Interactive Web-based Modeling of Pesticide Loss in a Watershed Using GIS

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Abstract

Agricultural pesticides are effective in controlling pests, weeds, and insects and thereby increasing crop yields and food quality. However excessive application of pesticides presents a threat to the surface and ground water quality. It is not cost effective to monitor pesticide loss, primarily because of the random nature of the hydrologic processes. Thus mathematical models had been relied upon to help assess the magnitude and extent of pesticides in the watershed environment. This paper describes the development of an interactive, web-based, spatially explicit modeling environment for predicting pesticide runoff losses in a watershed. More specifically, this paper shows how embedding the pertinent modeling equations within the GIS facilitates the application of the system to large areas, and improves the user friendliness by eliminating the use of computer programs for input/output data transfer. This simplifies the modeling process and enhances detailed display and visualization of model outputs. Also the model improves environmental decision making by providing for analysis of “what-if” land-use, land management, and pesticide management options. Interactive web-based modeling environments are increasingly being used to support spatially explicit evaluation of impact of human activities on the structure and functioning of watershed ecosystems.

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1. Introduction

The quality of more than one-third of the Nation’s assessed surface waters is impaired, with many implications for human health and well being. Nearly 40 percent of the Nation’s surveyed waters remain too polluted for uses such as fishing, swimming and other recreational activities (US EPA 1998). State source water assessments, prepared in response to the Clean Water Act, identified agriculture as a leading source of impairment to surveyed estuaries. For 60 to 70 percent of river and stream miles assessed, 50 percent of lake acres assessed and more than 30 percent of estuarine miles assessed, agriculture was identified as a contributing source of impairment (US EPA 1995 and 1998a; Economic Research Service, 1997). These assessments, contained in the state's 305(b) report, implicate nonpoint sources as the primary causes of water quality degradation and the failure of surface waters to maintain their designated uses.

Nonpoint source (NPS) pollution can be defined as contaminants of the surface and subsurface soil and water resources (e.g., salts, trace elements, sediments, fertilizers, pesticides) that are diffuse in nature and cannot be traced to a specific location within the landscape (Corwin and Wagenet, 1996). Excessive off-field losses of pesticide poses serious environmental and human health problems, because of potential impacts on drinking water supply systems and on aquatic life. In August of 1950 there were simultaneous fish kills in fifteen Alabama tributaries following a rainstorm (McCall and Lane, 1985). This event brought to light the seriousness of the pesticide pollution problem and showed that a significant amount of pesticide could be transported from field to watercourses, causing acute water quality problem.

Of the many factors that influence the extent of pesticide runoff from agricultural land, several may be controlled to minimize pollution. If the effects of interactions of pesticide type and formulation, soil properties, climatic conditions, watershed characteristics, and agricultural practices were clearly known, usage guidelines could be developed to prevent runoff and subsequent pollution (Tim et al., 1996).

Since field measurements to determine the quantity of pesticides leaving fields and entering streams during runoff events is difficult and expensive, mathematical modeling provides the only cost-effective method to describe pesticide movement both, quantitatively and dynamically. Mathematical models can be used to: (1) predict the potential contribution of agricultural runoff to water pollution, (2) provide a basis for making pesticide use recommendations (i.e., specifying type, formulation, and application rates given cultural, management, climatic, and soil conditions), and (3) guide pesticide manufactures in tailoring pesticide formulations to meet requirements for pollution prevention (Bailey et al., 1974).

Environmental fate and transport studies have mostly depended on lumped parameter models that do not account for the spatial variability that exists in ecosystem landscapes. Therefore, spatially explicit or distributed models, in which a watershed is partitioned into a series of hydrologically homogenous land units, provides a more accurate representation and estimation than lumped models. This large-scale variability and spatial heterogeneity of ecological landscapes have necessitated the use of geospatial technologies such as geographic information systems, distributed databases, and environmental remote sensing systems. The use of tools such as GIS have increased remarkably because many environmental models require large amounts of spatial and non-spatial data (e.g., topography, soil, land cover, climate, and land management) for each of the interacting processes. For example, GIS, with their ability to store, organize, analyze and display spatial data, provide additional support to environmental modeling (Fedra, 1996 PP 413 of Goodchild et al. 1996). Embedding distributed environmental models within the GIS significantly reduces the bottlenecks associated with the manipulation of spatio-temporal data for modeling purposes and facilitates interdisciplinary studies of coupled human and natural systems. One of the many advantages of a GIS in environmental modeling is that it provides a framework for modeling as well as for the effective interpretation and display of output data from the model (Maidment, 1993).

Although a traditional GIS has been able to solve some of the environmental problems, the increasing complexity of environmental systems coupled with the rapid growth in the World Wide Web, human-computer interaction, and client/server technologies offers new opportunities for the increasing use of GIS in environmental/hydrologic modeling. Because of these opportunities, numerous successful attempts have been made to enhance or improve environmental modeling and decision-making using the GIS and related information and communications technologies.

