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Developing virtual watersheds for evaluating the dynamics of land use change

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Developing virtual watersheds for evaluating the dynamics of land use change

by

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CHAPTER 1. INTRODUCTION

During the last millennium, the footprints of human activities have expanded to the point that humans now exert significant pressure on local, regional, and global environment systems. During the past century, the human population has increased five-fold, creating pressure on natural resources. Water quality and soil fertility in many regions of world have been severely degraded, and the biotic systems have been depleted and endangered by increased human demands (Ojima et al., 1991). Humans have transformed most of the world's largest river valleys into anthropogenic landscapes by utilizing floodplains for their resources (Hudson et al., 2006). Human activities are major factors for global changes, and they are intervening in the natural changes to ecosystems brought on by climate variations (Houghton et al., 1994). Most importantly, agriculture, forestry, and other land management practices undertaken by humans have modified natural landscapes and have altered natural habitats throughout the world (Turner et al., 1993).

Humans have converted forests and natural grasslands to cropland or pastures to meet the growing demands for food and fiber. These modifications to the natural landscape have resulted in a myriad of ecological impacts. For example, agricultural land uses have been associated with the nonpoint source contamination of surface and ground water across the United States. Globally, unsustainable land use and land development practices have exerted far reaching impacts on vital and fragile ecosystems. According to Vitousek (1997), between one-third and one-half of earth's land surface has been transformed by human actions. The potential consequences of this alteration are

manifested in the nearly 30% increase in atmospheric carbon dioxide since the beginning of the Industrial Revolution; degradation of water quality; excessive export of nutrients to surface waters, leading to hypoxia and anoxia conditions; loss of biological diversity; and destruction of vital wildlife habitats.

Agriculture is considered to be the major source of nutrients to surface and ground water (Rekolainen et al., 1999) due to heavy use of fertilizers in modern intensive agriculture. Fertilizer and animal manure application to land, above the requirements needed to sustain plant growth, has adversely affected ecosystem functioning on a local, regional, and global scale. For example, high nutrient loading (primarily nitrogen and phosphorous) in surface runoff from areas of high fertilizer and manure application has been implicated in a number of water quality problems such as eutrophication, hypoxia, and numerous impairments of surface and ground water quality. Agrochemicals (e.g., nitrogen, phosphorous, herbicides, and insecticides) moving from agricultural lands represent a potential source of water pollution, and their movement in surface or ground water follows two main paths (Novotny and Olen, 1994). Nitrogen (N), generally reaches ground water dissolved in the percolating water, while less soluble phosphorous moves with eroded sediments over the surface (Heathwaite and Sharley, 1999).

The future trends of human activities and the associated changes in land cover can be better understood through the use of integrated spatial decision support systems that combine simulation modeling with technologies for geospatial analysis, environmental sensing, scientific data mining, and visualization. At the core of a spatial decision support system are tools such as distributed eco-hydrological models, geographical information systems (GIS), and virtual reality (VR) immersive interfaces. Simulation models enable

the forecasting and prediction of cause-and-effect relationships; GIS provides tools and functions for storing, analyzing, modeling, and displaying of geospatial data and geo-referenced data; and the VR technology enhances user interaction with a representation of the real-world environment for improved decision making. The seamless integration of these tools and technologies into a spatial decision support system allows users to synthesize, analyze, and explore data representing various ecosystem components (e.g., the biotic and abiotic) and promotes modeling and visualization of ecological processes. Important challenges in environmental science include evaluation of how earth's biogeochemical cycles are being perturbed by human activities. Some of the application areas of spatial decision support systems are (1) predicting and managing changes in freshwater resources and the environment as a result of floods and contamination and (2) developing a systematic understanding of changes in land uses and land covers that are critical to ecosystem functioning and services.

1.1. Research Objectives

This research is focused on developing a virtual environment (VE) for ecological synthesis and for forecasting the effects of changes in land use and land cover on managed ecosystems function. More specifically, this research focuses on exploring new opportunities and capabilities offered by VR technology, spatially explicit hydrologic modeling, and geospatial technologies for improving resource management and decision-making related to land use management. With a focus on watershed and land use dynamics of the Upper Mississippi River Basin (UMRB) ecosystem, the VE holds the potential to enhance ecological decision making, particularly the decisions related to

implementation of agricultural best management practices (BMPs) and water quality and quantity. The desktop-based VE developed for this research contains tools to display, manipulate, interact, and visualize geo-environmental data. Interaction with the VE through a speech recognition interface assists users with rapid assessment of environmental problems related to changes in land use, and the interaction improves their understanding of natural and anthropogenic hazards, global climatic change, and water resource management. The specific objectives of this research are as follows:

1. To develop a VE that integrates distributed eco-hydrological models, ArcGIS tools, and VR interfaces to support ecological forecasting, focusing on watershed, and water resources management.

2. To test the application of the VE for assessing land use and land cover changes in an agro-ecological landscape in Iowa.

CHAPTER 2. LITERATURE REVIEW

2.1. Brief Overview

The fact that earth's ecosystem has become overburdened is no longer in doubt (Vitousek et al., 1997). Degradation of terrestrial and aquatic ecosystems is now pervasive on a local, regional, and global scale. The ready availability of geospatial, environmental, and remotely sensed data offers enormous potential to (1) assess changes in the health of earth's ecosystems, (2) identify risks of further degradation, and (3) create opportunities for restoration. Thus far, however, little of this potential has been realized, due to the lack of an appropriate conceptual framework that captures the biocomplexity of the environmental system (including important biophysical, socioeconomic, and human health dimensions) and due to the lack of diagnostic tools that are adequate to represent the underlying biocomplexity and support a predictive level of understanding.

The intensity and spatial extent of contemporary human alterations of the earth's land surface are unprecedented. Land use and land cover change within watershed ecosystems are among the most significant and pervasive of these human influences. There is clear evidence that watershed land use and land cover dynamics and their spatial patterns exert significant impacts on terrestrial and aquatic systems, as well as on economic and social welfare. Most of the impacts are local, while others are regional and global in nature. For example, land use and land cover changes within watersheds contribute significantly to earth-atmosphere interactions and biodiversity loss, and these changes affect water quality and biotic integrity. The spatial patterns of land use change and other forms of human alterations of natural systems can also have disastrous

environmental effects to the degree that resulting landscape patterns undermine ecological service functions. To address these complex environmental and land use challenges, scientists and resource managers have generated large amounts of data, most of which have geographic references. Analytical tools and technologies have been utilized to fuse, mine, and interpret the significance of the data. The following sections briefly describe some of these technologies and their utility and relevance for addressing human environmental problems.

