaran et al. 2003; Zhang et al. 2007] and environmental modeling [Zhang and Wang 2001; Sugumaran et al. 2004; Compas and Sugumaran 2004; Dung and Sugumaran 2005; Shriram et al. 2006]. Although there has been some progress in the use of the Web as a medium for environmental data sharing and data visualization [Dragicevic et al. 2000; Houle et al. 2000; Sugumaran et al. 2003], not many studies focused on developing a Web-based planning tool using SDSS. There is now increased interest in pursuing the development of SDSS on the Web to support better decision making and policy formulation [Zhang et al. 2007].

The client-server model used in designing “Internet-based GIS” applications enables users to gain access to GIS databases through remote procedure calls and open database connectivity. However, the client can access only one source at a time with prespecified connection frameworks. Some researchers [Tsou and Buttenfield 2002] argue that this is very limiting and that the client should be able to access various sources dynamically and also have the capability to act as a server. Since network computing is gaining momentum and the Web provides the infrastructure needed to materialize “peer-to-peer” computing, the next phase in the GIS-based development progression is the mobile GIS environment. This architecture will permit many-to-many communications and facilitate distributed-spatial problem solving. Mobile GIS integrates several technologies such as mobile devices, Global Positioning Systems (GPS), and wireless communications for Internet GIS access. Mobile GIS are constructed by partitioning client and server sides of an application into self-contained units that can interoperate across networks, integrating languages, applications, tools, and operating systems [Tsou and Buttenfield 2002]. Advances in wireless technology have given rise to the development of mobile SDSS, which provide access to spatial data as well as decision-support applications using hand-held devices from remote locations. One such example is the development of integrated mobile geo-spatial information services to support and help optimize field-based management tasks for border security agents [NASA 2005].

Due to the driving forces of the Internet and network communication technology, the paradigm of Geographic Information Systems (GIS) is shifting to Distributed GIS [Tsou, and Buttenfield 2002]. According to Tsou and Peng [2002], a distributed GIS refers to “a distributed platform for accessing and analyzing geospatial data on the Internet.” A few case studies have been developed using distributed GIS [Yeang, et al. 1999; Bandopadhyay et al. 2003].

SDSS functionalities can be modularized and implemented as components or services that one could subscribe to or embed in other applications. These services can be executed at the provider's site to alleviate incompatibility problems. For example, Yeh and Qiao [2004] developed a component-based approach for implementing a knowledge-based planning support system. Thus, a service-based SDSS provides ubiquitous access to "spatial computational services" from anywhere, anytime, using any device. Taking it one step farther, these components can actually act as "Spatial Web Services" and users can compose a set of these services to achieve a particular functionality. Web services technology is supported by several key protocols and standards such as Extensible Markup Language (XML), Web Services Description Language (WSDL), Simple Object Access Protocol (SOAP) and Universal Description, Discovery and Integration (UDDI). Service-based SDSS can be effective in minimizing the cognitive load on end users because of its ability to deal with heterogeneity in hardware as well as software components that may be written using different languages. It provides interoperability by seamlessly taking care of the translations that need to be performed for different components or services to work together.

III. SDSS ARCHITECTURE

Similar to DSS, a generic SDSS consists of the following components: 1) spatial and non-spatial data management; 2) model management (spatial and non-spatial); 3) knowledge management; and 4) dialog management including display and report generators [Murphy 1995]. Typically, SDSS are flexibly integrated systems built on a GIS platform to deal with spatial data and manipulations, along with an analysis module, which could switch from exploration to explanation in an interactive, iterative and participatory way. Just like a DSS, SDSS support "what-if" analysis and also provide a range of tools to help the user in understanding the results [Goodchild 2000]. Much of the early work on SDSS development focused on developing stand-alone applications that incorporated sophisticated models for analyzing spatial data in various application domains [Jarupathirun and Zahedi 2005; Heurta et al. 2005]. Some of the popular decision-analytic models supported by SDSS are: multi-criteria evaluation models, network optimization models, ordered weighted averaging, artificial neural networks, spatial regression, and spatial clustering. With the advent of the Web, existing and new SDSS are designed to take advantage of this ubiquitous environment. The following section discusses the overall architecture and the high level components of the Web-based SDSS (WebSDSS).

WebSDSS ARCHITECTURE

WebSDSS includes a Web-based geographic information system as a problem solver and facilitates geographic data retrieval, display, and analysis. It combines several different components including HTML user interfaces, Internet interface programs, computational models and geographic databases. There are two ways to set up a WebSDSS: 1) server-side processing; and 2) client-side processing. The server-side approach uses a thin client and most of the processing, including spatial data access and manipulation, is performed on the server side. The resulting information and image objects are then sent to the client to be rendered. The client-side processing approach uses a thick client in which GIS functionality is preloaded on the client machine and only the geographic data is accessed from one or more servers. The server-side WebSDSS requires only a browser installed on the client machine to carryout SDSS tasks. However, every user action requires communication between the client and the server. The typical components of a server-side WebSDSS include (Figure 2): GIS Server, Decision Support Server, Database Server, Knowledge Server, and the Web Server. These components are briefly described below.

GIS Server: The GIS server enables access to maps, models, and tools within or outside of an organization. GIS servers usually manages large GIS databases, delivery of geographic information, and provide comprehensive GIS functionality including query and modeling, MapInfo MapXtreme, ESRI ArcIMS, ArcGIS Server & Image Server, and Minnesota MapServer are some of the commercially available GIS servers.