This paper discusses the development of an interactive, web-based, spatially explicit modeling environment for predicting pesticide runoff losses at a watershed scale. More specifically, this paper describes how embedding the pertinent modeling component equations within the GIS facilitates evaluating pesticide impacts over large areas and improves the user friendliness by eliminating the use of computer programs for input/output data transfer. The study described in this paper is a component of a larger project to develop inquiry-based online modeling environments for environmental and watershed science education.

2. Modeling Of Pesticide Transport In Surface Runoff

For each runoff event, certain amount of pesticide is lost both in the runoff water as well as with the sediment in the runoff. In representing the processes that occur during a precipitation-runoff event, mathematical expressions are needed to describe the mass balance of a pesticide in the top 1 cm of soil, the mass transfer of pesticide into runoff, and the pesticide concentration in the runoff and in eroded soil particles. Pesticide degradation during transport is assumed to be negligible. In general, the total pesticide loss for each runoff event decreases with time and is strongly correlated with the total amount of pesticide remaining in the runoff active zone (0-1 cm depth) of the soil surface. Thus, the pesticide losses in runoff are dependent upon the “available” amount of pesticide in the surface soil and the amount applied to control weeds or pests. These losses, in turn, are determined by the persistence, retention, and mobility of the pesticide.

In this study, the model described by Haith (1980) was used to estimate pesticide losses in runoff. A mass balance of pesticide in the top 1 cm of soil formed the basis of the model. It is assumed that the pesticide mass, which percolates below this soil depth, is not available for runoff. The assumption of 1 cm depth is an arbitrary cutoff point in this study. Many researchers believe this depth to be reasonable estimate of the active runoff zone (Donigian and Crawford, 1976; Rao, 1982; Rhode et al., 1980).

Pesticides in the soil are assumed to decay exponentially with time. If a precipitation-runoff event occurs t days after application, the pesticide mass in the top surface soil layer is given by:

[1]

$$P_t = P_o \exp(-\alpha t)$$

in which P_t is the pesticide mass in the surface soil (kg/ha); P_o is the initial pesticide content of the top surface soil layer immediately after application (kg/ha), usually the application rate; α is the pesticide decay rate (day-1), which can be expressed as:

$$\alpha = 0.693 / t_{1/2}$$

where $t_{1/2}$ is the half-life (day) of the applied pesticide.

The total pesticide available for runoff (P_t) can be divided as follows:

[2]

$$P_t = P_s + P_w$$

where P_s and P_w are the potentially available adsorbed-phase and dissolved-phase pesticide levels, respectively.

Adsorbed-phase pesticide loss

The potentially available pesticide level in the adsorbed phase, Ps (kg/ha), can be obtained by using the expression:

[3]

$$P_s = P_t / (1 + \theta / K_d \rho)$$

in which θ is the volumetric available water (cm/cm), ρ is soil bulk density (g/cm3), and K_d is the adsorption partition coefficient (cm3/g), which can be expressed as:

[4]

$$K_d = K_{oc} * f_{oc}$$

where K_{oc} is organic carbon partition coefficient (cm3/g) and f_{oc} is soil organic carbon fraction.

Thus, the actual adsorbed-phase pesticide loss in runoff, P_{rs} (kg/ha) can be calculated by:

[5]

$$P_{rs} = (A_s / 100 * \rho) * P_s$$

where A_s is the soil loss, which can be obtained by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978).

[6]

$$A_s = EI_{30}*K*LS*C*P$$

in which EI_{30} is rainfall intensity factor; K is soil erodibility factor; LS is topographic factor; C is management and cropping factor; and P is conservation practice factor.

Dissolved-phase pesticide loss

Pesticide in the dissolved phase of the top soil are a function of soil water content. For runoff-producing event (represented with total precipitation P), the potentially available pesticide in the dissolved phase, P_w (kg/ha), can be expressed as:

[7]

$$P_w = P_t / (1 + (K_d \rho / \theta))$$

Neglecting volatilization losses, the dissolved-phase pesticide can fall into one of the three primary pathways: the surface soil runoff, percolate deeper into the soil, or remain in the surface layer. It is assumed that these three pathways are proportional to the distribution of rainfall (P) into runoff (Q), percolation (P-Q-θ), and available soil water (θ). Then, the actual dissolved phase pesticides loss in runoff water, P_{rw} (kg/ha), becomes:

[8] $$P_{rw} = (Q / P) * P_w$$

The total pesticide remaining in the top soil layer, P_{total} (kg/ha), after the rainstorm is:

[9] $$Ptotal = P_t - P_{rs} - (1 - \theta / P) P_w$$

The Soil Conservation Service (SCS) curve number model described in the Technical Release SS (U.S. Soil Conservation Service, 1986) was used to estimate surface runoff from a land element. Thus, runoff volume Q is:

[10] $$Q = (P + SM - 0.2S)^2 / (P + SM + 0.8S)$$

in which P is the rainfall amount (cm), SM is the snowmelt water, and S is soil-water storage potential (cm) given by:

[11] $$S = 2.54 [(1000 / CN) - 10]$$

where CN is SCS curve number dependent on the antecedent moisture condition.