2.2. GIS: A Brief Introduction

Nearly all processes related to human-environmental systems have a spatial dimension. Traditionally, solutions to environmental problems were obtained using non-spatial methods or by the manual manipulation of mapped data. The ongoing advances in geospatial technologies, primarily those related to the geographic information systems (GIS), have significantly enhanced the manipulation and analysis of data associated with human-environmental systems.

From a cinderella and an enabling technology developed in the mid-1960s, the GIS has advanced rapidly to become an important component of environmental management and decision making. GIS and similar geospatial technologies (e.g., global positioning systems and environmental remote sensing) have been disseminated into all levels of government, industry, academia, and society. GIS has become an indispensable tool for customizing, integrating, transforming, and analyzing a broad range of disparate data. Applications of GIS can be found in areas such as urban and rural land use planning, natural resources management, utilities and infrastructure management,

military planning and warfare logistics, health care, agriculture, archaeology, and homeland security. The ability of GIS to relate disparate data and information within a spatial context and to enhance the decision-making process makes it a powerful tool for environmental and natural resources management.

What is GIS? Depending on the domain of application, different definitions of GIS have been proposed in the literature (Goodchild et al., 1991). For example, Devine (1986) defined GIS as "a form of Management Information System (MIS) that allows map display of the general information." Burrough (1986) defined GIS as "a powerful tool for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world." Smith (1987) also defined GIS as "a database system in which most of the data are spatially indexed, and upon which a set of procedures are operated in order to answer queries about spatial entities in the database." In all of these definitions, the GIS technology can be considered as being comprised of components and tools for data input, data fusion, manipulation, geo-processing, display, and visualization. GIS can be considered to have three major components:

- Data input component: The data input to GIS are most commonly in the digital form obtained using GPS and environmental remote sensing satellites.

- Data fusion and data manipulation component: This is an important aspect of GIS which include data management, data processing, and data analysis. The data management and data processing is comprised of the organization of data into files and folders for analysis. The user can extract appropriate information by using GIS to perform different queries and can produce information for research and management (see Figure 1).

- Data display and visualization component: The information available can be displayed and visualized in the form of maps, layers, or tables, making it easy for the user to form various interpretations of the data (see Figure 2).
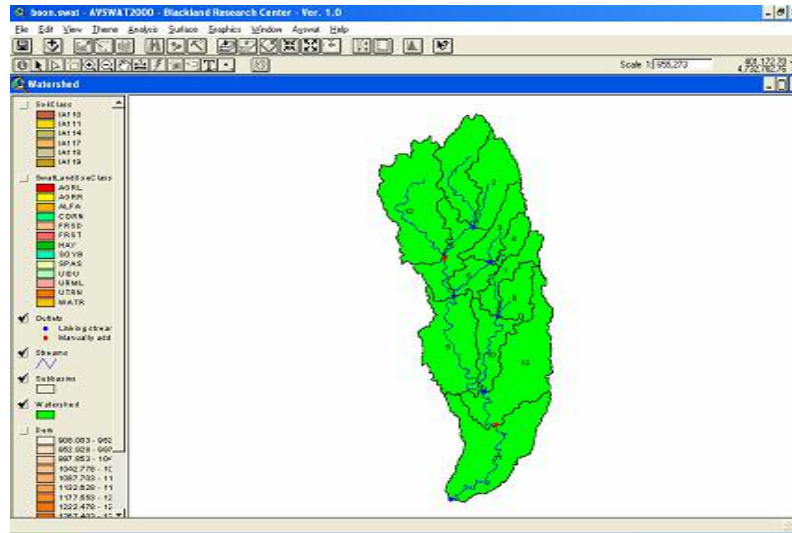
Figure 1. Boone, Iowa watershed view in ArcMap (ESRI, Redlands, CA)
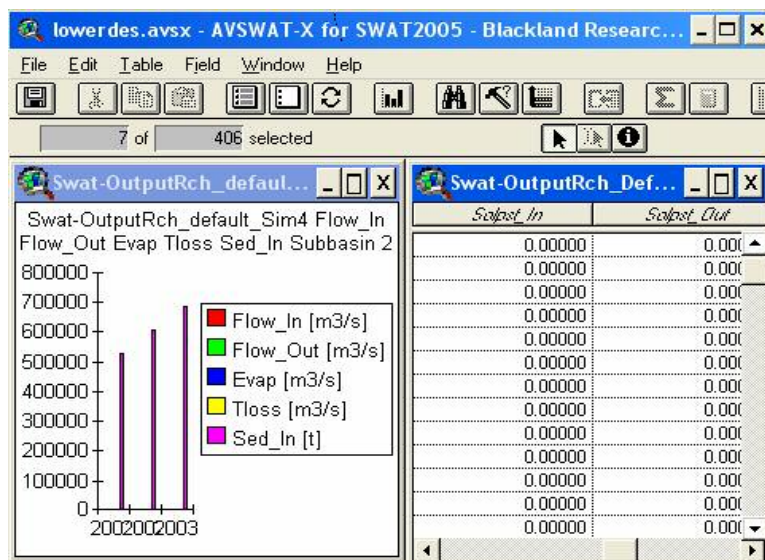
Figure 2. Amount of sediments flow in Lower Des Moines, Iowa watershed

The advent of sophisticated geospatial information technologies has led to the extensive use of GIS for environmental planning, prediction, and decision making. The tools of GIS have provided researchers with the capability to compile and organize disparate environmental information into coherent databases, to integrate simulation models with the spatial environmental data, and to display the results of the modeling for improved, scientifically sound decision making. In other application areas, such as business and commerce, GIS data mining capabilities have accelerated the fusion of data within enterprise commercial databases and have facilitated the discovery of knowledge inherent in the data.

Effective use of the GIS technology in many application areas is based upon accurate representation of spatial features and phenomena. Traditionally, real-world features and objects have been classified within the GIS using two primary data structures: raster and vector. Objects in the raster data structure are conceptualized as two-dimensional grid cell elements having a unique value and location. Thus, an area (object) can be conceptualized as a contiguous set of grid cells, while a point object can be represented by a single grid cell. In the vector data structure, however, objects and features are conceptualized as one of three primitives—point, line, or polygon. Points are used to represent features or objects that are too small, such as cities or schools. Lines represent objects and features that are too narrow to be signified by polygons, such as rivers or highways. Polygons represent features or objects that are large enough to have boundaries, such as states, land parcels, and water bodies.

