Web-based GIS and spatial decision support system for watershed management

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ABSTRACT

Geographic Information Systems (GIS) have been widely used for spatial data manipulation for hydrologic model operations and as a supporting tool to develop spatial decision support systems (SDSS). Information technologies, including GIS and the Internet, have provided opportunities to overcome many of the limitations of computer-based models in terms of data preparation and visualisation, and provide the possibility to create integrated SDSS. This paper examines the relationship between changes in GIS technology and watershed management SDSS. It also describes a conceptual web-based SDSS framework in terms of system components and data flow. A prototype watershed management web-based SDSS that utilises the conceptual framework is examined (URL: *http://pasture.ecn.purdue.edu/ ~ watergen/owls*). The SDSS uses web-GIS for watershed delineation, map interfaces and data preparation routines, a hydrologic model for hydrologic/water quality impact analysis and web communication programs for Internet-based system operation. The web-based SDSS can be helpful for watershed management decision-makers and interested stakeholders. The watershed management SDSS also provides insight into the role of GIS and information technologies in creating readily accessible and useable SDSS capabilities.

Key words | decision support system, hydrologic model, Internet GIS, watershed management

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INTRODUCTION

Recent advances in information technology, including hardware, software and networks, provide potential solutions to the problems of data accessibility. Current advances in computational speed, storage, World Wide Web (WWW) and software provide great opportunities to develop Decision Support Systems (DSS) with the advantage of information dissemination for decision-makers and program integration (Shim *et al.* 2002).

Geographic Information Systems (GIS) have had a profound effect on hydrologic modeling and model development (Xu *et al.* 2001). GIS tools are now commonly used in DSS for hydrologic model operation and data preparation, and GIS have become an essential tool to develop watershed management Spatial Decision Support Systems (SDSS) (Tayler *et al.* 1999).

The Internet is another factor to be considered when developing DSS nowadays. Advances in communication networks have overcome many difficulties in the use of timely and spatially distributed resources in the decision-making processes. Therefore, one of the greatest benefits of using information technologies in decision-making is the potential to overcome limited resources in terms of time, data and communication (Pandey *et al.* 2001).

This paper explores relationships between information technology and hydrologic/water quality analysis DSS. It also describes a conceptual web-based SDSS framework in terms of system components. Further, this paper presents a prototype of a web-based watershed management SDSS that has been operating based on this framework using web-GIS for watershed delineation, map interfaces and data preparation, a hydrologic model for hydrologic/water quality impact analysis and web interface programs for operation through the Internet.

HISTORICAL BACKGROUND

Watershed management queries typically include "how" and "what-if" questions. For example, if a watershed has experienced land use changes, or will be altered in the future, then the question may be how the land use alterations affect hydrologic conditions and water quality. To answer such a question, hydrologic models are commonly used to evaluate the impact of changes. The problems in operating hydrologic models are typically not only the information technology and computational requirements, but also the effort required for data acquisition and preparation to run the model to obtain appropriate results that can be used in identifying a solution for the problem, including model validation. Thus, advances in information technology, including databases, GIS, graphical user interfaces and the Internet, have significant roles in hydrologic/water quality analysis SDSS. These information technology advances have already profoundly affected watershed management SDSS development (Tayler *et al.* 1999). Examples include automatic geospatial hydrologic model input/output manipulation using GIS, massive input/output manipulation including weather data arrangement using databases, menu-driven and graphical user interfaces for the user's convenience and data transfer through the Internet (Pandey *et al.* 2001).

Since the introduction of the Stanford Watershed Model (Crawford & Linsley 1966), information technologies including hardware and software have been utilized for hydrologic modeling and water quality impact evaluation. During the 1970s and 1980s, computers were largely used as calculation tools to meet the massive computational demands of hydrologic models rather than as information systems. Numerous efforts have been undertaken to develop hydrologic models, and therefore it is impossible to introduce every significant model in this paper. Examples of such models include the Tank model (Sugawara *et al.* 1976), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley *et al.* 1980), Système Hydrologique Européen (SHE) (Abbott *et al.* 1986) and TOPMODEL (Beven *et al.* 1984).