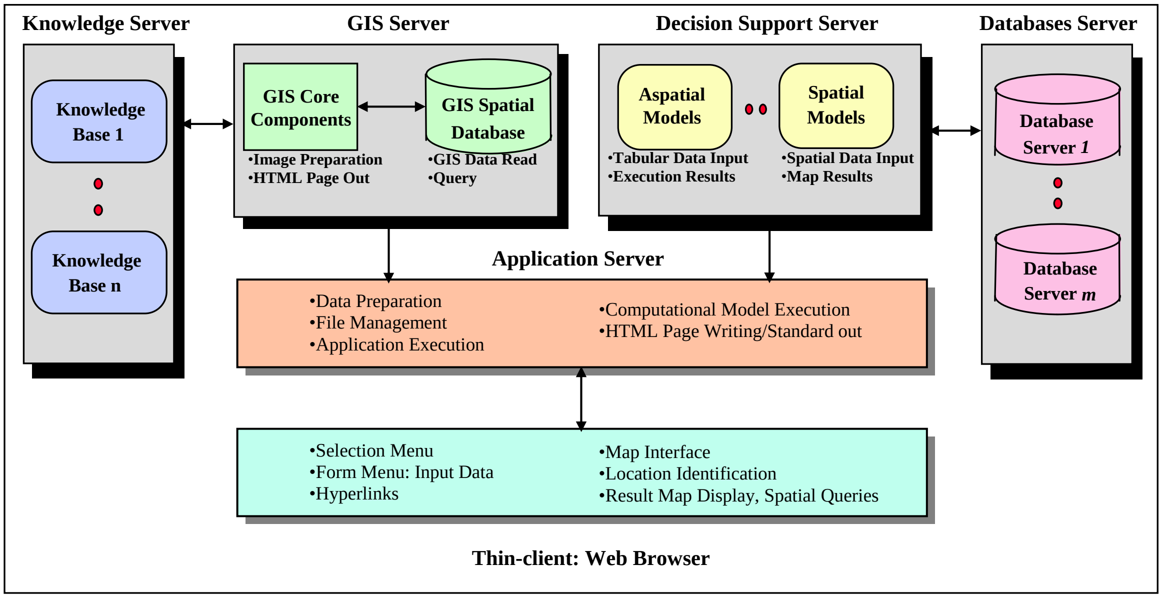

Figure 2. Schematic Representation of WebSDSS Components

Decision Support Server: The Decision Support Server provides access to a large number of models necessary for analyzing and solving unstructured problems. It supports both aspatial and spatial models and also facilitates the development and testing of new models. The decision support server may incorporate different types of models such as univariate and multivariate models.

Database Server: The database server provides access to non-spatial data stored within the organization. Managerial decision making requires easy access to large volumes of different types of data (quantitative, qualitative, spatial, temporal etc.). The database interface component provides access to the necessary data both internal and external to the organization.

Knowledge Server: The knowledge server shown in Figure 2 may contain rules that enable the user to select the appropriate type of model to use for a particular task and perform sensitivity analysis. It may also contain organizational policies, procedures, business rules, and constraints that may be relevant for the problem at hand.

Application Server: The application server acts as the front end that connects the client side to various components on the server side, namely the GIS server, decision support server, knowledge sever and the database server. It facilitates data preparation, file management, execution of appropriate application as well as computational model execution. It is also responsible for generating dynamic html pages with the results returned from the various servers.

The WebSDSS user interface includes menus, graphical maps, control buttons, and form input. These interface utilities execute selections, input data and map displays and queries, using HTML tags, Java Applet, Javascript and other Internet protocols. User inputs are submitted to the Web server through HTTP protocol, and jobs requested by the client are implemented through CGI or other Internet Interface applications.

The components described previously can be implemented using various technologies to create sophisticated, flexible and user friendly WebSDSS environments. These building blocks are discussed in the following section.

BUILDING BLOCKS FOR WebSDSS

Research on spatial decision support primarily focuses on providing easy access to a wide variety of spatial and non-spatial information and specific problem solving tools that help users generate, select, represent and evaluate spatial actions, thereby minimizing their cognitive load. These tools should allow decision makers to specify simple rule sets and generate tentative actions that could be further refined based on the context of the problem as well as the reasoning capability. To that end, recent advances in network and service oriented computing as well as intelligent technologies can enhance the spatial decision making process. We contend that the following advancements have the greatest potential to drastically impact the design and development of Web-based SDSS: 1) server-side technologies; 2) intelligent agents; 3) GIS Web services; 4) ontologies; and 5) Web GIS standards. These building blocks are briefly discussed in the following paragraphs.

Server-Side Technologies

Much of the recent SDSS development has utilized an n-tier architecture because it facilitates maintenance of the application and its data layers [Tsou and Buttenfield 2002; Wild and Griggs 2004]. In addition, the functionality of the application can be upgraded or replaced at any time without affecting the end user's computer [Zhang and Goddard 2007]. The architecture of typical Web-based spatial decision support system uses a three-tiered configuration consisting of: 1) a WWW client; 2) a Web server; and 3) a WWW-based GIS server. Although several techniques exist for Web-based data visualization and decision support, such as Browser Plug-Ins, and ActiveX controls, current applications primarily utilize Java-based viewers. A Java-based environment is desirable because it is object-oriented and supports the development of portable, system independent, and distributed applications served on the Web [Ray 2007].

The server-side environment typically includes a Web server (Apache, IIS etc.) and a map server (ArcIMS ArcMap Server) that provides GIS services. The map server software establishes a common platform for the exchange of Web-enabled GIS data and services. The Web server transfers spatial and non-spatial data between the client side (Web browser) and the map server through sockets (Figure 3). The client side user interface is developed using JavaScript, HTML, and Applets. JavaScript is used to format URLs for communicating with map server (Figure 3) and allows users to interact with the spatial applications. Custom map display and report generator can be developed using java applets.

Intelligent Agents

Intelligent agents can act on behalf of humans and assist them in executing complex tasks. They can be integrated into knowledge-driven WBSDSS environments to shield the complexities of spatial modeling and analyses and help novice users tackle unstructured problems with spatial components [Bui and Lee 1999]. Development of multiagent systems is also increasing [He and Jennings 2003; Wang et al. 2002; Hendler 2001], and these systems contain agents that are capable of acting autonomously, cooperatively, and collaboratively to achieve a collective goal. An agent by itself may not have sufficient information or expertise to solve an entire problem; hence mutual sharing of information and expertise is necessary to allow a group of agents to produce a solution to a problem. Agent collaboration involves joint work by a group of agents on a common task.