3. GIS and Environmental Modeling

A geographic information system (GIS) is an automated approach to locational and non-locational data synthesis, which combines a system capable of data, capture, storage, retrieval, analysis and manipulation, and display (Burrough, 1986). Dangermond et al. (1987) defined the GIS technology as “an organized collection of computer hardware, software, and geographic data designed to effectively capture, store, update, manipulate, analyze, and display all forms of geographically referenced information.” In addition to these definitions some authors have also defined GIS as a decision support tool that facilitates the integration of spatially referenced data in a problem-solving environment (Cowen, 1998; Densham, 1991). All of these definitions identify the GIS technology to be both a means of storing/retrieving spatial data and as a system by which data can be transformed , managed, and manipulated interactively for studying the impact of planning decisions.

Traditionally, the use of GIS technology has been limited to manipulating geographic databases and producing maps. Recently, however, this rapidly emerging technology has been used extensively for planning water quality protection programs and in studying environmental processes (Goodchild et al., 1993, 1996). In environmental modeling, GIS does not provide users with immediate applications; rather it provides a platform and suite of modeling functions that can be tailored to a wide range of environmental modeling tasks.

In environmental modeling, several alternatives of GIS applications have been described in the literature (Maidment, 1993). Several methods of coupling GIS and environmental models have been described by Tim (1996). One method that is widely adopted to couple GIS and simulation models requires the development of an application programming interface and a customized user interface that enhances the selection of input parameters, selection of appropriate modeling components, and the manipulation of model outputs. This method is considered to be time-consuming and inefficient. An alternative approach is to embed the modeling equations inside the GIS, thereby utilizing the data management, geoprocessing, and display capabilities of the GIS. In this research, the advantage of incorporating the pesticide runoff model inside GIS is that the modeling environment simplifies model modification, maintenance and examination of the effect of spatial variability. Modeling inside the GIS also enhances the evaluation of "what-if" and the incorporation of stakeholder inputs into the modeling process.

4. GIS and The World Wide Web

The linkage of GIS and Internet technologies is a relatively new area of application development. These technologies allow the user to interact with data and maps on the Internet. Users are able to determine the variables to be mapped and the type of thematic display, as well as zoom in/out, and identify features on the map (Ralston, 2002). There are basically two types of architectures/strategies for developing Internet-based GIS applications; client-side, and server-side. In the client-side strategy, the server passes data, geoprocessing and mapping application to the client, whereas in the server-side strategy the client sends a request for a map or a function and the server after processing the request sends back the resulting map back to the client.

Client-Side (Java-Based) Applications: Java is an object-oriented programming language that has gained a unique status for supporting a diverse array of Web applications and can be used for distributed applications across the Internet. Small Java programs, called ***Java applets***, can be embedded in Web pages (these are called ***Java powered pages***). Java enabled Web pages can be downloaded to the Web client side where they run. Java is one foundation of client-side applications, since Java applets can run on Java-enabled browsers. Basically, the Java applets are downloaded to the Web browser site when the user clicks on the Java powered pages, where they carry out whatever they were programmed to do. There are several implications of this: (1) Java applets exemplify “downloadable code” that is developed at one site and is migrated to another site on demand and this introduces many security challenges but also creates many interesting research opportunities; (2) Java applets make Web applications really client/server, because the Java code can run business logic on the Web client site; (3) the Web screen layout can be changed dynamically based on the user type, and a Java program can determine the user type and modify the screen layout; and (4) users can produce graphs and charts dynamically at his/her browser instead of fetching predefined graphs and images from the Web server.

By using Java applets, access to remote applications and databases can be invoked directly from the browser. This does depend on whether the Web browser allows the Java applets to establish remote interactions for security purposes. Indeed, many Web browsers are configured to disallow remote connections from Java applets because this increases security risks. The browser can, however, be configured to allow Java applets to invoke remote operations if the security concerns have been taken care of. If allowed, the Java applet can ask the user to issue a query and then send this query directly to a remote application or database.

A standard called JDBC has been developed to allow Java programs to issue calls to relational databases. In addition, Java applets can use CORBA or Sun Microsystem’s Remote Method Invocation (RMI) to invoke remote interactions. If restricted, the Java applets can issue remote resources through the Web server. However, it is difficult to convert large-scale applications into Java applets.

Server-Side (CGI-Based) Applications: Common Gateway Interface (CGI) is a program that resides on the Web server. This program, usually known as a CGI gateway, can be a script (e.g., a UNIX shell script or a Perl script) or an executable program (C or C++ code). After this program has been written it is readied for execution by the Web server (this step typically involves placing of the CGI program in the /cgi.bin/directory or another designated library of the server). Hyperlinks to the program can then be included in the HTML documents in the same way as they are included in any other resource. When the user clicks on this hyperlink, the CGI program URL is passed to the Web server. The Web server locates the CGI program in the /cgi.bin/directory and executes it. The output produced by this program is sent back to the Web browser.