Development of DSS for watershed and water resource management in the 1990s almost always considered GIS an essential component in creating a SDSS for spatial data manipulation due to GIS advantages for spatial data manipulation. GIS is beneficial for spatial data preparation and results visualization (Wilson *et al.* 2000), and this is why GIS has become such a useful tool for hydrologic model operation. Research on the integration between GIS and hydrologic models has been widely implemented for decision support purposes and data preparation in dealing with hydrologic problems (Nageshwar *et al.* 1992). The value of GIS in this role has been demonstrated for various hydrologic models including ANSWERS (Rewerts 1992), AGricultural Non-Point Source Pollution Model (AGNPS) (Mitchell *et al.* 1993), Soil and Water Assessment Tool (SWAT) (Srinivasan *et al.* 1998), TOPMODEL (Beven *et al.* 1995), Long-Term Hydrologic Impact Assessment (L-THIA) (Pandey *et al.* 2000) and Cell-based Long-Term Hydrologic Model (CELTHYM) (Choi *et al.* 2002). These models have typically been integrated with GIS for spatial data access and output visualization.

GIS integrated with hydrologic models can supply watershed information including watershed slope, aspect, stream lines, soil attributes, land use and numerous other data in grid and vector formats. Grid format data are relatively easy to manipulate compared to vector-based data because grids store "implicit topology", whereas vector data requires "explicit topology". The operators are more efficient for grid data and the grid format is often well matched with the spatially distributed simulation model conceptualization and data needs (Wilson *et al.* 2000). Thus, grid-based GIS tools have been widely integrated with distributed hydrologic models (Rewerts 1992; Arnold *et al.* 1995; Warwick & Haness 1994; Schultz 1996). Several distributed models have been integrated with GIS data preparation and visualization capabilities (Olivera & Maidment 1999; Xu *et al.* 2001).

In integrating hydrologic models and GIS, data exchange has proven to be difficult and inefficient due to the different data formats used by GIS. Djokic *et al.* (1996) presented a generic format and method for data exchange called GOODES that stands for generic, object oriented, open data exchange system. This protocol for geographic data exchange can significantly streamline the integration process between information users and information providers. As a packaged system including GIS, data and model, Better Assessment Science Integrating point and Nonpoint Sources (BASINS) (US EPA 2002) has been developed to meet the needs of pollution control agencies. It integrates a GIS, national watershed and meteorological data, and state-of-the-art environmental assessment and modeling tools into one convenient package.

The trend toward web-based watershed management system development that is integrated with GIS to manipulate spatial information for hydrologic/water quality analysis can be viewed as a natural trend due to the potential benefits of the Internet (Pandey *et al.* 2001). The spread of broadband Internet has stimulated operation of hydrologic models via the Internet communication environment, and several hydrologic models including WWW-enabled L-THIA (Pandey *et al.* 2000) and WWW National Agricultural Pesticide Risk Analysis (NAPRA) (Lim & Engel 1999) have been developed and operated in Internet environments.

The final conceptualization of web-based SDSS for watershed management is not possible to imagine, because significant information technology advances, including object-oriented GIS (OOGIS) and Geography Markup Language (GML), are still ongoing. Since the proliferation of object-oriented concepts, the development of OOGIS or object-oriented spatial databases (OOSD) has been a major research issue in geographic information sciences and it has been argued that OOGIS is more advantageous than the conventional raster- or vector-based GIS in modeling geographical information (Leung *et al.* 1999). Although it is currently difficult to find an object-oriented SDSS integrating a hydrologic model, the object-oriented data model (OODM) and object-oriented concepts provide the potential to develop an Internet-based SDSS for disseminating geospatial information in a visual and interactive manner to users based on Common Object Request Broker Architecture (CORBA™) (Kaehkoenen *et al.* 1999).