2.3. GIS and Environmental Simulation Modeling

With the rise of geo-information science and engineering, the existing non-spatial models have been transformed into GIS-based prediction models, such as the Soil & Water Assessment Tool (SWAT) (Arnold et al., 1998). Integration of GIS survey data with modeling provides an effective tool for estimating relationships between resources and their degradation. GIS are used to provide information on resources such as vegetation, biodiversity, natural resources degradation, and utilization, while modeling is used to predict future cause-and-effect relationships for enhancing decision making and improving management practices. Several techniques have emerged over the past few years to link GIS and environmental modeling software. These techniques vary from being loosely integrated to being tightly coupled or fully integrated GIS and environmental modeling systems (Tim, 1995).

Loose integration between GIS and environmental models involves using GIS for storing, generating, organizing, and displaying input and output data from the model. The GIS is used for organizing the input data to the model and displaying outputs of the model for analysis. This technique uses two formats for exchanging data—an ASCII file format and a binary file format. An interface program extracts data from either file format, reorganizes the data, and saves that data in the format required for modeling. Figure 3 shows a schematic diagram for loose coupling of GIS and an environmental model.
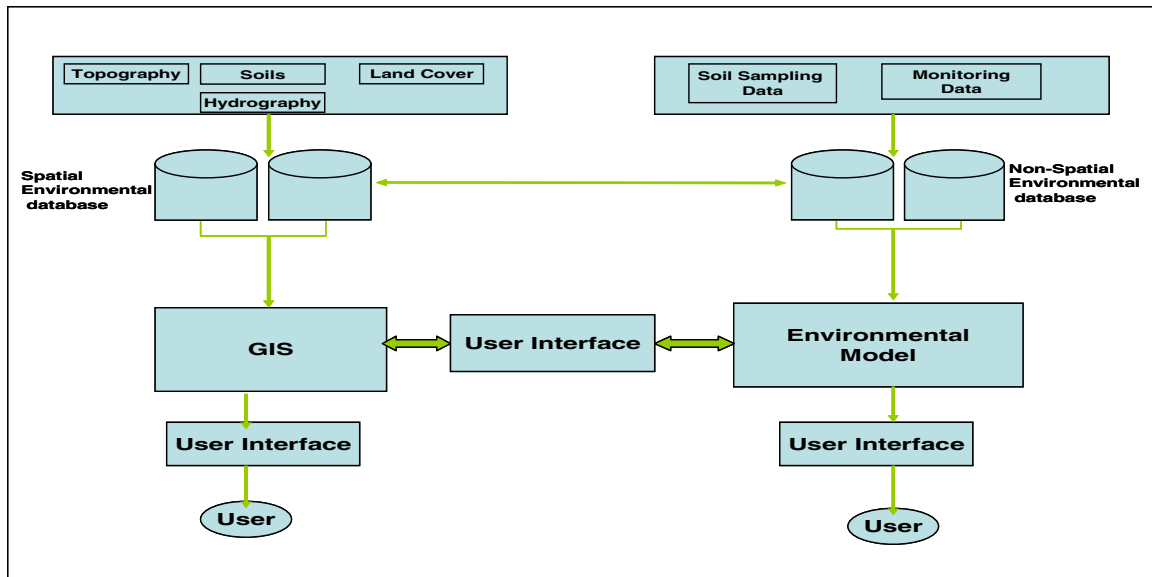
Figure 3. Schematics of a loose coupling of GIS and an environmental model (Tim, 1995)

The second technique used in integrating GIS and environmental models is close integration. This is accomplished by developing an enhanced computing environment for data transfer between the model and the GIS. This strategy adopts standard client server architecture and middleware and establishes the relationship between the two disparate components, the model and GIS. The gap between data transfer and the ecological model is bridged by memory resident database models rather than external files. These provide interactive capabilities and offer apposite access for designing programming interfaces. The closely integrated modeling environment provides better data communication and performance compared to the loosely coupled strategy described earlier. However, there are two major limitations with the close-coupling strategy: (1) the design of the data transfer interface increases development complexity and (2) internal data extraction can result in decreased processing speed. Figure 4 shows a schematic diagram for close coupling of GIS and an environmental model.
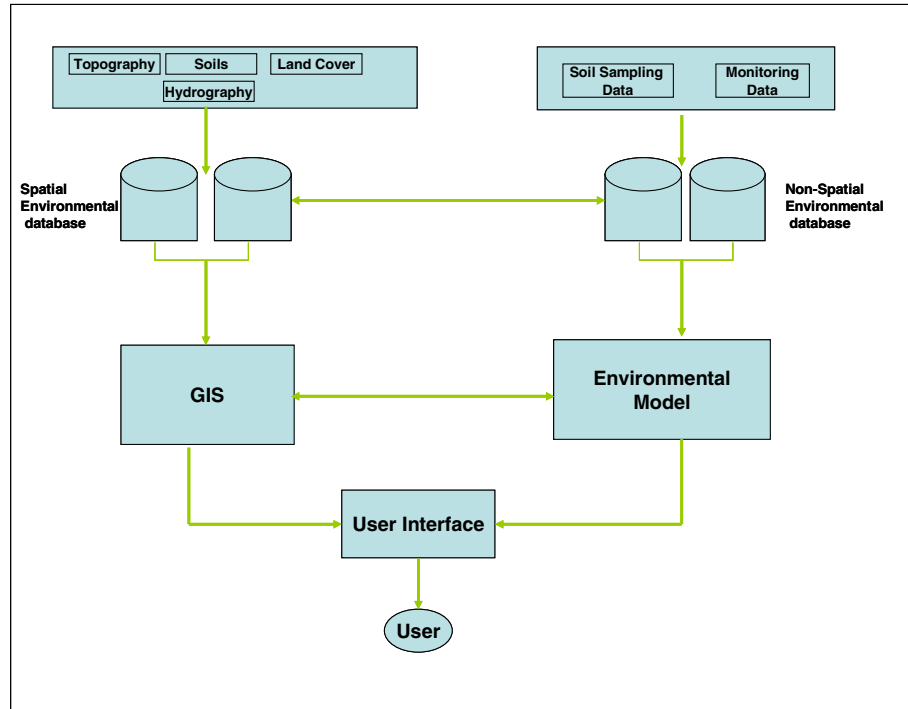
Figure 4. Schematics of close coupling of GIS and model (Tim, 1995)