The fundamental difference between a user accessing a regular HTML file and accessing a CGI program is that the CGI program is executed on the server to perform some specialized functions (including the creation of HTML pages, if needed) instead of just fetching and displaying an existing page. In general, CGI gateways fall into two categories:

(1) ***Single-Step CGI Gateway*** **–** An application program is executed as a CGI executable itself, thereby forking the application process for every request. In this case, the CGI executable contains the application logic invoked by the Web client.

(2) ***Two-Step CGI Gateway*** **–** An application program runs as a daemon process. A CGI executable just dispatches the request rather than performing any application functions. In this case, the CGI gateway has no business logic and is just used as a dispatcher.

Single-step CGI gateways are typically used for quick and relatively simple functions. The two-step CGI gateways are more useful for large, and in many cases, legacy applications. Two-step CGI gateways are commonly used for existing applications with the Web (it is easier to invoke existing programs from CGI scripts than to rewrite them completely as CGI scripts). A combination of both can also be used. Table 1 provides a comparison of the two primary client-server architectures as found in Marshall (2003).

Advantages to Server-side Web GIS Applications	**Disadvantages to Server-side Web GIS Applications**
Simpler to develop	Primitive Graphical User Interface
Easier to deploy	Low graphics quality
Easier to maintain	One-click functionality from browser
Adheres to Internet standards	
Requires standard Web browser	
Low bandwidth required	
Advantages to Client-Side Web GIS Applications	**Disadvantages to Client-Side Web GIS applications**
Vector data can be used	Difficult to develop
Better image quality	Requires additional software
Enhanced GUI	Longer download times
	No adherence to standards
	Platform/browser incompatibility

Table 1: Client-side vs. Server-side Strategy

In case of large data sets and/or if data security is an issue, the client-side strategy may not be applicable. Web-GIS applications requiring the downloading of huge shapefiles containing thousands of features to the client’s machine, may be time consuming. Another important factor to be considered is that in order to process the data and run the application the client’s machine may require periodic upgrades.In case of the client-requested strategy, if the site receives heavy traffic the server could be very busy processing the requests from each user. This could lead to server overload but the stress on the server can be limited. Some data checking and form processing tasks can be incorporated in the web pages that are to be processed by the client.

To develop the application described in this study, use was made of the ESRI’s MapObjects™ software that supports the server-side strategy. Based on the aforementioned issues and in order to achieve the research objectives the client-requested (server-side) software architecture was chosen over server-supplied (client-side) software architecture. All the data and the programs/functions reside on the server. The server can handle multiple requests from multiple clients at the same time and can keep record of each client, processing their requests, and sending back the results.