The OpenGIS Consortium (OGC) published the GML 2.0 on 20 February 2001 (Lake 2001) that builds on the evolving world of EXtensible Markup Language (XML). GML is an XML encoding for the transport and storage of geographic information, including both the geometry and properties of geographic features in a web page. Currently GML version 3.0 is being developed. Although the authors have not found a hydrologic model that adapts new cutting-edge technology in a modeling scheme, these advances can potentially provide a better environment for developing web-based SDSS for watershed management.

A FRAMEWORK OF WEB-BASED SDSS FOR WATERSHED MANAGEMENT

Web-based SDSS components for model-based approach

A web-based DSS is a computerized system that delivers decision support information or decision support tools to a manager or business analyst using a "thin-client" Web browser like Internet Explorer or Netscape Navigator. The computer server that hosts the DSS application is linked to the user's computer by a network with the Transmissions Control Protocol/ Internet Protocol (TCP/IP) protocol. In many companies, a web-based DSS is synonymous with an enterprise-wide DSS that supports large groups of managers in a networked client–server environment with a specialized data warehouse as part of the DSS architecture (Power 1999). The web-based DSS definition can be extended such that a web-based SDSS includes a web-based GIS as a problem solver using a geographic data query/display/analysis process.

Although a web-based SDSS can combine several different components, essentially a web-based SDSS is comprised of Hypertext Markup Language (HTML) user interfaces, Internet interface programs, computational models and geographic databases. Web-based SDSS components are depicted in Figure 1 that are based on Common Gateway Interface (CGI) Internet communication and server side operation.

As shown in Figure 1, a conceptual web-based SDSS framework using CGI has user interface HTML pages, interface CGI applications, a computational model, a web-GIS application and a GIS database and files. This approach results in a "heavy" server side and "light" client

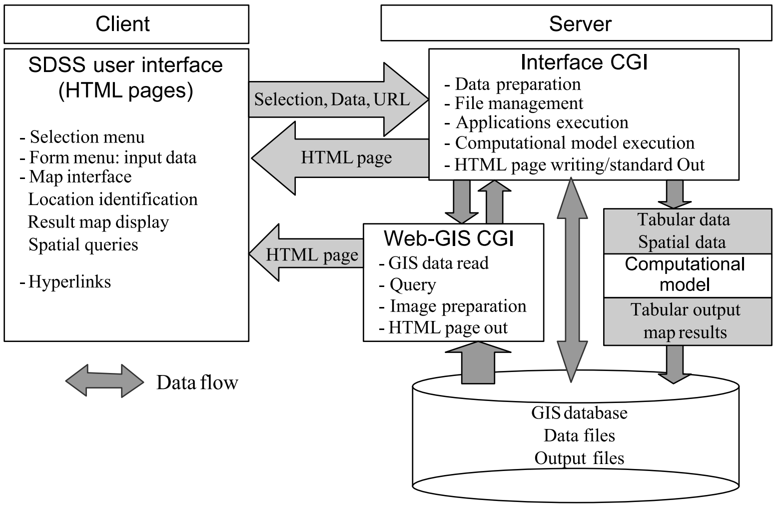

Figure 1 | Schematic diagram for a web-based SDSS framework using common gateway interface.

side, which is beneficial for data integrity, system management, communication speed and "lightweight" download HTML pages when using high performance server platforms (Plewe 1997).

Web-based SDSS user interfaces include menus, graphical maps, control buttons and form input. These interface utilities conduct selections, input data and map display/queries, usually using HTML tags, Java applets, Javascript and other Internet protocols. The events occurring on the client side are submitted to the server through the HTTP protocol and jobs requested by the client are implemented through CGI or other Internet interface applications. The interface CGI works for communication including receiving data submitted, file management on the server side, running applications including computational models and writing results into files or standard out to the client browser. A web-GIS CGI performs GIS database manipulation including GIS data reading, querying, image preparation for requests from the client and HTML page standard out preparation.