A more sophisticated technique for integrating GIS and environmental modeling can be realized in a full integration or embedding strategy. With this strategy, a tightly coupled Graphical User Interface (GUI) is developed between the model and GIS to embed the functional component of one system within the other. This may, for example, take the form of embedding modeling equations inside the GIS or embedding the GIS object modeling functions inside the model. The modules of the GIS and of the environmental model are linked together for optimal sharing and processing of data. The GUI is developed to provide the user with a robust and easy-to-use navigation environment. However, there are a few limitations for full integration. Firstly, there is the slow response of GIS and model developers to provide open-source tools that can enhance the embedding of individual components. Secondly, this coupling strategy

requires models to have a modular structure so that coupling of individual components

and data can be possible within the common GUI (see Figure 5).
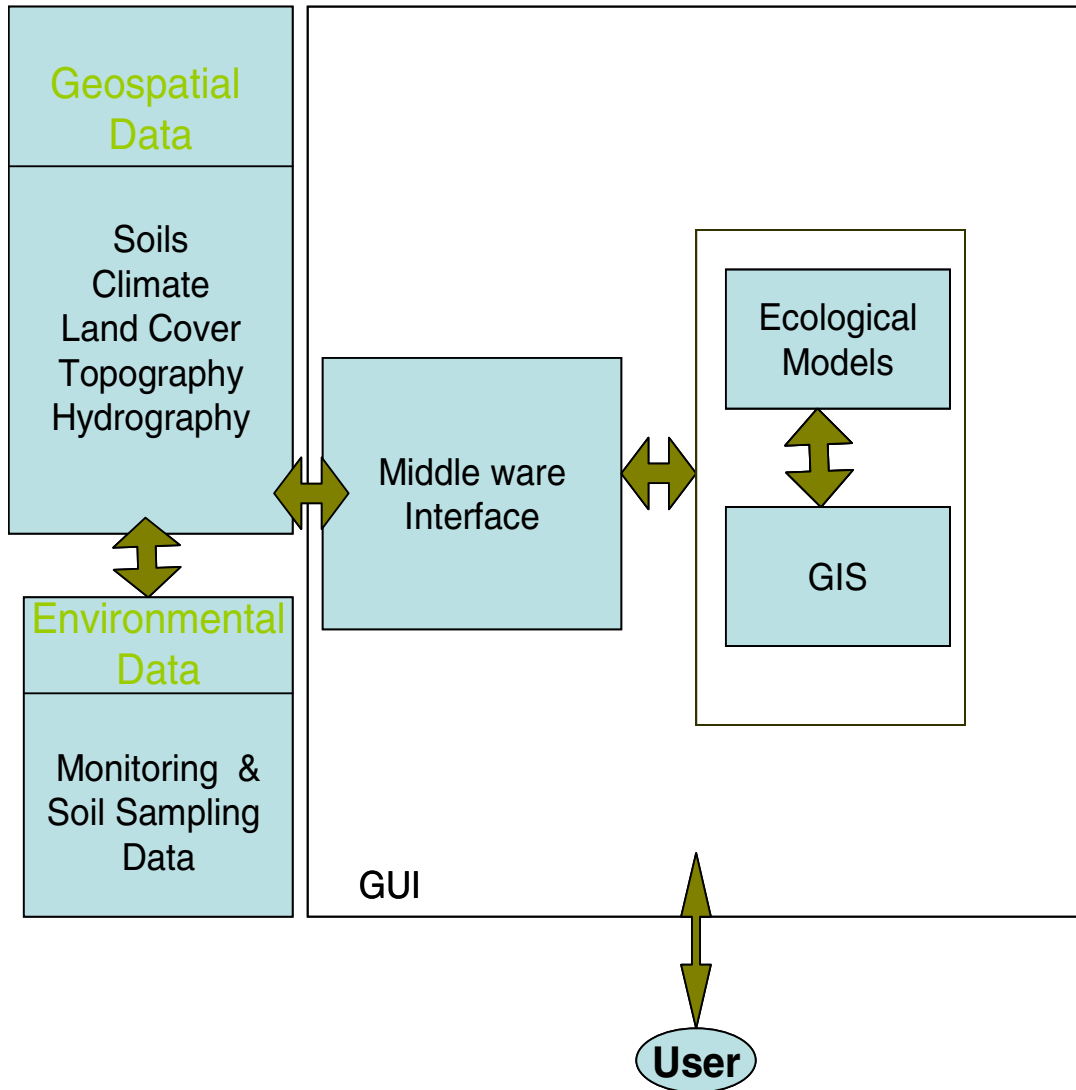
Figure 5. Schematics of full or tight coupling of GIS and model (Tim, 1995)

The integration of both GIS and environmental models, using either of the

strategies described above, has been shown to facilitate both efficient environmental

management and effective decision making.

Gorokhovich (2000) used GIS and modeling techniques for superimposing data layers to extract the areas contributing to surface runoff in a catchment. The catchment was divided into different hydrological response units (HRU) based on land use, soil type, and topography. The study created a hydrological surface that provided users with information about areas that were contributing and delivering surface runoff to the stream channel.

Tsihrintzis et al. (1997) used GIS-based aided modeling techniques to predict the impacts of nonpoint source pollution on surface and ground water in South Florida. A nonpoint source pollution model, The Hydrologic Simulation Program – FORTRAN (HSPF) was coupled with a GIS interface to facilitate (1) data storage, management, and display, (2) the derivation of model input parameters, (3) and the effective presentation of results. The model was internally programmed within the GIS module to enhance GIS application, and it proved to be an effective tool for the prediction of water quality.

Sadek et al. (2003) used a field scale quasi-two-dimensional mechanistic flow model (DRAINMOD) in combination with a GIS to model leaching of nitrate to surface water. The GIS was used to define the spatial distribution of land use and soil data within the area of interest. The DRAINMOD model calculated the daily nitrate leaching for a given soil, crop, climate, geo-hydrological and farming scenario at field scale. The model was calibrated using the state variable of the nitrate-nitrogen concentration in the soil profile of Molenbeek and the Mark catchment situated in Belgium. Upon calibration, the integrated system (DRAINMOD and GIS) was used to develop nitrogen leaching vulnerability maps for three agricultural catchments in Belgium. The study illustrated an application of GIS for modeling nitrate leaching at catchment scale.