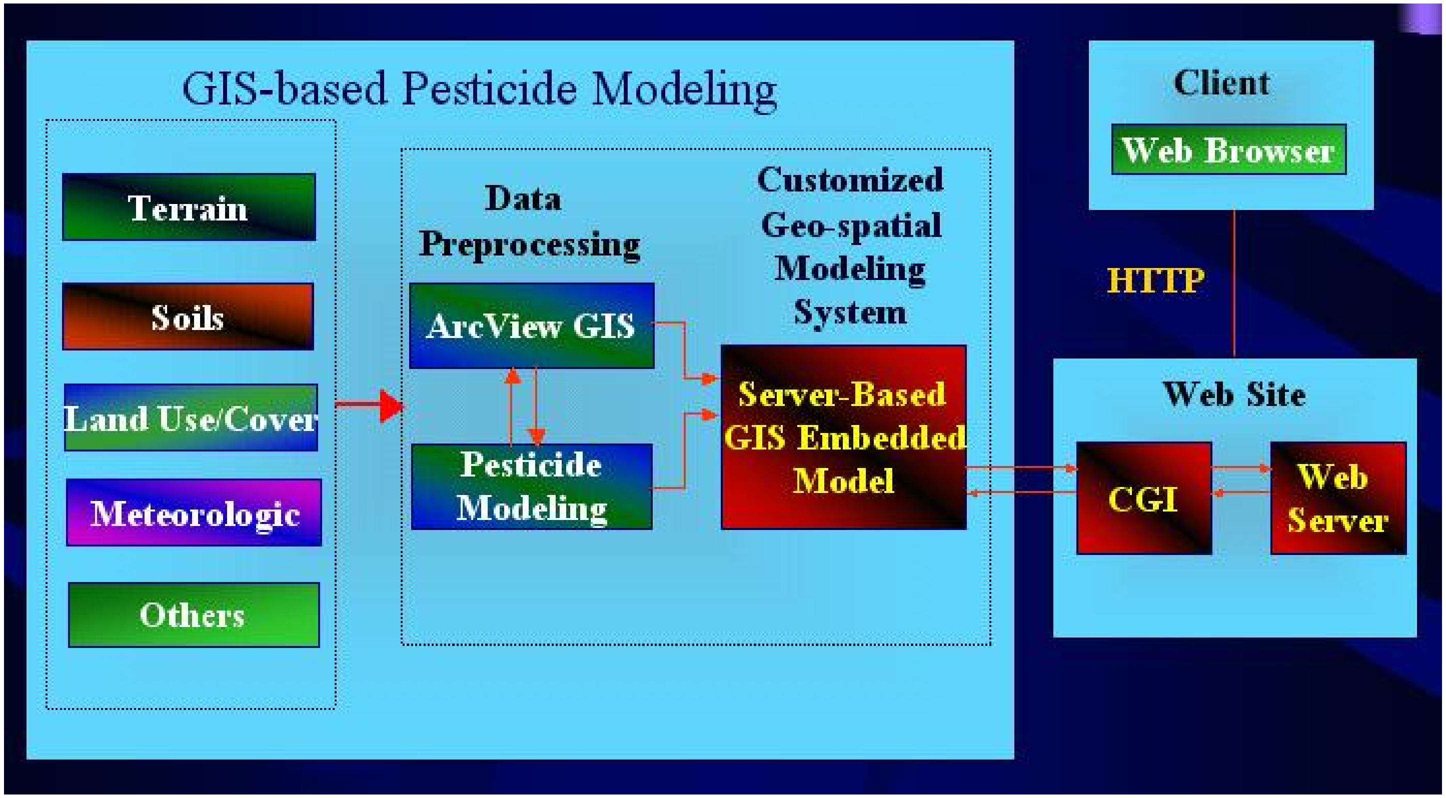


Figure 1: Server-Based Pesticide Modeling Using GIS

5. Application Development and The Modeling Processes

The overall aim of this study was to develop a physically based, interactive, web-based spatially explicit pesticide runoff modeling environment that can be used for resource planning and inquiry-based education and training in environmental/watershed science. Figure 1 shows the architecture of the pesticide modeling environment. Development of this modeling environment was based on the hypothesis that completely embedding the modeling equations within the GIS would significantly improve the user-friendliness and interactiveness of a water quality model, and having the model available on the Web would make it remotely accessible to a diverse cadre of users (watershed stakeholders, resource planners, and distant learners). Thus, a user-friendly, web-based, interactive, event-based pesticide runoff modeling system was developed. In order to accomplish this task three separate modules were developed to determine the curve number, soil loss, and the pesticide runoff losses from a watershed landscape. Microsoft's Visual Basic and ESRI's ArcObjects software were used to incorporate the mathematical equations described earlier within ArcGIS and to simulate the distribution of pesticide loads in runoff at the watershed-scale. ESRI® ArcObjects™ is the development platform for the ArcGIS™ family of applications such as ArcMap™, ArcCatalog™, and ArcScene™. The ArcObject's software components expose the full range of functionality available in ArcInfo™ and ArcView® to software developers. ArcObjects is a framework that allows users to create domain-specific components from other components. It provides an infrastructure for application customization. A customized desktop GIS application was developed initially to model the pesticide runoff losses (Figure 2). This application consisted of three modules, which were used to determine the curve number, soil loss, and the cell-level predicted pesticide runoff losses from the watershed. A brief description of the modules follows:

Curve Number Generator: The curve number generator derives a numerical indicator of an areas soil type (hydrologic group) and land use/land cover. It does this on a cell-by-cell basis for the entire watershed. This module had another component attached to it that was used to determine the rainfall runoff from the study area using the SCS Curve Number Method.

Soil Loss Calculator: The soil loss calculator uses preprocessed digital terrain data, land-use data, and the soils datasets (along with a rainfall erosivity index and conservation/structural practice factor for the entire study area) to determine soil loss values for the study area on a cell-by-cell basis. The resulting information combined with a delivery ratio, provided the amount of sediment exported from the watershed.

Pesticide Loss Calculator: The pesticide loss calculator determines pesticide loss in the dissolved and adsorbed phases for each cell of the study area within the watershed. This module allows the selection of different pesticide and options to apply a uniform rate or a variable rate of the pesticide within the watershed.