A computational model is a core application among web-based SDSS components for a model-based DSS. A computational model performs computational work using numerical models for a DSS specified purpose. For example, numerous hydrologic models could be the computational application in a web-based SDSS for watershed management. Usually a hydrologic model is chosen that can be readily run through a network environment with readily available data considering connection speed, model execution time and data availability.

Web-based SDSS development languages and protocols are abundant. Although most computer languages can write CGI applications, specific languages for web application development are often preferred because of their efficiency and functionality. HTML, C, Practical Extraction and Report Language (PERL), Java and Hypertext Preprocessor (PHP) are commonly used for web application development.

A PROTOTYPE OF WEB-BASED SDSS FOR HYDROLOGIC/WATER QUALITY ANALYSIS

A prototype application that utilizes the conceptual system described in the previous section is presented in this section. Basically, any SDSS for hydrologic/water quality analysis for watershed management must be based on a model to assess pollutant loadings from diverse sources in a watershed. The web-based SDSS hydrologic/water quality analysis system prototype is comprised of two main web systems and an HTML-based user interface including web-GIS functionality (Figure 1). The primary physical model in the SDSS is the L-THIA web application for estimation of direct runoff and Nonpoint Source (NPS) Pollution, and this is integrated with a Web-based HYdrologic GIS (WHYGIS) that has real-time watershed delineation capability, hydrologic data extraction/preparation functionality and web-GIS data publishing.

WHYGIS: Web-based HYdrologic Geographic Information System

Online watershed delineation

Various topographical data for hydrologic analysis including the catchment or watershed area, land use and soil distribution are typically summarized based on delineated watershed boundaries. A watershed boundary is determined by selection of the outlet point, and the process of defining the boundary of a watershed is known as watershed delineation using the United States Geological Survey (USGS) Digital Elevation Model (DEM) data (Djokic & Ye 2000). Watershed delineation is often the first step in hydrologic analysis. To truly support and realize the Internet operation of hydrologic models in a straightforward manner from data preparation to interpretation of results, real-time watershed delineation functionality is required. Therefore, a system should be developed to support the needs of watershed delineation functionality on the Internet in real time.

The system integrates web-GIS user interfaces, a web-GIS capability and watershed delineation as shown in Figure 2. To delineate a watershed boundary, the double seed array replacement scheme using an eight-flow direction matrix (D8) (Turcotte *et al.* 2001) was adopted, requiring an outlet point and flow direction grid as input. The user interface for this web-based system was developed using the MapServer web-GIS application (MapServer 2001), HTML Javascript and Java applet as described in Table 1. The web user interface has menus that are used for view control and links to other web pages. The interface also uses HTML form protocols to submit Universal Transverse Mercator (UTM) coordinates for the watershed outlet and MapServer CGI variable values. The watershed delineation capability was developed using the C language to manipulate the elevation grid data format and to facilitate fast execution. Although several languages are used for the data exchange between the client and server, in this study PERL was adopted to connect the client and server side application. PERL is a typical language for CGI and supports the protocol for HTML form input and HTML standard out.

MapServer CGI

The MapServer web GIS tool was selected as the CGI engine for developing the web GIS map user interface. MapServer was originally developed by the University of Minnesota ForNet project in cooperation with NASA and the Minnesota Department of Natural Resources (MNDNR) (http://mapserver.gis.umn.edu). The MapServer, a CGI, is an OpenSource development environment for building spatially enabled Internet applications. The CGI, running on the server side, provides a "lightweight" page for the client. Thus, if the server is powerful enough to control the processes from multiple connections within a reasonable time, it is the preferred choice to support potential