The link between GIS and environmental modeling becomes practical when the use of computers for ecological analysis involves spatially distributed terrain parameters (Bajwa, 2002). Enhancements in technology have created the need for visuals from full-color thematic maps to dynamic images, which are more than maps. The idea of viewing the same dataset in different perspective views and dimensions is growing rapidly. The application of GIS for diverse fields and users makes visualization an important factor for GIS. This provides a need to implement VR with GIS in order to make it a more effective tool. Efforts have been made to integrate GIS and VR tools with three-dimensional (3D) and animation capabilities for collaborative decision making. Indeed, collaborative Virtual Geographical Environments have been developed to enable a wide range of people, including government officials, residents, and domain experts, to collaborate virtually and to navigate, query, and select features through virtual scenes while simultaneously communicating with each other (Qi et al., 2004).

2.4. Virtual Reality

Over the last decade, the terms "VR" and "virtual environments" (VEs) have become ubiquitous within all aspects of society, synonymous with a developing generation of fully interactive computer-generated environments. Today, VR and VEs have found widespread applications in a variety of contexts, from analyzing the effects of alcohol intake on automobile drivers to training surgeons and astronauts, from calming nervous dental patients to creating utopian worlds within which individuals can socialize and organize, and from assessing potential visual impacts of rural development to creating digital reconstructions of ancient cities and artifacts (National Research Council,

1994). A VE (a.k.a. "virtual world") can be generally described as interactive, virtual image displays enhanced by special processing and by non-visual display modalities, including auditory and haptic, to convince users that they are immersed in a synthetic space (Jacobson, 1994). VEs that allow real-time visualization have found widespread application in science, manufacturing, industry, and society in general. In industry, companies are increasing their global competitiveness by using VEs to design innovative products. In science, VEs are helping researchers decipher the knowledge embedded within massive volumes of data. In medicine, physicians are using VEs to design treatment and therapy options as well as remote surgery and tele-presence. In academia, VEs are bringing exciting new resources into the classroom to enhance experiential and cognitive learning. Indeed, VEs use a variety of VR technologies to enable users to directly interact with modeling and simulation systems by using a range of visual, auditory, and tactile cues and by manipulating objects directly.

The term "VR" was initially coined by Jaron Lanier, the founder of Visual Programming Language (VPL) Research, Inc. It refers to technology that reinvents the way individuals interact with computers and consists of a 3D computer-generated (virtual) world. Satava (1993) defined VR as a "fully 3D computer-generated world in which a person can move about and interact as if he (she) actually were in an imaginary place. This is accomplished by totally immersing the person's senses…using a head-mounted display (HMD)."

The VR technology has experienced significant advances during the last decade, and is now used by military, industry, government, and academia. Typical application areas include health care, engineering, medicine, manufacturing, education, and training.

In many of these areas, VR has significantly enhanced exploration and manipulation of massive amounts of multi-dimensional data in ways that were not previously possible.

In addition to 3D graphics in the engineering field, the scientific community uses VR tools in fields such as micro-modeling, fluid mechanics, environmental science, biology, academics, industrial research, and for modeling complex systems such as hydrology, genetics, mechanics, and micro-sciences. In the past, 3D color stereo displays led to the evolution of new ideas in research. These images provided scientists with control and interaction with their data, which further lead to creative and inventive thinking and also encouraged creation, investigation, and collaborative communication.

The increased curiosity of scientists has led to the progression in stereo displays to simulated VEs. These simulated stereo environments, generated through VR technology, appear as real-world environments. Today's VR systems and technology use human-machine interfaces to present multi-dimensional information, which can be interacted with through gloves, tablets, pens, joysticks, and space mouse, and users can collaborate face to face to make efficient decisions. The discipline of human-machine interfaces or human computer interaction (HCI) in VR has led to the development of multi-user interaction interfaces that support collaborative decision-making. According to Joseph (2005), the implementation of HCI in VR supports: (1) interactive processing of speech, (2) interactive processing of gesture, and (3) interactive processing of haptics.

Cruz et al. (2002) developed an interface that incorporated VR and speech recognition. This interface was used for tutoring a signal analysis course to undergraduate students at Autonomous Metropolitan University at Azcapotzalco, Mexico. The virtual world consisted of six rooms and one center hall, each room corresponding to each

tutorial theme. The graphics in each room illustrated the chapter concepts. The speech recognition allowed users to navigate through the virtual world with spoken commands. The spoken commands like *index*, *world*, and *exit* allowed the user to access the principal sections of the tutorial. This intelligent and multimodal tutoring system was designed to help the users better understand the concepts of signal analysis.

Laviola (2005) developed a multimodal visualization tool for visualizing fluid flow around an object. The human-computer interaction for this tool was initialized through hand and speech input. For example, in order to instantiate a virtual object, a user made a pointing gesture and then used voice as a mode of interaction. The gesture provided information about the position of an object and the speech provided information on the type of the object. The user could also issue a voice command to ask queries about the object while navigating with gestures. This interface also used a push-to-talk interface wherein the speech modality received information from a hand gesture instructing it that speech should be activated.

Nojima et al. (2002) developed a system called SmartTool that responded to a real-time environment through a real-time sensor and haptic display. The SmartTool consisted of a sensor to measure the real-time environment and a haptic display for displaying sensory information. A conventional tool was used to work with the environment, and the sensor on the tool tip responded to the actuators to generate additional force if it detected something. This system was tested on the cutting of a hard-boiled egg. The egg corresponded to a human body and the yolk indicated the vital tissues. A scalpel was used as a conventional tool on the SmartTool. An optical sensor

was also used to detect the egg yolk. The results from the test proved SmartTool as an effective tool.

2.5. VR Applications in Ecology

The application of VR technologies has become important for present and future design and planning activities. Advancement in science and technology has led to an extensive use of VR to solve a variety of problems in different fields such as ecology, hydrology, and environmental planning. Introduction of multi-dimensional visual displays of the proposed scheme can help in enhancing clarity and understanding of the phenomena by scientists, resource planners, and policy makers.

Sidjamin (1998) developed a design support tool for cognitive mapping, analysis, design, and evaluation of an urban environment. The design tool generated a computer-based urban environment that helped to identify problems within city sites. The campus area of Delft University of Technology was visualized using VR technologies. The world coordinates for buildings were maintained while constructing the virtual scene. An interactive mode of navigation was embedded into the scene. Users could interact with the virtual model by flying or walking through it. This VE was used to enhance urban planning.