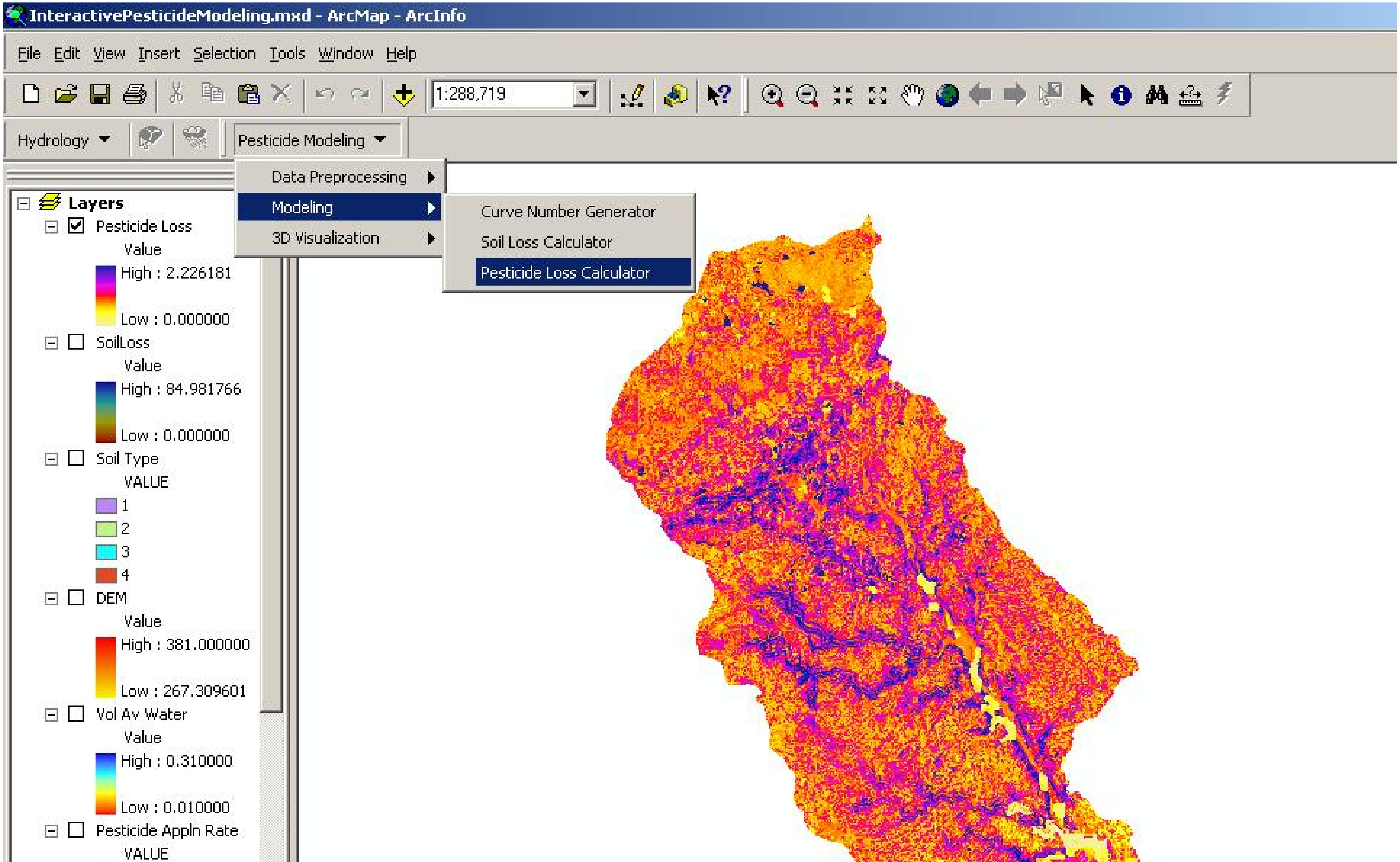
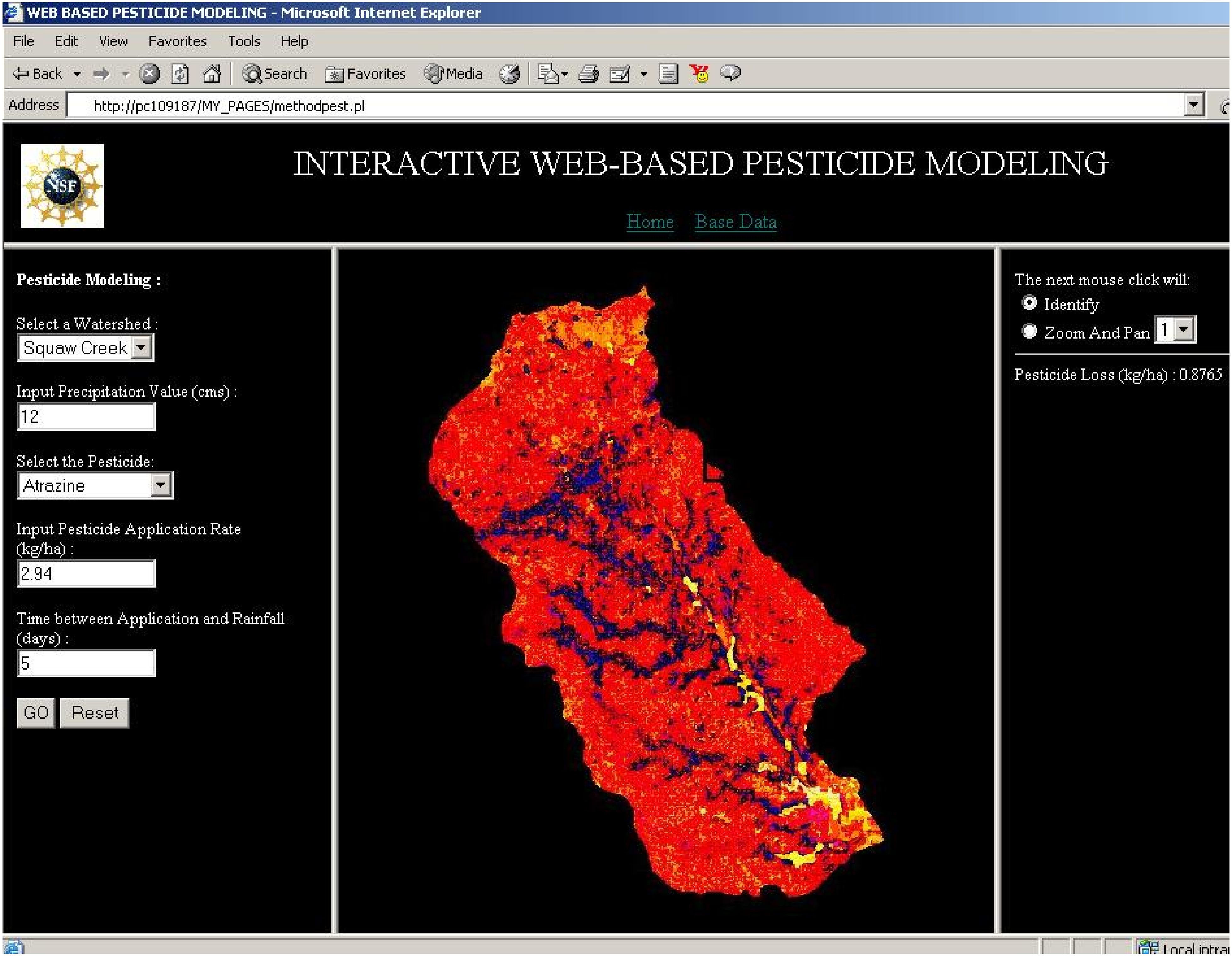


