GIS AND WEB-BASED DSS FOR PRELIMINARY TMDL DEVELOPMENT

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Abstract: TMDL development and implementation have great potential for use in efforts to improve water quality management, but the TMDL approach still has several difficulties to overcome in terms of cost, time requirements, and suitable methodologies. A well-defined prioritization approach for identifying watersheds of concern among several target locations that would benefit from TMDL development and implementation, based on a simple screening approach, could be a major step in solving some of these difficulties. Therefore, a web-based decision support system (DSS) was developed to help identify areas within watersheds that might be priority areas for TMDL development. The DSS includes a graphical user interface based on the HTML protocol, hydrological models, databases, and geographic information system (GIS) capabilities. The DSS has a hydrological model that can estimate non-point source pollution loading based on over 30 years of daily direct runoff using the curve number method and pollutant event mean concentration data. The DSS provides comprehensive output analysis tools using charts and tables, and also provides probability analysis and best management practice cost estimation. In conclusion, the DSS is a simple, affordable tool for the preliminary study of TMDL development via the Internet, and the DSS web site can also be used as an information web server for education related to TMDL.

Keywords: TMDL, GIS, Internet, WWW, Decision Support System

1. INTRODUCTION

The 1972 Clean Water Act in United States of America focused attention on identifying polluted waters and subsequently on pollutant load tolerances for acceptable water quality, called "Total Maximum Daily Loads" or "TMDLs". In the 1970s and 1980s, the EPA and individual states focused primarily on point sources because these were the most obvious sources of pollution, and control mechanisms were technically and legally available. Historically, the typical TMDL has been developed as a wasteload allocation for a particular point source and most of these primarily focus on impairment by point sources. This approach has produced significant improvements in water quality by establishing point source controls for particular chemical pollutants. However, some point sources need additional controls and many non-point source impacts - such as agriculture, forestry, and development activities - cause or contribute to impairments in water quality (U.S. EPA, 1999). Thus, those responsible for managing the TMDL process for large areas are forced to prioritize sites for TMDL development; it is simply not feasible to undertake TMDL projects for all possible water bodies simultaneously.

Faced with a need to prioritize, decision makers need a clear, efficient, and ready to use system to estimate priority ratings under a variety of scenarios. If a simple and practical method to identify priority areas can be developed based on a preliminary watershed water quality analysis, this method should be very useful to decision makers. To satisfy these goals, an Internet based decision support system (DSS) for setting TMDL development priority in a preliminary study of a watershed has been developed. A well-defined prioritization approach using information technology for DSS and based on a simple screening approach for identifying watersheds of concern among several target locations that would benefit from TMDL development and implementation could be a breakthrough in supporting decision-makers prioritization needs. The decision making process, even in hydrology, has generally been performed with limited data and human resources, and decisions are occasionally based on incorrect or misleading information.

Advances in information technology involving computer hardware, software and communication networks have overcome many difficulties in the use of timely and spatially scattered resources in decision-making processes, in part through the development of DSS. One of the biggest merits of using information technologies in decision-making is that it overcomes limited resources in terms of time, data, and communication. Nowadays, the application of information technology is a general approach to solving problems that need many steps in data processing, and adaptations of the technique in hydrology are no exception. Interdisciplinary work combining hydrology and information technology includes a strong emphasis on making computationally and data intensive approaches easy to use through approaches that combine geographic information systems (GIS), access to distributed databases, and web communication techniques.

In this paper we describe a web-based DSS developed to help identify areas within watersheds that might be priority areas for TMDL development. This preliminary TMDL DSS web application is based on an integration of web-based hydrological programs, GIS, and databases. It also introduces DSS enhancement features that are associated with useful functions like impact evaluation, treatment suggestions, and urban best management practice (BMP) cost estimation.

2. BACKGROUND

The proliferation of GIS and widespread access to the web has produced an environment in which DSSs with extensive functionality can overcome spatial remoteness by providing access to data and other resources via the Internet. Many researchers have incorporated GIS and hydrologic models in environmental tools (Heaney et al., 2001), and the usefulness of GIS has been verified in many applications that make use both of basic features and more advanced spatial data manipulation functionalities. A GIS can now be considered as a routine element of a DSS tool to support automated mapping and visualization of results (Choi and Lee, 1999, Choi et al, 2001).