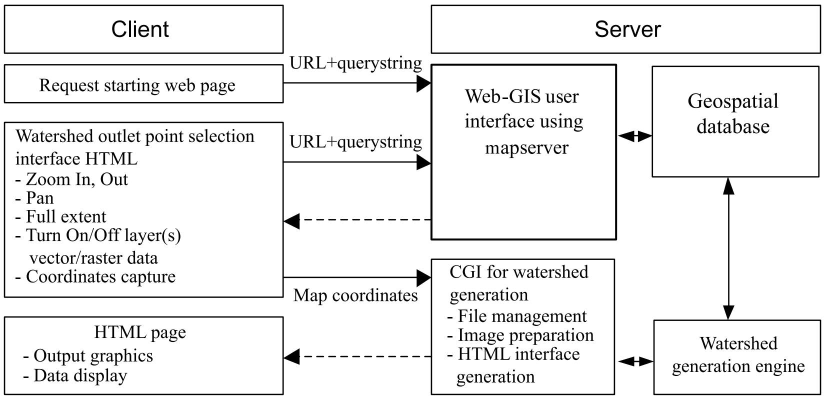

Figure 2 | Schematic diagram for the description of procedures in watershed delineation system operation.

Table 1 | Description of the watershed delineation system components

System	CGI and programming language	Type	Functionality
Web-GIS user interface	MapServer CGI, HTML, Java applet, Javascript	CGI, Web pages	Watershed selection Outlet point selection Data input Results display
Watershed delineation server engine	C	Executable application	Watershed generation
CGI	MapServer CGI, PERL (Practical Extraction and Report Language)	CGI application	Client–server interface Parse data File management Application operation HTML standard out

users since concerns regarding client side computer capability and connection speed are minimized.

Web-GIS interface

The watershed delineation system starts by the request of the URL http://pasture.ecn.purdue.edu/ ~ jychoi/wd_home from the client for the watershed delineation menu as shown in Figure 3. Using the menu, users can choose the region of interest and then graphically select the outlet point of interest as shown in Figure 3. After the outlet point is selected, the Run Watershed Delineation submit button is selected as shown in Figure 3 and users obtain the generated watershed image and information including the watershed area as shown in Figure 4.

The layers included in the map display are important to provide location information in selecting the outlet point. For the system map interface, the layers are divided into two

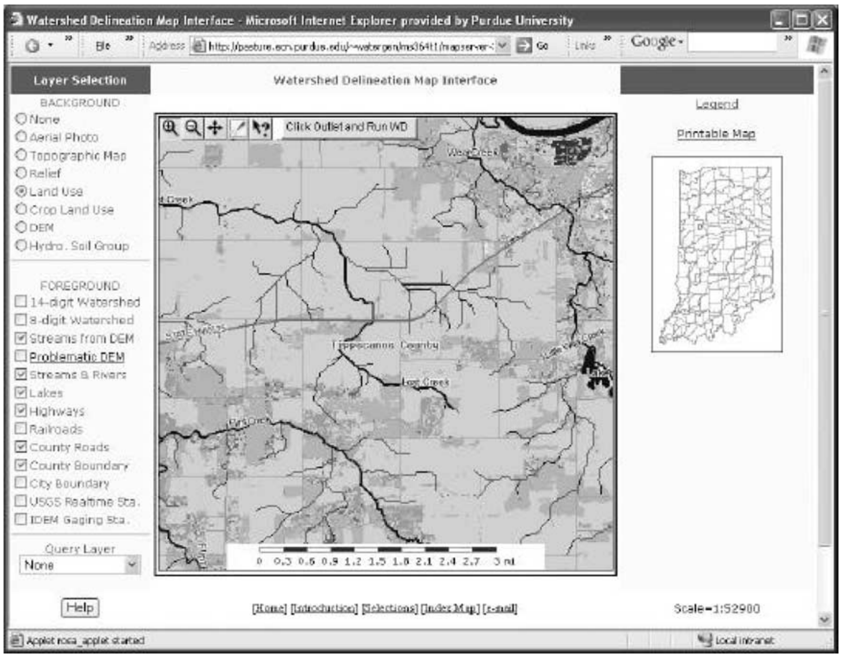

Figure 3 | Map user interface for selecting an outlet, obtaining the map coordinate and submitting data.