Several research efforts have been reported that use agent technology in addressing spatial-decision-making problems [Manson 2000; Sugumaran and Sugumaran 2003; Brown and Xie 2006; Schoenharl et al. 2006]. Sengupta and Bennett [2003] provide an agent-oriented modeling framework to overcome some of the limitations of traditional SDSS. Rodrigues et al. [1997] describe a multi-agent system for modeling geographic elements for environmental analysis in land use management. Ferrand [1996] reports on a system used to search for the least environmental impact area. As demonstrated by these projects, there is great interest in applying agent technology to GIS and SDSS environments.

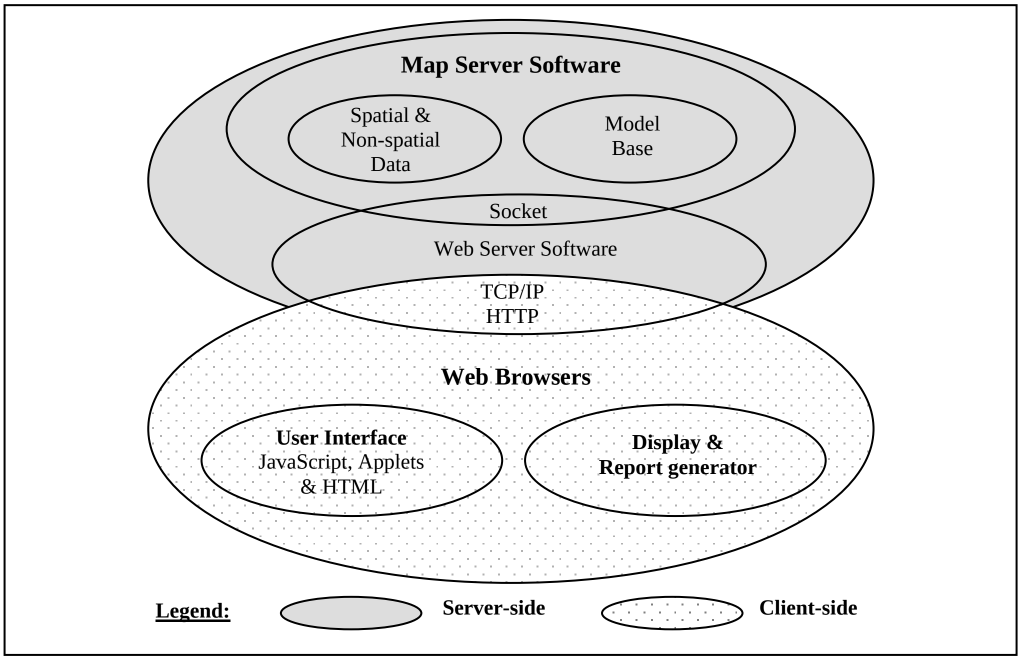

Figure 3. Client-Server Technologies for WebSDSS Development

GIS Web Services

GIS Web Services provide commercially hosted spatial data and GIS functionality via the Internet to Web applications and users [Zhao et al. 2007]. In short, GIS Web Services provide GIS content and functionalities to applications without having to invest in costly GIS software and platforms. The clients do not have to host the GIS data or develop sophisticated tools to incorporate GIS capabilities within their applications [Kralidis 2005]. This facilitates even smaller organizations with limited resources to take advantage of GIS capabilities without having to incur development cost and time. Companies no longer have to address the technical side of GIS to exploit its value.

A GIS service repository is a distributed directory of services with mechanisms for searching and registering. In the service registry, information about a service's location and usage are included [Di 2005]. A particular user could use one or more of the services at run time to accomplish a particular task. This is the primary focus of service oriented architectures [Wang and Cheng 2006; Papazoglou and Georgakopoulos 2003]. The following standards are used to perform the service integration function: 1) SOAP (Simple Object Access Protocol) [Box et al. 2000; SOAP 2007], an XML based RPC used for calling Web Services; 2) WSDL (Web Service Description Language) [Vedamuthu 2007], a language used to describe Web Service Component Interface; and 3) UDDI (Universal Description Discovery, and Integration) [UDDI 2005], a Web Services API for publishing and discovering Web services. GIS Web Services can revolutionize how companies use and interact with geo-spatial information [Gonzales 2003].

Ontologies

Ontology-based GIS facilitate exchange of data and knowledge among GIS users [Arpinar et al. 2006]. GIS interoperability is a major concern, and initial attempts focused on direct translation of geographic data from one format to another. However, this leads to information loss, particularly, the semantic information. Hence, ontology based semantic interoperability is receiving considerable attention [Casey and Austin 2002]. The next generation of SDSS must support interoperability of geographic data based on the semantic content as opposed to data formats and geometric representation. Fonseca et al. [2002, 2006] argue that geo-ontologies are essential for geographic data modeling and point out that the next generation of GIS-based systems should provide a systematic collection and specification of geographic entities, their properties and relations. Geo and eco-ontologies are being created by several researchers [Smith and Mark 2001; Frank 2001; Camara et al. 2000] to deal with the semantic heterogeneity, and enable different information communities to exchange geographic information [Hart and Greenwood 2003].

Web GIS Standards

The OpenGIS Consortium (OGC) is an international body of more than 220 companies, government agencies, and universities to develop publicly available geo-processing standards and specifications. One such standard is Geographic Markup Language (GML) for storing geographic information in eXtensible Markup Language (XML) encoded files. It provides a vendor-neutral format that is optimally suited for distribution over a network. OGC is also working toward establishing a standard for Web services called OWS (OGC Web Services) that will enable seamless integration of a variety of online geo-processing and location services. OWS will allow distributed geo-processing systems to communicate with each other using technologies such as XML and HTTP [OWS 2006]. Thus, systems capable of working with XML and HTTP will be able to both present and use OGC Web Services. In addition, OGC Web Services will allow applications to be assembled from multiple, network-enabled geo-processing and location services based on the rules established to present the functionality they provide and to send service requests via open, standard methods [Kolodziej 2004; OGC 2007].