To address the complexities of pollutant control including cumulative impacts of point and nonpoint sources, air deposition, effects from contaminated bottom sediments, and groundwater flow into the surface water, watershed approaches have become the preferred focus for achieving water quality goals. TMDLs are a part of the watershed approach (U.S. EPA, 1999). Moreover, during recent years, the EPA and individual states have begun to focus on more complex TMDLs for waters impaired by nonpoint sources. However, many of these TMDLs have been very difficult and time consuming to define due to the limited availability of appropriate scientific tools (U.S. EPA, http://www. epa.gov/ wow/ tmdl/), human resources and funding. Among several efforts to support scientific assessment of TMDLs, Better Assessment Science Integrating point and Nonpoint Sources (BASINS) 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.

Weintraub et al. (2001) demonstrated a decision support system (DSS) to develop TMDLs for various pollutants within a river basin. The DSS is composed of a watershed simulation model, a database, a consensus-building module, and a TMDL module. This system generates multiple combinations of waste load allocation and nonpoint load allocation to meet the water quality criteria. Although the TMDL development procedures and implementation includes complicated steps and the on-line DSS has been applied with restrictions that basically come from the web environment. the Internet based DSS system still has potential for TMDL development with advanced information technologies and advantages of on-line application operation.

3. WEB-BASED DECISION SUPPORT SYSTEM

3.1 Decision Support System (DSS)

3.1.1 Definition of DSS

Although definitions of a DSS are abundant and varied, there is a basic consensus that a DSS must be a helpful system for decision makers. The decision support area has been defined by Sol (1983) as the: "development of approaches for applying information systems technology to increase the effectiveness of decision makers in situations where the computer can support and enhance human judgment in the performance of tasks that have elements which cannot be specified in advance." van Voris et al. (1993) suggest that DSSs must provide integration of information and feedback loops to support the exploratory nature of the process of scientific discovery.

3.1.2 Web based DSS

A web based DSS is as a computerized system that delivers decision support information or decision support tools to a decision maker using a web browser (Power, 2000). In general, a DSS has complicated internal structures and processing capabilities, and a Graphical User Interface (GUI) to allow the user to interact with the model in a simple, understandable way. During the early stage of developing DSS applications, GUIs were typically developed with Windows toolkits and libraries (Andreu et al., 1996, Jamieson and Fedra, 1996). However, after the introduction and popularization of HTML (Hyper Text Markup Language) for web and Internet browsers, e.g. Netscape™ and Internet Explorer™, web pages have become the typical user interfaces for web based DSS. In using the HTML protocol, the GUI can support not only the standalone platform but also Internet network applications. On the other hand, the HTML protocol does have several limitations for use over networks. The main limitations come from network speed, security and over simplification, and this produces barriers in applying sophisticated models, data intensive applications and time consuming jobs.

3.2 Preliminary TMDL DSS Development

Information technologies and the Internet provide opportunities to overcome the data, expertise, and access difficulties associated with hydrologic models and analytical tools integration. The web provides a convenient way to contact people who are potential users. Although complex programs are still difficult to integrate, various techniques that can be used are already available to create web-based DSS applications. The GIS-web-based system has several advantages in terms of data resources, potential users, visualizations and remote operation, and some limitations by network communication (Choi et al., 2001).

3.2.1 Systematic description of the preliminary TMDL DSS

Basically, any DSS for watershed quality evaluation must be based on a model to assess pollutant loadings from diverse sources in a watershed. The preliminary TMDL DSS is comprised of two main web systems and an HTML based user interface including web-GIS functionality (Fig. 1). The primary physical model in the DSS is a Long-Term Hydrological Impact Assessment (L-THIA) web application for estimation of direct runoff and NPS loading and this is linked with a watershed delineation web application for hydrological input data preparation.

3.3 L-THIA web

DSSs typically have three main parts (Ariav, 1985), a model system, a data system, and a user interface. The L-THIA web system also fits this general DSS structure.