Qi et al. (2004) developed a virtual forest environment for collaborative forest resource management. Multigen Creator (version 3.5.1) was used to create 3D terrain. Vegetation (mainly trees) was created with help of IMAGIS software (Supresoft). VRML language was used for publishing the 3D environment on the World Wide Web. The goal of the collaborative virtual forest was to enable users to participate, in different places at

the same time, to navigate, query, select, and label through the environment and communicate with each other at same time.

Wang et al. (2002) used VR techniques for designing virtual scenes for the Institute of Remote Sensing Application (IRSA), based in Beijing, China. The real-time visualization of a 3D urban environment provided effective interactive planning, designing, and evaluation for planners and decision makers. The virtual scenes provided users with visual realism and real-time navigation and interaction. While navigating through the virtual scene, a user could identify existing problems and could quickly evaluate alternative solutions to those problems. Thus, as stated above, application of VR in ecology has the potential to provide planners, managers, and modelers with a tool that could assist them to make decisions while being immersed in the real-world environment.

2.6. VRGIS: Integrating VR and GIS

The integration of GIS and VR could lead to more refined analytical tools for the exploration of geographical landscapes. Traditionally, geospatial data analysis, such as that available through the GIS, has involved static manipulation of two-dimensional (2D) thematic maps. Recently, however, a paradigm shift has emerged—a shift towards dynamic simulation and immersive visualization of large volumes of geospatial data representing several aspects of human-environmental phenomena. The rapid advances in computer technology have not only enabled manipulation and simulation of 2D phenomena, but have also facilitated dynamic visualization of results in multi-dimensional immersive environments. In order to make GIS a more usable tool, the linkage of VR with GIS has attracted attention of the GIS community. VRGIS includes

the concept of VR functions (navigation, color, symbolization and dynamic elements) and geometric-based GIS functions (measurement, analysis, and comparison) (Sidjanin, 1998).

The development of a VR in GIS involves how the GIS users use GIS and how they think of GIS. The functional integration of GIS and VR tools would enable users to spatially visualize and manipulate data. For example, the GeoVista Center at Pennsylvania State University is working on different projects associated with combining GIS and VR. Example projects include the Dialogue Assisted Visual Environment for GeoInformation (DAVE_G), the Human Environment Regional Observatory. DAVE_G (Pennsylvania State University) focused on developing principles for implementing and assessing natural, multi-modal, multi-user dialogue-enabled interfaces for GIS that made use of large-screen displays and VE technology. Specific HCI goals for research were to achieve natural, human-centered interfaces for complex information systems and to facilitate a two-way dialogue between the computer and the user. Through the dialogue-enabled interface, DAVE_G supported effective decision-making about public safety and health risks (and responses to those risks) and provided input to important public decisions made by a wider range of participants.

The integration of GIS with VR technologies (VRGIS) has also attracted the attention of scientists and resource planners. The accurate depiction of environmental features and phenomena within multi-dimensional GIS framework adds a new dimension to the simulations of real-world situations. The relationship between people and the land has always been an important issue for public and private land use planners and for decision makers (Sidjanin, 1998). The human-environment relationship is based on how

individuals respond to their environment and on their perceptions and interpretations of

the environment, which depend on their previous experiences (Sprout and Sprout, 1965).

, At the same time, proper visualization of the scene and all data related to the scene

increases understanding and decision making (Hearnshaw, 1994). Navigating through a

virtual world or synthetic environment provides proper visualization, and GIS is a tool to

add spatial data within the scene. VRGIS can be used as an important tool for providing

visual realism to ecological problems (e.g., land use management, landscape planning,

and urban planning) and interacting with them in natural and realistic ways, such as with

gestures, voice, and even with keyboard, mouse, and wand. Today, hydrologist and

environmental scientists use VRGIS to address a wide range of eco-hydrological

problems including flood management and forecasting, climate change induced by

unsustainable land use practices, and water pollution from chemical application.

CHAPTER 3. MATERIAL AND METHODS

This chapter begins with a discussion on the geospatial system used in the research for acquiring, manipulating, displaying, and analyzing the spatial data related to land use and land cover change. Next, VR technologies, including the range of available immersive and interactive virtual system environments, are described. Finally, this chapter ends with the documentation on creating VE for evaluating land cover dynamics.

3.1. Geospatial Data Exploration System

Geospatial data analysis and display systems are important component of scientific visualization, as they enable users to gain new understanding and insight into the data in ways that were previously impossible. Visualizing large amounts of data is one of the most attractive and useful capabilities of GIS. Defined earlier as a computer-based system for gathering, storing, analyzing, and displaying spatial or geo-referenced data, a GIS enhances the spatial exploration of data in a multi-dimensional environment. Data and information can be presented in the form of maps, images, 3D views, and charts. New variables can be derived by combining basic mapped variables with their spatial data attributes. For example, in analyzing the spatial dynamics of land cover change, the geo-processing capabilities of the GIS allow the derivation of maps that depict the spatio-temporal effects of human decisions.

3.2. Desktop GIS

The ArcGIS is a desktop geographic information system developed by Environmental System Research Institute (ESRI) of Redlands, California. ArcGIS is the

primary software used in this research. ArcGIS is an integrated collection of GIS

software products for building user-desired applications. It enables users to utilize

extensive GIS functionality in the form of desktops, servers, or custom applications. The

ArcGIS desktop provides the primary platform to analyze, store, and display geospatial

data. These spatial data are stored in the form of features, rasters, and coverages, along

with information describing the data. The descriptive spatial information for features and

rasters are stored in geo-databases and can be accessed through their attribute tables.

Features and their attributes are linked and managed interactively as layers. Each layer is

described according to the shapes of geographic objects (i.e., polygon, line, or point).

The ArcGIS desktop provides a suite of products that create, edit, import, query,

analyze, and publish geographic or spatial data. It consists of ArcView, ArcInfo,

ArcEditor, ArcReader, and various ArcGIS extensions. ArcView enables users to

explore, analyze, and visualize spatial data to reveal underlying and hidden patterns,

relationships, and trends. ArcInfo provides an environment for building a comprehensive

desktop GIS. It provides tools for data integrity, management, visualization, spatial

modeling, analysis, and advanced cartographic functions. ArcEditor provides advanced

editing, data visualization, and data management tools that assumes data integrity.

ArcReader allows users to view, explore, and print maps. It also provides simple tools to

explore and query maps. ArcGIS desktop extensions, described below, provide additional

functionality for such tasks as raster geo-processing.