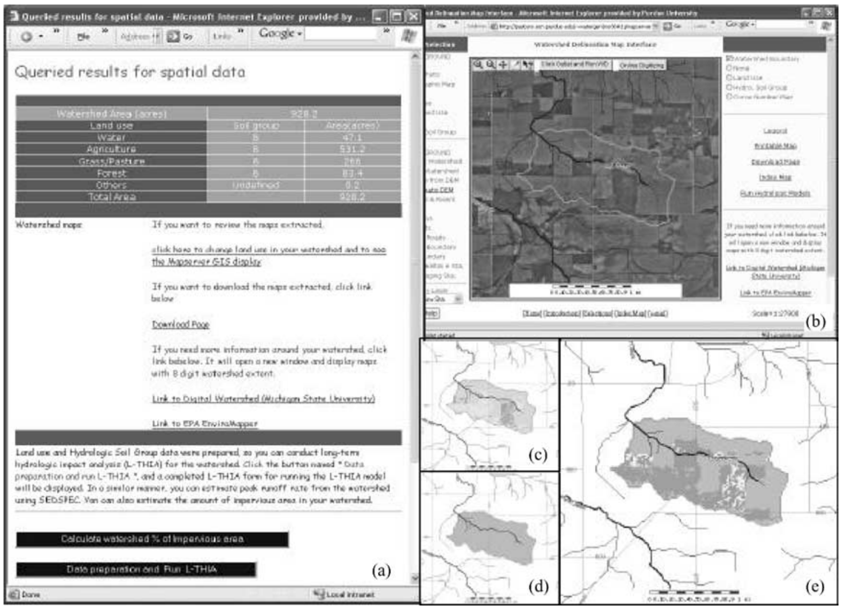

Figure 4 | Web page for the delineated watershed output and results display. (a) Summarized watershed data tabulated with land use, hydrologic soil group and curve number. (b) Delineated watershed map display and map interface web page. (c) Land use map. (d) Hydrologic soil group map. (e) Curve number map.

groups of data: background and foreground. The background data includes the shaded relief map, shadowed DEM, land use data and hydrologic soil group data, each of which can be used as a map background, and the foreground data include roads, railroads, rivers, county boundaries and 8-digit watershed boundaries. The web-GIS interface also supports ancillary map graphics including a scale bar, legend, index map and display control.

Hydrologic data extraction and preparation

The soil and land use map are the data required to implement hydrologic analysis, and if the data can be obtained automatically for a watershed, that will greatly simplify the users' efforts in conducting hydrologic analyses. In fact, the results of the watershed delineation can be applied to clip the other grid data sets including soil and land use. To accomplish this, a grid clipping application and CGI were developed. The CGI runs the data extraction applications and results are sent by HTML standard out to the client browser.

To apply the results of watershed generation within hydrologic analyses, a grid map clipping module for the basic data extraction of watershed characteristics involving land use, hydrologic soil group and Natural Resources Conservation Service (NRCS) curve number maps is run. The land use map from the USGS and the hydrologic soil map from the NRCS State Soil Geographic Database (STATSGO) soil map were prepared and used. Using the land use grid map and hydrologic soil group map, the NRCS curve number map can be created. The data prepared from the data extraction applications were described in Table 2. The land use and hydrologic soil group map are created right after the watershed delineation using this function, and users can download these results in American Standard Code for Information Interchange (ASCII) grid format for their own analysis purposes using desktop GIS.

Hydrologic model operation using WHYGIS

L-THIA operation from WHYGIS results

If a user does not have hydrological data but knows the outlet point of the watershed to be evaluated, they access the L-THIA input form page after passing through the WHYGIS. The input form fields for running L-THIA are automatically completed by the WHYGIS application.

WHYGIS for data preparation starts with the user requesting watershed delineation from an options menu.