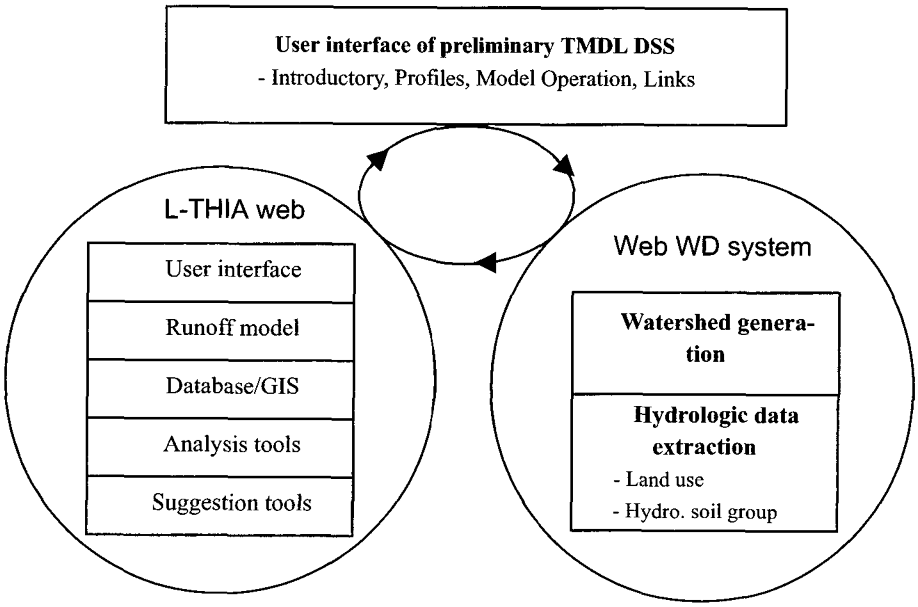

Fig. 1 Diagram of preliminary TMDL DSS configuration and operation.

3.3.1 Model system

Runoff Model and Nonpoint Source Pollution Loading Estimation

The web-based L-THIA DSS contains a hydrologic model, L-THIA, to simulate direct runoff. The L-THIA model estimates long-term average annual runoff for land use types in a watershed based on long-term climate data, soils and land use data for that area. By using more than 30 years of daily precipitation data in the daily direct runoff calculation with the United States Department of Agriculture Soil Conservation Service (SCS), which is now the Natural Resources Conservation Service (NRCS), curve number (CN) method (USDA, 1971, 1986), L-THIA produces the long-term average impact, rather than an extreme year or storm event impact. It also provides comparative impact assessments of land use change in terms of annual average non-point source pollution loadings multiplying event mean concentration (EMC) data to daily direct runoff. The EMC data were introduced to estimate nonpoint source (NPS) pollution loading from non-urban and urban areas of a watershed (Baird et al., 1996).It provides comparative impact assessments of land use change by annual loading estimation for a long period, and the model is quick and easy to use with readily available data, in contrast to other models that require considerable additional data collection to use, but which provide results suitable for detailed engineering design. The L-THIA model was re-written in the "C" programming language and an executable L-THIA created to run within the web based L-THIA system by CGI (Common Gateway Interface).

BMP cost computation

A cost computation program for urban BMPs (Best Management Practices) was prepared to support planners when they need data for budget estimation. The USEPA (1999) report recommended empirical cost estimation methods for 7 different kinds of urban BMPs on the basis of several historical reviews, and the equations originally came from several related studies by Wiegand et al. (1986), Schueler (1987), and Brown and Schueler (1997). The urban BMP cost analysis needs several inputs including watershed name, area of the watershed, rainfall zone and % of impervious area. Using empirical equations and a unit price approach, the urban BMP cost is estimated.

% exceedance

To help users understand probability data within long term average values for runoff and NPS loading, a % exceedance program was developed. The program calculates % exceedance with annual average series of runoff and NPS loading over 30 years. The % exceedance can be computed by the rank divided by total number of years, and the results give yearly runoff and NPS loading by percentiles. The results from the program are presented as charts on the web.