3.2.1. GIS Extensions

3.2.1.1. Spatial Analyst

ArcGIS Spatial Analyst Extension, fully integrated into the ArcGIS desktop, allows users to (1) create, query, and analyze cell-based raster data and perform integrated raster/vector analysis, (2) query information and derive new information from existing raster data, and (3) generate information related to terrain, hydrology, and suitable sites based on raster processing of multiple attributes. It is used in different fields such as agriculture, geology, meteorology, hydrology, archaeology, forestry, healthcare, mining, real estate, and many others. Environmentalists use Spatial Analyst to analyze water quality by using a landscape modeling approach. Complex terrains, based on digital elevation models (DEM), are analyzed with the Spatial Analyst Extension to enhance determination of flow direction grids, flow accumulation grids, and pollutant loading grids for expected mean concentration modeling. Hydrologists and environmental scientists, in turn, use these grids to model flow using various raster inputs such as precipitation, temperature, elevation, stream gradient, and drainage area for delineated watersheds. Various hydrological models are based on cell-based raster data sets. These models use principles of ArcGIS Spatial Analyst Extension to analyze the flow and trends for spatial modeling.

3.2.1.2. ET GeoWizards^{TM}

ET GeoWizards™, developed by ET SpatialTechniques is a set of powerful functions that enable ArcGIS users to manipulate data with significant ease and a user-friendly interface. It enables the ArcGIS users to perform some data processing functions

with just ArcView licenses, which are currently available only in ArcEditor and ArcInfo. The surface functions in ET GeoWizards^{TM} allow 3D analysis in ArcMap without the use of the ArcGIS 3D Analyst Extension. Users can modify and analyze their spatial data through (1) a user-friendly wizard-like interface, (2) user scripts written in the ArcGIS VBA environment, and (3) a set of tools for ArcToolbox (ArcGIS 9.0 or above) that can be used in the Model Builder, Command Line, Python, Java, or VB scripts. The primary targets of the software are the ArcView license holders.

3.3. Virtual Immersive Environment

An immersive environment can be defined as a synthetic, simulated, or artificial environment designed by humans to represent the real world, with which they can interact and manipulate objects through different forms of input devices. Users can travel within this synthetic environment and interact by grasping and manipulating simulated objects. Rheingold (1991) has defined a VE as an experience in which a person is "surrounded by a 3D computer-generated representation, and is able to move around in the VE and see it from different angles, to reach into it, grab it, and reshape it." In a fully immersive VE, users feel that they are truly present in the real world and that their experiences in the virtual world match those in real world. In the past decade, VEs that allow real-time visualization of ecological and geospatial data have been the subject of attention. Visualization has become an important part of GIS application. The multitudinous demands of visualization and interaction are no longer satisfied by general-purpose GIS. The inherent geospatial capability of GIS software to accurately map feature position has led to the application of GIS in different fields such as urban

planning, environmental sciences, business, and homeland security. In order to generate real time VEs, VR technologies are incorporating GIS as a primary tool to capture, manipulate, and store spatial information. VEs use a variety of VR technologies to enable users to interact with the simulation system, which encompasses visual, auditory, and touch interaction. The following section describes the most common types of VR display systems.

3.4. VR Systems

Immersion is the key issue in VR systems, as it is central to the paradigm where the user becomes part of the simulated or virtual world. There are three different forms of VR systems defined by the quality of the immersion. The following sections describe the commonly used VR immersive systems. The first and by far the most common is low-immersive desktop VR.

3.4.1. Low-Immersive VR Systems

The basic type of VR system can be defined as a desktop-based lower-immersive system. This is the least expensive and most commonly used system, which is comprised of a graphics workstation, an emitter, and stereoscopic glasses. The traditional computer system is supplemented with advanced graphics card to view stereo images. This system has the advantage of switching the display from monoscopic to stereoscopic view, but it provides a limited sensation of immersion. Figure 6 shows a low-immersive desktop-based environment.

Figure 6. Desktop-based VR system (PS-Tech)

3.4.2. Medium-Immersive VR Systems

A medium-immersive VR system consists of a high-resolution screen with a head tracking device that tracks the head position of the user. The user movement is tracked and the scene is synthesized according to the position of the user. This system provides users with a feeling of being slightly immersed by the VE. The mostly commonly used medium-immersive devices include the workbench or tabletop display, the reach-in display, and the power wall.

The workbench is a single-screen projection system display that provides high resolution and stereoscopic and head-tracked images. Multiple users can simultaneously view and interact with the scene. A greater sense of immersion is created by projection on a large screen, which provides a larger field of view. Figure 7 shows a BARCO workbench environment used at Iowa State University (ISU) in Ames, Iowa.

Figure 7. Workbench display system (Barco)

3.4.3. Highly or Fully Immersive VR Systems

The fully immersive system completely immerses the user's viewpoint in the

virtual world. Suitable examples of this type of system are the head-mounted display

(HMD) and CAVE (Automatic VE).

3.4.3.1. Head-mounted displays

A HMD is comprised of two portable viewing screens that add depth to flat

images. As the name suggest, these display are mounted on the head and housed inside a

helmet to be worn by the user. The viewer wears this helmet and looks through two

lenses at a viewing screen. Two different images are displayed on the screen for the same

view; one image is displayed as seen through the right eye and the other is displayed as

seen through the left eye. These two images at parallax (i.e., change of angular position

of two stationary points relative to each other as seen by an observer, due to the motion of

an observer) are fused together by the brain to view the a 3D image. In order to track the

movement of the user's head, a tracker is mounted on the helmet to send signals to a

stationary tracking device. The perspective view on the screens is updated as the user

moves his head forward, backward or sideways. Figure 8 shows a HMD system.

A high frame rate and synchronized stereo frame display provide better

immersion with a HMD. The weight of the helmet causes physical discomfort and also

restricts the natural movements of the user. Since usage of this system is restricted to a

single person, it cannot be used by a group of persons to interact inside a single

environment.

Figure 8. Head-mounted display system (VRealities)

3.4.3.2. The CAVE

CAVE is a projection-based VR system that was developed by Dr. Cruz Neira,

Dr. Daniel Sandin, Dr. Thomas Defanti, and staff of the Electronic Visualization

Laboratory (EVL) (Vrealities). It was first demonstrated at the 1992 SIGGRAPH

conference. In CAVE, multiple users can simultaneously interact within the virtual world.

The ISU has two CAVEs, named C4 and C6.