Table 2 | Extractable data sets

Data set	Source	Items
Land use	USGS land use map	7 land use categories including: water, agricultural, commercial, industrial, grass/pasture, forest, and high and low density residential
Soil	NRCS STATSGO soil map	Hydrologic soil groups: A, B, C and D
NRCS curve number	Combination of land use and hydrologic soil group that are extracted	NRCS curve number

Using the map interface, users can graphically select the outlet point of interest by simply clicking on the watershed map. After a watershed is generated, a grid-map clipping module for basic data extraction of watershed characteristics is applied to derive maps of land use, hydrologic soil group and NRCS curve number, and extracted results are displayed through the web-GIS map interface and a data table (Figure 4). The land use map has 7 USGS land use categories, and a hydrologic soil map is generated from STATSGO data. Combining the land use grid map and the hydrologic soil map, an NRCS curve number map can be created.

Once the user has reviewed the information required by L-THIA, they select the Run L-THIA button to run the model (Figure 5). Optionally, users can edit L-THIA inputs generated by WHYGIS and prepare alternative land use change scenarios to evaluate. In the L-THIA web interface and WHYGIS input generator interface, depending on the location the user selects, weather data for the nearest weather station are queried from the database and reformatted for the L-THIA run. L-THIA runs on the web server and generates a series of tables, bar charts and pie charts for runoff and NPS pollution.

Web-GIS for soil map access

Hydrologic soil group maps can be requested from the interface for each of the 48 states in the continental US (Figure 5). This capability allows users to identify the appropriate soil group(s) to use if they choose not to use the watershed delineation and data preparation module. The internet-GIS technology provided by the MapServer CGI has been developed to serve STATSGO soil maps. The hydrologic soil group maps along with counties and major roads appear in a second web browser window (Figure 5). The user can interactively zoom to the location of interest and determine the appropriate hydrologic soil group(s) to use in the L-THIA input form link.

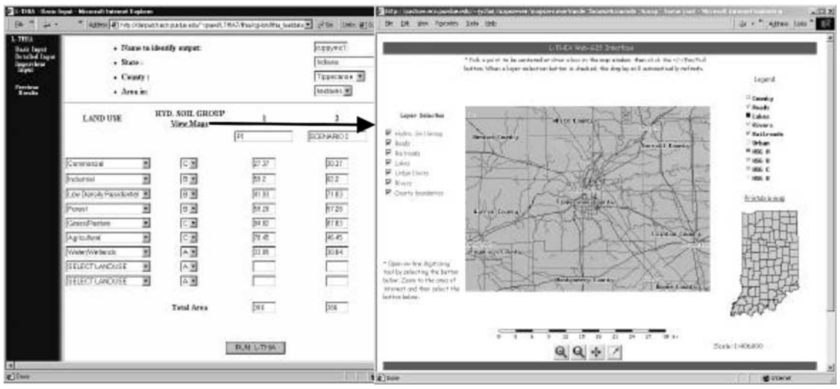

Figure 5 | L-THIA input form generated from results of WHGYGIS and web-GIS for "View Maps" link in the HTML page.

SUMMARY AND CONCLUSIONS

This paper explored the relationship between changes in information technology and hydrologic/water quality analysis DSS through the background review presented. A conceptual web-based spatial decision support system (SDSS) framework in terms of system components was described. Two web-based systems were integrated and developed further to construct a prototype hydrologic/water quality SDSS utilizing the conceptual SDSS framework. Online watershed delineation and spatial data extraction capabilities were introduced as an example of a CGI-based web-GIS application to generate watershed boundaries and to prepare hydrologic data in real time for straightforward operation of hydrologic models via the Internet. The Long-Term Hydrological Impact Assessment, L-THIA, model was incorporated with the WHYGIS SDSS and contains additional weather data preparation and output analysis tools to facilitate its use. The WHYGIS SDSS integrating web-GIS capability, hydrologic models and web applications, which is running at http://pasture.ecn.purdue.edu/ ~ watergen/owls/ can be a useful system for decision-makers who are in charge of watershed management and for potential users who require ready access to easy-to-use hydrologic model capabilities.

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