3.3.2 Data system

Weather data manipulation

The location data provided by the user is used within a CGI script written in PERL to query an ORACLE database on the web server to obtain the long-term daily precipitation data needed within L-THIA. Thus, the user need only select the location of interest rather than prepare a rainfall data file. Long-term daily rainfall data for approximately 500 locations within the continental US are currently stored within the L-THIA web-based system.

Web-GIS for soil map

Hydrologic soil group maps can be requested from the interface for each of the 48 states in the continental US. With the internet-GIS technology provided in mapserver, CGI have been developed to serve STATSGO soil maps. The hydrologic soil group maps along with counties and major roads appear in a second WWW browser window. 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.

3.3.3 Dialog System

In the L-THIA web 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. The user provides the area of each land use and hydrologic soil group for each time of interest. Areas of land use and soil combinations can be provided for one to three time periods. For example, a user may wish to analyze the effects of historical and future land use changes. Areas of unique land use and soil combinations can be provided for a past time period, as they are at present and as they might be at some time in the future. Once the user has provided the information required by L-THIA, they select the Run L-THIA button to run the model. L-THIA runs on the web server and generates a series of tables, bar charts, and pie charts for runoff and NPS pollution.

3.3.4 Analysis and suggestion system

BMP cost analysis

The empirical BMP cost estimation methods that were proposed by USEPA (1999) report were adapted into the DSS. The urban BMP cost analysis needs several inputs including watershed name, area of the watershed, rainfall zone and % of impervious area through a web input form. The CGI for the cost estimation runs the computation program, and finally the cost results for 7 kinds of BMPs are displayed in tabular form. Although, the urban BMP cost analysis system was programmed from simple empirical equations and a unit price approach, it can support decision makers within appropriate error ranges. In the cost analysis web page, users can also get access to additional information on urban BMPs.

"What can I do" section

If the DSS is targeted to novice users, the system should include useful functionalities to help users understand the results. Numeric output from hydrologic models is hard to understand for many users. If users can understand the effect of urbanization with cause-and-effect relationships, the decision they make will more likely be the best decision. Hence, functionalities to assist with understanding the output can make the results helpful in analyzing and understanding output. In L-THIA web, several useful functions were integrated including BMP categories, results analysis and examples as shown in Fig. 1. This section was prepared to increase users' comprehension of the effects of urbanization and to suggest methodologies that can be used as a solution for mitigation of runoff and pollutant increases by urbanization.

3.4 Internet based watershed delineation and data extraction system

Watershed delineation system development

The L-THIA web application supports Internet based hydrologic model implementation, and to help hydrological impact analysis and to have interactive operations including user definable analysis boundaries, watershed delineation functionality is needed on-line. Fundamentally, many potential users are not sure where the watershed boundaries are for a site of interest, so it is important that the DSS helps them obtain this information. To fulfill the need for watershed delineation (WD) on the Internet, a prototype system for web-based WD and data extraction was developed and implemented initially for the 2080 km^2 Wildcat Creek watershed in Indiana. As typical web-based systems are comprised of a user interface, client and server interface, and server side engine applications, the web based WD system was developed as described in Table 1. The web pages of the WD system serve as the' other web pages, and can be used to input data using a form.

4. APPLICATION OF SYSTEM IN A PRELIMINARY TMDL STUDY

4.1 Steps in using the DSS

In this section, the DSS features are described rather than hydrological analysis. The recommended web-based preliminary TMDL DSS working flow in fig. 2 suggests the appropriate use of the decision support tool for setting TMDL development priority in a preliminary study of a watershed. First, the user should prepare the hydrologic data for a watershed that will be evaluated. If areas of land use and soil data are available, then users go to the L-THIA input form page to run L-THIA so that hydrological evaluation can be implemented for the watershed. However, if 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