Figure 2: Desktop-Based Pesticide Modeling Using GIS

These three modules were then combined into a single simulation modeling environment. Using the modeling environment, it is possible to evaluate the effects of land use changes on watershed water quality and to explore alternative management scenarios. It also provides a powerful analytical tool for planning cost-effective measures to mitigate the impacts of pesticides on surface water quality.

The idea of modeling NPS pollution for an entire watershed is from distributed model, which intends to divide the study area into uniform grid cell and to perform the modeling process for each individual cell. As the cell size decreases, the information extracted from the original data would be more realistic than lumped model, which would aggregate information and use only one value to represent the entire study area. For this purpose raster grids have been used as inputs to the modeling system. When the model is run, it generates three new grids on the fly, which have the curve number, soil loss, and the pesticide loss values for the entire watershed. These new grids have similar cell resolution and spatial reference as the input grids to the system.

The modeling system was made available on the Web using HTML, PERL, and ESRI’s MapObjects software. Apache (http://httpd.apache.org) was installed as the server software on the web server computer. The client layer consists of a personal computer running a Web browser. This layer provides the user interface and operates by generating requests to the application server via HTTP and displays the resulting HTML file in a Web browser. The user interface provides an interactive modeling environment that facilitates user access to the modeling components, selection and implementation of modeling options, and display of simulation results (Figure 3). The client has the capabilities to zoom in/out and identify features on the generated maps. The client can also view the various base/input datasets (Figure 4). The users can navigate the entire modeling process by making appropriate selections and inputting values in the pull down menus and text boxes on the interface.



INTERACTIVE WEB-BASED PESTICIDE MODELING

Pesticide Modeling :