Two other standards aimed at promoting interoperability between GIS-based applications are Spatial Data Transfer Standard (SDTS) [USGS 1998] and Spatial Archive and Interchange Format (SAIF) [Sondheim et al. 1999]. SDTS provides a practical and effective way to exchange spatial data between different platforms and its use has been mandated for federal agencies. SDTS was ratified by the National Institute of Standards and Technology, and many federal agencies such as U.S. Geological Survey (USGS), U.S. Census Bureau, and Army Corps of Engineers produce and distribute spatial data in SDTS format.

IV. EXAMPLE WebSDSS APPLICATIONS

In the past two decades, there has been a tremendous growth in the development of PC-based or stand-alone SDSS for planning and management of natural resources, environmental and business related applications [CARES 2003; Makropoulos et al. 2003; Shim et al. 2002; Sugumaran 2002]. Recent developments and availability of powerful GIS and visualization tools in conjunction with the rapid growth of Internet technologies have played an important role in the emergence of Web-based decision making and policy formulation [Rinner and Jankowski 2002; Sugumaran et al. 2003; Hilton 2007].

There is increased interest in pursuing the development of SDSS on the Web to support better decision making and policy formulation. Examples include: HYDRA – an SDSS for water quality management in urban rivers [Taylor 2002], fish and wildlife assessment in the Columbia river [Parsley et al. 2000], business applications [Sikder and Gangopadhyay, 2002], agricultural farm analysis [Vernon 1999; Dung and Sugumaran 2005], emergency planning [Carver et al. 2001], environmental decision making [Kingston et al. 2000; Sugumaran et al. 2004], and urban prediction modeling and visualization [Compas and Sugumaran 2004].

In order to classify the existing WebSDSS applications, we have adapted the DSS classification scheme articulated by Power [2004]. Although many PC-based SDSS have been implemented over the last twenty years, only a handful of WebSDSS are reported in the literature, and most of them focus on spatial data, spatial modeling, communication-driven, or knowledge-driven. Hence, we use the following WebDSS classification scheme to characterize these systems: 1) Data-driven WebSDSS; 2) Model-driven WebSDSS; 3) Knowledge-driven WebSDSS; and 4) Communication-driven WebSDSS. A search of the Web-based SDSS literature yielded the list of applications shown in Table 1. These systems were analyzed and categorized according to the above classification scheme. The type of each application was determined based on its focus.

This was performed by the authors jointly through consensus. A summary of these applications is given in Table 1 and is further discussed in the following sections using the classification scheme mentioned above.

Table 1. WebSDSS Summary

No.	Author (s)	Application	Application Type	*Architecture*
1	Sugumaran et al. 2000	Floodplain management http://maproom.missouri.edu/analysis/analysis.asp	Data-Driven	ArcView GIS and Internet Map Server, Java, ASP, JavaScript, and Avenue
2	MapQuest, 2002	Routing application http://www.mapquest.com/	Data-Driven	Client-server architecture -ASP
3	Realtor.com, 2003	Find a Home http://www.realtor.com	Data-Driven	Client-server architecture -ASP
4	Navtrak, 2004.	http://www.navtrak.net/aboutnavtrak.cfm	Data-Driven	Client-server architecture - ESRI's ArcLogistics Route
5	Trackwell, 2004	http://www.trackwell.com/products.html	Data-Driven	Client-server architecture- ArcSDE and ArcIMS
6	Carver et al. 1996	Radioactive waste disposal http://www.ccg.leeds.ac.uk/mce/	Model-Driven	Client-server architecture - Html forms and C for the GIS engine
7	Menegolo & Peckham 1996	Multi-criteria geographic information system (MC-GIS) Not available online	Model-Driven	Client-server architecture - Intergraph's MGE as the server-side and Html forms for the client.
8	Bhargava & Tettelbach, 1997	Recycling decision support system, Not available online	Model-Driven	Html - CGI – DBMS -MMS
9	Jensen et al. 1998	Decision support in crop management (Pl@nteInfo) http://www.planteinfo.dk	Model-Driven	Html forms - CGI in Perl
10	CARES, 1999	Selecting optimal sites for animal production facilities http://maproom.missouri.edu/analysis/analysis.asp	Model-Driven	ASP and JavaScripts, ESRI ArcView GIS, Java, ArcViewIMS
11	Jankowski et al. 2001	DECADE : Allocating primary health care services Not available online	Model-Driven	Java Applets and MCE.
12	Zhu et al. 2001	Vegetation manager (VegMan & JavaAHP) http://www.centralhighlands.com.au/CHRRUP/Tools/VegMan/	Model-Driven	Html and Java Applets on the client and server components developed in Java
13	Rinner & Malczewski.	Site selection for skiing resorts http://ifgi.uni-muenster.de/	Model-Driven	Java applet (CommonGIS with extension)

No.	Author (s)	Application	Application Type	*Architecture*
	2002	~rinner/papers/jgs2002/		
14	Sugumaran et al. 2004	Environmental Sensitivity http://maproom.missouri.edu/analysis/analysis.asp	Model-Driven	ArcView GIS and Internet Map Server, Java, ASP, JavaScript, and Avenue
15	Voß et al. 2002	Locating bike rental stations http://www.commongis.com/start_eng.html	Model-Driven	Integration of Zeno, a server-side component and commonGIS, a client-side Java applet.
16	Rinner, 2003	Online decision analysis education tool	Model-Driven	HTML forms, VB, CGI scripts & Idrisi32 software
17	Campus and Sugumaran, 2003	Urban prediction model using AHP (pair-wise comparison) http://maproom.missouri.edu/analysis/analysis.asp	Model-Driven	ASP and JavaScripts, ESRI ArcView GIS, Avenue, Java, ArcViewIMS
18	CARES, 2003	Habitat suitability http://cares.missouri.edu/projects/completed/irms/interface.asp	Model-Driven	ASP and JavaScripts, ESRI ArcView GIS, Java, ArcViewIMS
19	Taylor, 2002	Spatial Information Systems, Hydra-5 http://www.cmis.csiro.au/sis/hydra.htm	Model-Driven	Not available
20	Parsley et al. 2000	Fish and wildlife assessment wfrc.usgs.gov/research/ geospatial%20studies/STGeospat5.htm	Model-Driven	Not available
21	Zhang et al., 2007	WMPI: a Web-based Watershed management Spatial Decision Support System to Environmental Management	Model-Driven	ESRI ArcGIS Server, JavaScript, ASPX, ,NET VB
22	Rao et al., 2007	A Web-based GIS Decision Support System for managing and planning USDA's Conservation Reserve Program	Model-Driven	Not Available
23	Fan-Chieh et al., 2007	A Web-based decision support system for slopeland hazard warning	Model-Driven	Grass GIS, HTML,
24	Andrienko & Andrienko, 2001	Intelligent user guidance in analysis of geographical information	Knowledge-Driven	Java applet (Descartes)
25	Sugumaran	Development of a Web-based	Knowledge-	ESRI ArcIMS, RouteIMs,