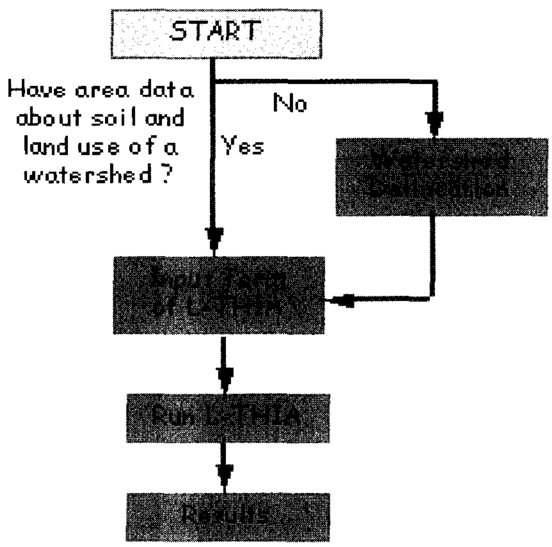

Fig. 2 Diagram for description of preliminary TMDL DSS operation.

the WD system. The input form fields for running L-THIA can be filled seamlessly from the WD system operation.

4.2 Preparation of data

The system for WD starts with the user requesting watershed delineation from an options menu. Using the menu, users can choose the Wildcat Creek watershed and then select the outlet point of interest by simply clicking on the watershed map. After entering a name for the watershed being generated, results are displayed as a watershed image and a data table (Fig. 3). To apply the results of this watershed to a hydrologic analysis, 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. The land use map has 7 USGS land use categories, and a hydrologic soil map is generated from STATGO data. Combining the land use grid map and the hydrologic soil map, an NRCS curve number map can be created, and the result is shown on the right hand side of Fig. 4. Using this function, the land use and hydrologic soil map are created after watershed delineation, and users can download results for their own analysis in ASCII format grid or apply the data directly in our DSS to run simple hydrologic models.

4.3 Run L-THIA

After input data is prepared into the form menu, the user can then select the "RUN L-THIA" button. Model results are generated and users can examine these in tables and figures. If two or three land use scenarios are input, users can compare the results with visual-aids like bar and pie charts. During the comparison phase of analysis, users can be helped from the "What can I do" menu to improve comprehension of the results. If users have acceptable results, they