Select a Watershed : Squaw Creek

Input Precipitation Value (cms) : 12

Select the Pesticide: Atrazine

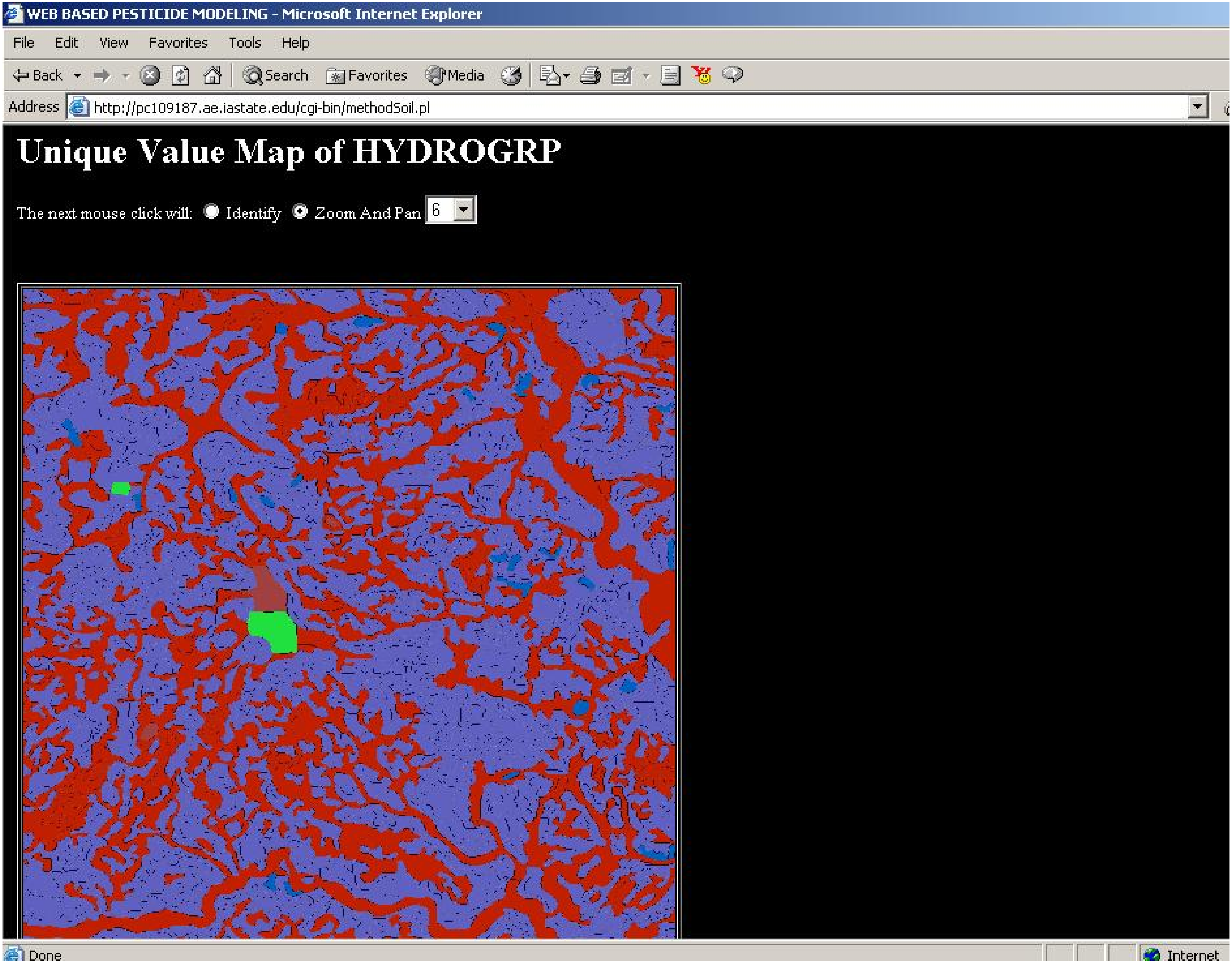
Input Pesticide Application Rate (kg/ha) : 2.94

Time between Application and Rainfall (days) : 5

The next mouse click will:
● Identify
○ Zoom And Pan 1

Pesticide Loss (kg/ha) : 0.8765

Figure 3: Web-Based Pesticide Modeling



http://pc109187.ae.iastate.edu/cgi-bin/methodSoil.pl

Unique Value Map of HYDROGRP

The next mouse click will: ○ Identify ● Zoom And Pan 6

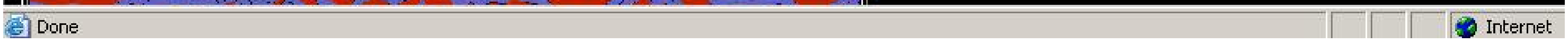


Figure 4: Visualization of Base Datasets

6. CONCLUSIONS

As the footprint of human activities continues to expand at local, regional and global scales, environmental problems will present great challenges and opportunities in the next decade. Due to the highly complex interrelationships between humans, ecosystems and the Earth's biosphere, the health of the world populations are intricably linked to the integrity and sustainability of local, regional and global ecosystems. Therefore research that integrates emerging computing, simulation modeling, information and communication technologies are needed to address current and future long-standing scientific questions as well as issues of immediate societal concern.

Pesticide pollution of surface and ground water systems and the resulting effects on humans and other non-target organisms, continues to be of heightened societal concern. For example, pesticide routinely applied in agriculture and similar land uses have been observed in the drinking waters of developed and developing countries. In the early 1960s in the United States, for example, Richard Carlson's widely acclaimed book "Silent Spring" documented the ecological impacts of DDT and other toxic pesticides. Concerns about the unintended effects of pesticides continue to this day, necessitating holistic evaluation of potential environmental and human health impacts.

This study constitutes one of the many attempts to integrate current and emerging technologies to model and track pesticide transport processes within watersheds and the human activities that affect them. The study integrates simulation modeling, GIS and web-based technologies into an authentic, interactive environment for water quality assessment. The integration of GIS and the Web (or Web-GIS) is a relatively new field and it offers a lot of opportunities for shifting over from the traditional desktop to remotely accessible GIS applications. Many web-GIS applications today allow the user to request a certain kind of map, and then allow him/her to interact (zoom in/out and identify features) with it. In this study a successful attempt has been made to move a step further by allowing for real time modeling on the Web using the various geo-hydrologic datasets. Water quality scientists can use the application for various planning and management purposes. The application being Web-based allows for an improved collaborative environmental decision-making by providing for analysis of “what-if” land-use, land management, and pesticide use options. This application can also be used for training and educating the future environmental scientists who can visualize the processes and learn-by-doing in a more realistic simulated environment. This interactive web-based modeling environment provides a cost-effective way for a spatially explicit evaluation of impact of human activities on the structure and functioning of watershed ecosystems.

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