No.	Author (s)	Application	Application Type	*Architecture*
	et al., 2007	intelligent spatial decision support system (WebSDSS)	Driven	JavaScript, ASP, MD Rule Studio
26	Cloudberry, 2004	http://www.cloudberry.com/Products/airtrak/overview.htm	Communication-Driven	Client-server architecture-ESRI's ArcLogistics Route
27	ESRI, 2004	The GeoFence (http://tuxedo.esri.com/geofence/)	Communication-Driven	ASP.NET and Dynamic HTML (JavaScript) using the Microsoft .NET application with ESRI's ArcWeb.

DATA-DRIVEN WebSDSS

Data-driven WebSDSS emphasize access to and manipulation of spatial and non-spatial data. This analysis is mostly achieved through multidimensional queries and retrieval tools to provide the most elementary level of functionality. In general, this type of SDSS allows users to extract and visualize useful information for supporting a particular decision using large spatial databases. Two major Web technologies are used to build this type of SDSS: static Web mapping with HTML forms and server programs [MapQuest 2003; Realtor.com 2003; Kingston et al. 2000], and interactive Web mapping using GIS such as ESRI's ArcView or ArcIMS [Sugumaran et al. 2000].

Finding a home using Realtor.com is an example of static Web mapping with Active Server Pages (ASP). This site provides a simple Web interface for the users to select a choice using multidimensional queries such as city, state name, or ZIP code. The second example by Sugumaran et al. [2000] uses interactive Web mapping for flood plain management. The goal of this project is to develop a Web-based decision support or advisory tool that allows developers, planners and other local government decision makers to utilize a high resolution Digital Elevation Model (DEM) and floodplain related Geographical Information System (GIS) data layers in making floodplain management decisions for a small subdivision in St. Charles County, Missouri. Design and development of this Data-driven WebSDSS used ArcView GIS and Internet Map Server, Java, JavaScript, ASP, HTML and Avenue programming.

Several data-driven SDSSs were developed in location-based business applications to analyze trade areas, evaluate competitors, identify new store locations, find new customers, and reveal untapped markets. For example, Trackwell is a leading provider of personal locator and enterprise tracking and dispatching applications deployed throughout several wireless carrier sites in western Europe [Trackwell 2004]. Similarly Navtrak offers an affordable, easy-to-use real-time AVL and mobile-tracking management tool set for the enterprise and business markets [Navtrack 2004]. Marketmaker provides producers, buyers, sellers, and distributors in Illinois with an online marketing tool to find supply chain partners and improve knowledge of where food consumers are located and how they make food-related purchasing decisions [Marketmaker 2004]. In addition, ESRI's latest Business Analyst Online software combines GIS technology with extensive business, demographic, and consumer household data to deliver Web-based decision support system for location-based services [ESRI 2004].

MODEL-DRIVEN WebSDSS

Model-driven DSS emphasize access to and manipulation of a model, for example, decision analyses, optimization and/or simulation models to provide decision support [Power 2002]. Model-driven WebSDSS use spatial and non-spatial data and criteria provided by decision makers to aid them in analyzing various “what if” situations. Many WebSDSS fall into this category. For example, the following WebSDSS case studies use different models such as Multi-

Criteria Evaluation (MCE) and Analytical Hierarchy Process for environmental planning and management: CARES [1999], Menegolo and Peckham [1996], Carver et al. [1996], Compas and Sugumaran [2003], Jankowski et al. [2001], Jensen et al. [1998], Rinner and Malczewski [2002], and Sugumaran et al. [2003a]. There are several model-driven WBSDSS applications that use Internet mapping software such as ArcViewIMS or ArcIMS [Compas and Sugumaran 2003].

Sugumaran et al. [2003a] developed a WebSDSS to prioritize local watersheds on the basis of environmental sensitivity using a multicriteria evaluation model with weighted linear combination method for the city of Columbia, Missouri (Figure 4). The “Midwest Partnership work group of EPA” has developed a Web-based Watershed Management Decision Support System that uses a hydrologic/water quality model to assesses pollutant loadings from diverse sources in a watershed and help manage watersheds in the Midwest [EPA 2003]. Qiu (2001) developed a Web-based Watershed Hydrologic SDSS for St. Charles County, MO, which uses the Hydrologic Simulation Program - FORTRAN (HSPF) to simulate the predicted runoff at a user-defined outlet point along a stream network.