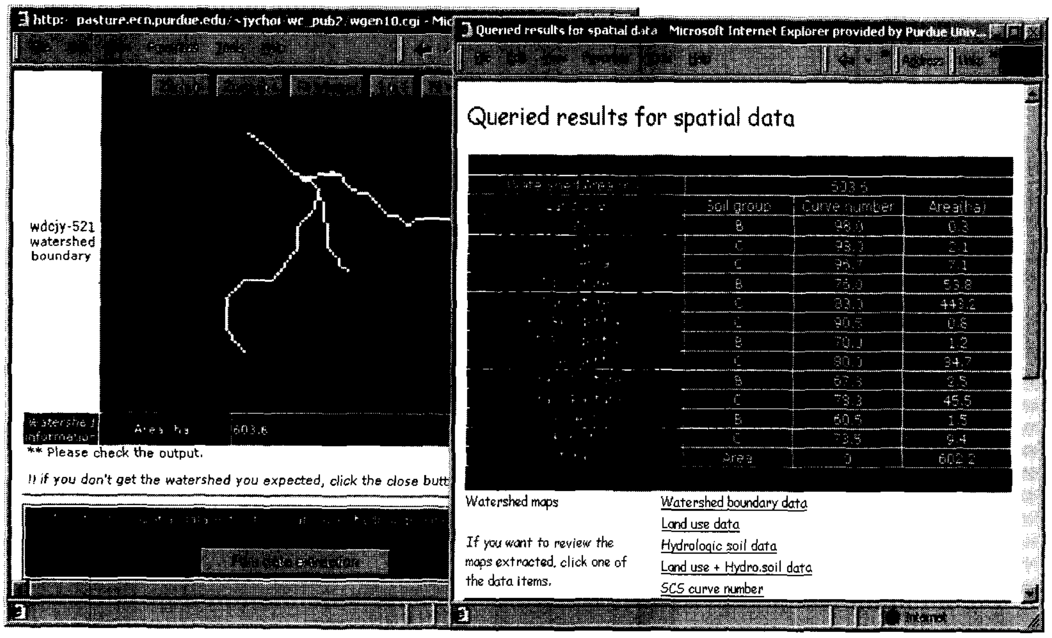

Fig. 3 Web page for the delineated watershed re-

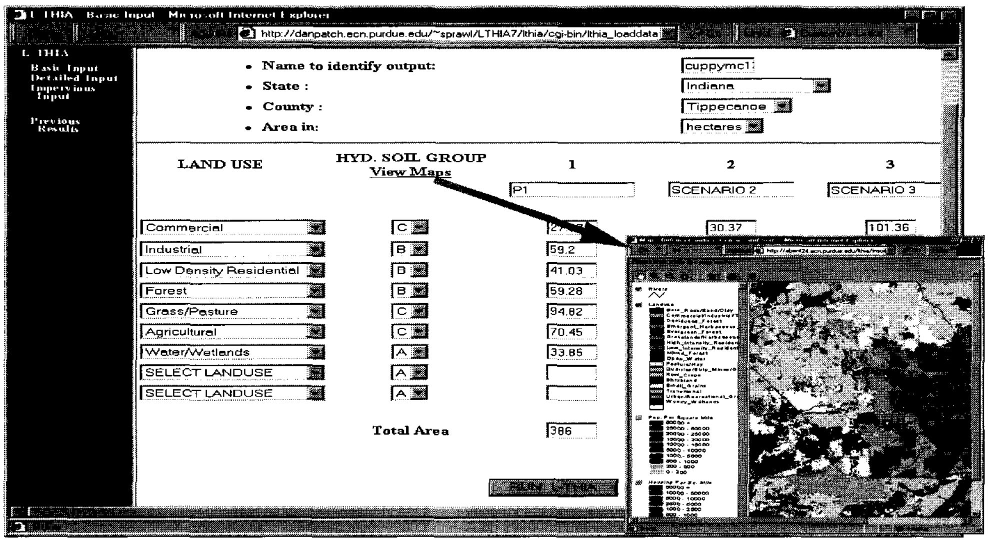

Fig. 4 Input form and web-GIS contents.

can go into the results report preparation section. The preliminary TMDL DSS web is available at http://danpatch.ecn.purdue.edu/ ~jychoi/ tmdl. The analysis can be carried out using present land use and two hypothetical land use change scenarios. This process illustrates the type of results produced by this method and demonstrates how the impacts of present and proposed land uses on the amount of runoff generated by different land uses can be easily estimated. Seven existing land use types; commercial, industrial, residential, forest, grass, agriculture and the wetland; have been used for this analysis. The prepared data input with the form is shown in Fig. 4. While the users are preparing input data, they can refer to soil and land use data with web-GIS as shown in Fig. 4.

4.4 Getting results and analysis aids

After running L-THIA, the hydrologic model engine, users can get results in terms of runoff quantity and NPS pollutants loading. To help comprehension of the hydrologic simulation results and comparison of hydrologic impact, the DSS presents the output in tables, bar, pie and series charts about runoff and 12 kinds of NPS pollutants. Fig. 5 (a) shows the menus for output results and table form of runoff. Fig. 5 (b) shows the input land use as the pie charts, and Fig. 5 (c) shows the runoffs as the form of bar charts and, for example, easy to compare the runoff increasing by the land use change from agricultural to commercial by scenario 3. Fig. 5 (d) shows the percent of exceedance of annual series of runoff and users can understand the impact of land use change with the relationship of probability. In particular, for TMDL applications, the results clearly identify the relative contribution of different land use and soil combinations to the generation of specific nonpoint source pollutants, which can be tied in to the land use and soils maps of the watershed.

5. CONCLUSIONS

A DSS is a system developed to help decision makers appropriately and simply develop and analyze data in ways that support the decision making process preliminarily. Although, development of TMDL needs sophisticated analysis including optimization processes, this approaches used to solve problems that arise in integrating databases, decision support, and server-provided GIS capabilities may help others involved in DSS development to find new ways to solve the challenges they face on the screening step. The web-based decision support system (DSS) described here helps a user identify the relative contributions of different areas in a watershed to pollution generation, that could form the basis for considering these as priority areas for TMDL development.