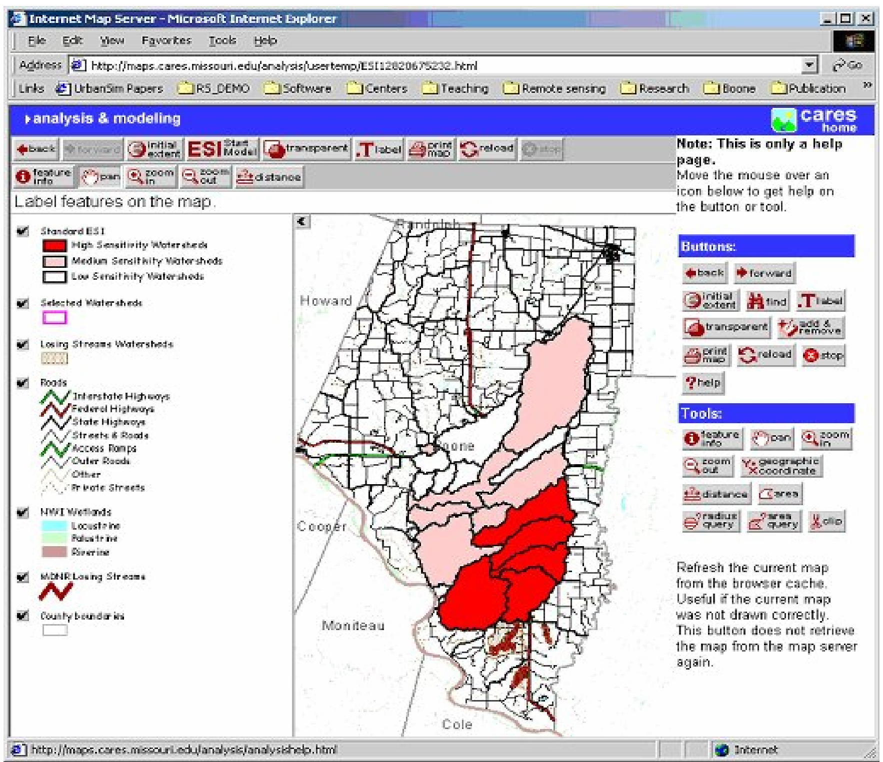

Figure 4. Web-Based Environmental Sensitivity Model

Carver et al. [1996] developed a WebSDSS called "open spatial decision making" (OSDM) which uses GIS and the MCE method. It uses a client-server architecture with HTML forms on the client side and C programming language for the GIS engine and the MCE tool on the server. This site search model performs two tasks: a series of binary map overlays using datasets chosen by the user and a simple multi-criteria evaluation routine based on datasets and weights specified by the user. The results from the model are displayed as a map showing good and bad areas for a disposal site based on the choices made by the user. Bhargava and Tettelbach [1997] present a Web-based system that supports consumers in finding the best options to dispose recyclable materials using a route finding algorithm with time and cost/benefit constraints. In another study, Rinner and Malczewski [2002] present a prototype implementation of ordered weighted averaging (OWA) in an Internet-based interactive mapping environment based on the CommonGIS system.

Wan et al. [1999], Zhu et al. [2001] and Compas and Sugumaran [2003] have developed model-driven WBSDSS using the Analytical Hierarchy Process. Compas and Sugumaran [2003] developed a Web-based urban growth model and visualization tool to assist the St. Charles County's planning and zoning department in urban growth planning and management. This tool implemented a complex multi-criteria evaluation approach and the Analytical Hierarchy Process to support end-users' decision-making processes and generate model weights. Zhang et al. [2007] developed a Web-WMPI as a Web-based watershed management spatial decision support system using the Watershed Management Priority Indices (WMPI) approach using multi-criteria evaluation model.

KNOWLEDGE-DRIVEN WebSDSS

Knowledge-driven DSS can suggest or recommend actions to managers [Power 2002]. These DSS are person-computer systems with specialized problem-solving expertise. The "expertise" consists of knowledge about a particular domain, understanding of problems within that domain, and "skill for solving" some of these problems. Tools used for building knowledge-driven DSS are sometimes called *expert systems* and *intelligent decision aids*. Although several researchers [Casey and Austin 2002; Dhar and Stein 1997; Sengupta and Bennett 2003; Tsou and Buttenfiled 2002] have developed stand-alone knowledge-driven SDSS, only few have explored the possibility of knowledge-driven WebSDSS [Shriram et al. 2006; Andrienko and Andrienko 2001; Gar-On Yeo and Qiao 1999; Sugumaran and Sugumaran 2003; Sugumaran et al. 2004]. Andrienko and Andrienko [2001] developed a knowledge-driven WebSDSS, that provides intelligent guidance for users in the analysis of geographical information. Recently, Sugumaran and Sugumaran [2003] have proposed an architecture for an agent-based SDSS environment on the Web, which incorporates Web services and a variety of intelligent agents to guide the user in executing core business processes.

COMMUNICATION-DRIVEN WebSDSS

Communication-driven DSS is a type of DSS that emphasizes communications, collaboration and shared decision-making support [Power 2002]. The communication-driven approach utilizes Web communication technologies to assist decision makers who might be at different locations, at different times, to collaborate and resolve problems. Recent developments in mobile GIS technologies such as mobile hardware in the form of lightweight devices and ruggedized field PCs, global position systems (GPS) and wireless communications for Internet access have enabled several organizations to add real-time information to their enterprise database and applications, speeding up analysis, display, and decision making by using up-to-date, more accurate spatial data. For example, AirTrak of Nextel uses GPS-enabled handsets for location and messaging with ESRI's ArcLogistics Route. It facilitates back-office mapping, routing, dispatching, and fleet logistics [Cloudberry 2004]. The GeoFence and Tracking showcase application enables users to watch real-time as vehicles travel along their designated routes on the Web [ESRI 2004]. The GeoFence application was developed using ASP.NET and Dynamic HTML (JavaScript) using the Microsoft .NET application framework to communicate with ESRI's ArcWeb for developer services. The application has been published through a Microsoft IIS Web server.

V. DISCUSSION

FUTURE APPLICATIONS AND ARCHITECTURES

There is consensus that using the Web has the potential to deliver GIS and decision-support technologies to the masses. Hence, Web-based DSS and SDSS will continue to be a major focal point for application development and further research. Similarly, Web Services and Semantic Web are also showing signs of great potential and researchers are moving toward developing distributed applications using Web services. We postulate that GIS Web Services will pave the way for developing heterogeneous distributed GIS applications that span organizational boundaries. Advances in communication and networking technologies (Internet, intranet, wireless, and cellular) will facilitate the development and deployment of interorganizational SDSS that support spatial work flows.