The preliminary TMDL DSS is comprised of two main web systems including Long-Term Hydrological Impact Assessment (L-THIA) web for estimation of NPS loading and watershed delineation web for hydrological input data preparation. The L-THIA web system satisfies the general DSS structure with three main parts including a hydrologic model and results analysis system, database system and user interface. These tools were seamlessly integrated with

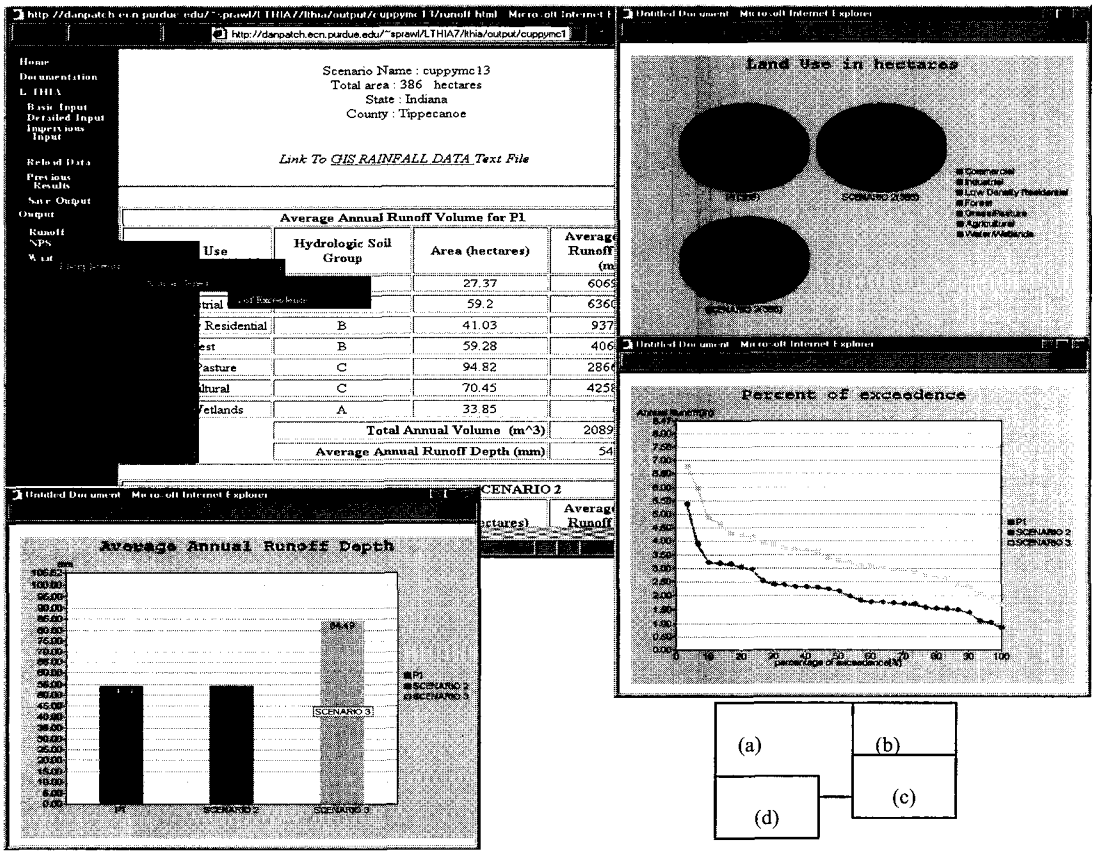

Fig. 5 Output table and charts. (a) tabular results and hierarchical side bar menu system for results to be shown. (b) pie charts of land use input for each scenario. (c) line charts for percent of exceedance of annual runoff that can assist understanding of annual variation of runoff,. (d) and bar charts of average annual runoff depth for each scenario.

L-THIA web to support data preparation in terms of land use and hydrologic soil group of the watershed generated. The system is now running on the site http://danpatch.ecn.purdue.edu/~jychoi/tmdl and is helpful for preliminary study of TMDL, and in fact for a wide range of other water quality and hydrologic assessments. Although TMDL development procedures and implementation include complicated steps, this web-based DSS system has the potential to considerably simplify the tasks involved in preliminary TMDL development.

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