Developments in intelligent agent technology, ontology-based information systems, knowledge-based systems, GIS Web services, data warehousing and analytical processing, spatial and non-spatial modeling, and Web technologies will have a profound impact on the next generation of SDSS. We envision a distributed WebSDSS environment that integrates current and future enabling technologies to provide sophisticated spatial modeling and analysis capabilities needed to efficiently solve unstructured problems with spatial characteristics and provide seamless linkages to a variety of spatial and non-spatial resources. A schematic representation of such an SDSS is shown in Figure 5.

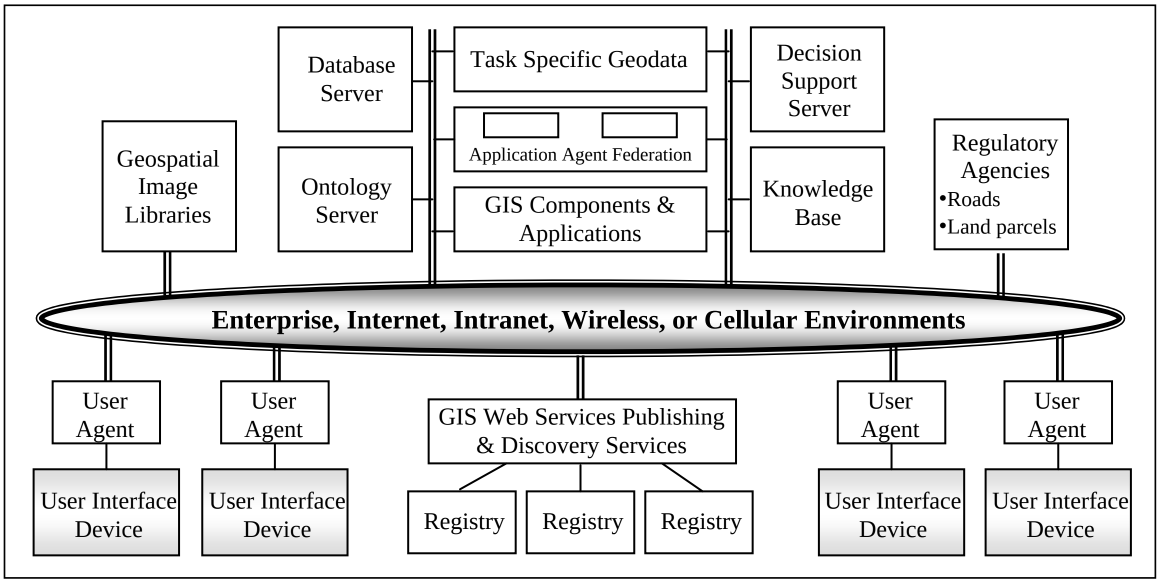

Figure 5. Distributed Web-Based Spatial Decision Support System Architecture

The components shown in the above architecture are connected together through Internet/intranet or wireless technologies and the user can engage in collaborative problem solving and decision making by utilizing one or more components. The open (plug-and-play) architecture facilitates the addition of new components or services. For example, geospatial image libraries, task specific geodata sources, access to regulatory agency databases, and other federated applications or components can be easily added to the architecture. Connectivity and interoperability of the components is an important aspect of this architecture, which is made possible through the evolving standards of service-oriented architecture. End users can utilize one or more agents to access the various spatial and non-spatial data sources and execute appropriate models through the decision-support server. The knowledge base can provide the necessary process knowledge. The user can also make use of the available GIS Web services by searching through the registries. The interoperability problems that may be caused by the heterogeneity of the applications and services can be alleviated through the ontology server.

CHALLENGES IN WebSDSS DEVELOPMENT

Designing and implementing SDSS over the Web presents several issues such as performance, technology integration, security, interoperability, etc. Though some of these issues are common to all IT applications, the following section provides some specific examples related to WebSDSS.

Technical Challenges

Performance: Performance is one of the most important limitations in the development of WebSDSS. It is mainly because most spatial data including raster and vector data are large in volume [Peng and Tsou 2003], and also involve moving large spatial objects over the network between server and client. Further, most of the SDSS models are complex and take substantial amount of time to run on the server. It is unreasonable to expect users to initiate the execution of a model and wait for hours or even days for the model results; Internet users expect results in a matter of seconds. Hence, it is crucial that users are informed of the incremental progress in model execution, which adds to the complexity of WebSDSS design. Besides the spatial data, SDSS models may use large non-spatial datasets (attribute data) that also have to be transported over the Web. Thus, the overall performance of a WebSDSS is impacted by the aforementioned issues in addition to the available bandwidth of the client and server as well as the number of simultaneous clients. If bandwidth problems are overcome in the near future, it is likely that mobile tools, mobile e-services, and wireless Internet protocols will mark the next major set of developments in WebSDSS.

Technology Integration: It is essential that SDSS are implemented using open architectures so that new components can be easily added resulting in “plug-and-play” geo-processing environments. In addition, these systems must be robust with efficient communication mechanisms via the Internet/intranet. Another challenge is integrating the distributed SDSS with legacy systems that may still have valuable GIS datasets and programs.

Interoperability: One of the main limitations of the present WebSDSS is the interoperability and noncompliance with widely accepted Web mapping standards. Creating interoperable commercial geo-processing software will still be a formidable challenge due to vendor and technology differences. Full integration of geospatial data and resources requires developing a common set of syntactic and semantic interoperability standards. GIS Web services will need to tolerate heterogeneous frameworks because no distributed component technology will be optimal for all kinds of tasks. Most of the existing WebSDSS are not based on OpenGIS® Consortium (OGC) standards and do not easily interface with other products.

Security and Privacy: Security and privacy will remain a major consideration in implementing WebSDSS because many geospatial data sets and services are proprietary and private. A WebSDSS application will face additional security problems because of the sharing of spatial objects over the Internet, and is prone to viruses, hackers, and network jams. Moreover, the introduction of mobile spatial technologies into WebSDSS will add an additional layer of security concerns due to the inherent risks associated with wireless technology.

Quality of Service: In a distributed SDSS environment with commercial services, the level of service provided by the individual nodes may vary because of node failures, unreliable communication or disconnected network links. Hence, the architecture must include technical solutions to combat such disruptive events.

Managerial Challenges

Task-System Fit: While several WebSDSS have been implemented and used in various domains, there are no clear guidelines as to which types of WebSDSS are suitable for what types of decision-making tasks. Hence, it is critical that organizations systematically evaluate the task-WebSDSS fit and its effectiveness in decision making before investing in a particular WebSDSS. In order to promote widespread use of WebSDSS within an organization, clear evidence has to be presented to demonstrate their appropriateness as well as usefulness for the task at hand.

Policy Issues: Clear policies need to be developed for service level agreements, and how to handle sudden or gradual fluctuations in the quality of service. Similarly, organizations have to develop concise policies to ensure security and privacy of sensitive spatial and non-spatial data. Contingency plans for disaster recovery and security breaches must also be developed.

Organizational Commitment: A strong resource commitment from upper management is needed to promote the widespread use of WebSDSS throughout the organization. Use of WebSDSS may also require redesigning of some of the business processes. Hence, adequate training is needed.

VI. CONCLUSION AND FUTURE DIRECTIONS

GIS and SDSS have traditionally been difficult to use because of the complex nature of spatial data representation, presentation, and computation. However, with the advances in Web technologies, intelligent agents, ontologies and Web Services, complex SDSS systems can be made user friendly by providing intelligent interfaces. This article has discussed the progression of SDSS development originating from both the GIS and DSS communities and presented an architecture for a generic WebSDSS environment. While some of the current WebSDSS have used some enabling technologies, we predict that future WebSDSS will incorporate Web services and a variety of intelligent agents and ontologies to guide the user in executing core business processes. We have presented a framework for distributed WebSDSS and discussed some of the challenges.

Further research is needed to address the challenges highlighted in the previous section. In particular, future inquiries should concentrate on: 1) novel ways of using intelligent agents and other knowledge-based techniques to minimize cognitive burden on the user in spatial modeling and analysis; 2) GIS Web Services and distributed component technologies for designing distributed WebSDSS; 3) wireless technologies, devices and communication protocols to facilitate true distributed WebSDSS environments; 4) open architectures and GIS interoperability standards; and e) developing effective inter-/intra-organizational WebSDSS.

Keen [1987] had proposed a DSS research agenda for the nineties and recently, Shim et al. [2002] have updated Keen's agenda and articulated a new DSS research agenda for the next decade. This new DSS research agenda is also pertinent to WebSDSS research and can be adapted to guide future developments in WebSDSS. Along similar lines, we propose the following tenets to shape future research in Web-based spatial decision-support technologies: 1) identifying potential uses for WebSDSS in solving business problems with spatial aspects as well as incomplete and uncertain data; 2) building intelligent WebSDSS using enabling technologies; 3) providing a distributed WebSDSS environment for cooperative spatial problem solving and linking GIS services; 4) facilitating interoperability of spatial data and systems; and 5) demonstrating and improving the effectiveness of WebSDSS in decision making through training and knowledge transfer. Considerable strides have been made in the development of Web-based SDSS, and we envision future WebSDSS playing a major role in analyzing and solving complex business problems and strategic decision making.

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EDITOR'S NOTE: The following reference list contains the address of World Wide Web pages. Readers, who have the ability to access the Web directly from their computer or are reading the paper on the Web, can gain direct access to these references. Readers are warned, however, that

1. These links existed as of the date of publication but are not guaranteed to be working thereafter.

2. The contents of Web pages may change over time. Where version information is provided in the References, different versions may not contain the information or the conclusions referenced.

3. The authors of the Web pages, not CAIS, are responsible for the accuracy of their content.

4. The author of this article, not CAIS, is responsible for the accuracy of the URL and version information.

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ABOUT THE AUTHORS

Vijayan Sugumaran is Professor of Management Information Systems in the department of Decision and Information Sciences at Oakland University, Rochester, Michigan, USA. His research interests are in the areas of Spatial Decision Support Systems, Ontologies and Semantic Web, Intelligent Agent and Multi-Agent Systems and Component Based Software Development. His most recent publications have appeared in Information systems Research, ACM Transactions on Database Systems, IEEE Transactions on Engineering Management, Communications of the ACM and Healthcare Management Science. Dr. Sugumaran is the editor-in-chief of the International Journal of Intelligent Information Technologies and also serves on the editorial board of seven other journals. He is the Chair of Intelligent Information Systems track for the Information Resources Management Association International Conference (IRMA 2001 – 2002 and 2005 - 2007) and the Intelligent Agent and Multi-Agent Systems in Business mini-track for Americas Conference on Information Systems (AMCIS 1999 - 2007). He served as Chair of the E-Commerce track for Decision Science Institute's Annual Conference, 2004. He is also the Information Technology Coordinator for the Decision Sciences Institute. He regularly serves as a program committee member for numerous national and international conferences.

Ramanathan Sugumaran is an Associate Professor of Geography at the University of Northern Iowa. He has over 14 years of experience in remote sensing, GIS, GPS spatial decision support systems (SDSS) applications for natural resources and environmental planning and management, He is and has been working with federal, state, local and tribal government agencies (FSLT) for the past 10 years and developed several SDSS tool and techniques. The methodologies developed for FSLT agencies by Dr. Sugumaran was widely published in Geographical Systems, IEEE Geoscience and Remote Sensing, Photogrammetry & Remote Sensing, Geocarto, Canadian Journal of Remote sensing journals. Dr. Sugumaran has served as PI or Co-PI on over $6 million worth of research grants funded by NASA, Raytheon, NOAA, USDA, MDNR, DOT, US Fish and Wildlife Service. He is currently serving as Director for the GeoTREE Center at the University of Northern Iowa which is funded by NASA.

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