3.4.3.2.1. C6 immersive VR system

The C6 is the most advanced CAVE technology. It is a 3D full-immersion synthetic environment. This system is comprised of four walls, a floor, and a ceiling that all act as projection screens which are capable of displaying back-projected stereoscopic images. The ISU C6 has a 3.048-meter by 3.048-meter by 3.048-meter area surrounded by stereoscopic projection surfaces on all six sides. It provides a fully immersive environment for the user to navigate and interact with the virtual world.

The C6 uses a wireless tracking system to update the perspective view on the screens relative to the user movements. The user's position is tracked by the sensors attached to the glasses and wand. Wireless LCD shuttering glasses are used for viewing VE in the C6. Figure 9 shows a sketch of the C6 environment.
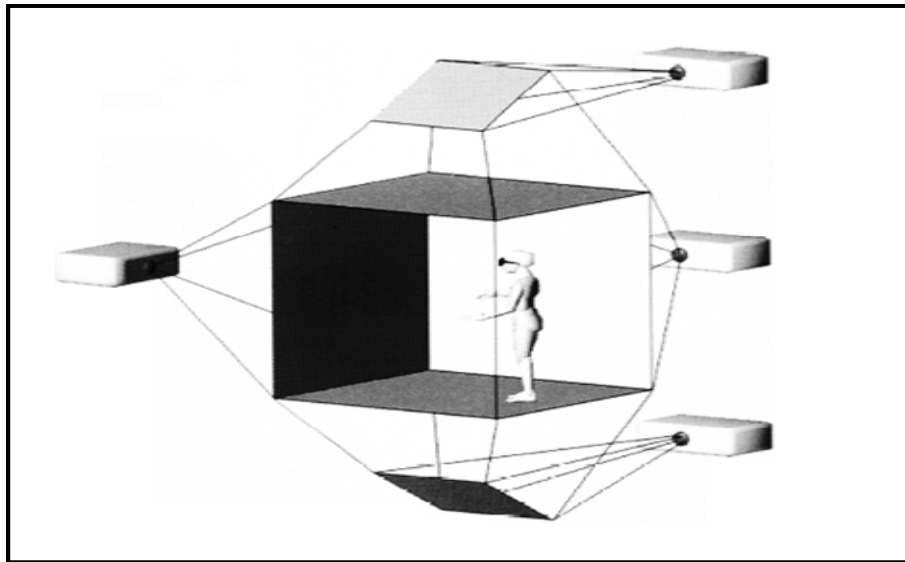
Figure 9. C6 immersive VE (Neira et al., 1992)

3.5. Development of the Desktop-Based Immersive Environment

This section discusses the development of a VE for land use dynamics. The major

component and steps required to accomplish the research goal are described below with

the help of a schematic diagram (see Figure 10). For this research, a VE is developed for

the UMRB and Lower Des Moines River Basin as an example application.
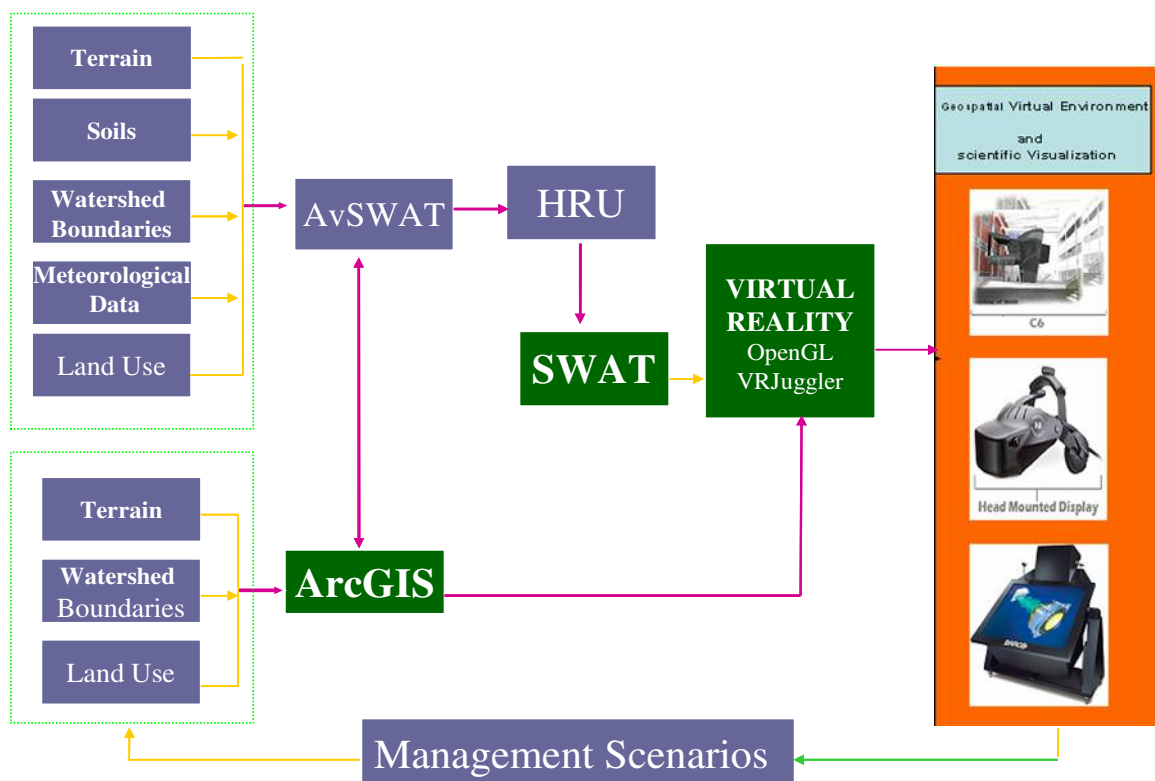

Figure 10. Schematics of modeling framework

3.5.1. Data Acquisition

The primary datasets that are required for building this VE are (1) a DEM or

terrain data, (2) land cover data, and (3) other ecological datasets such as stream flow,

sediments inflow, and nitrates inflow. These data sets were downloaded from different

GIS data warehouses. The data used in this application were downloaded from the U.S. Geological Survey (USGS), Iowa Department of Natural Resources (DNR) and National Water-Quality Assessment program (NAWQA) websites. The data downloaded from these websites were projected into the same coordinate system mentioned in the metadata. GIS is used as a tool to analyze, display, and manipulate the spatial data according to the requirements.

3.5.2. DEM Processing Using ArcHydro

A DEM is the key data set required for ecological modeling and building the virtual terrain. DEM can be defined as a data file consisting of a set of regularly spaced X, Y, and Z coordinates for a topographic surface, where Z represents elevation. The DEM data set is preprocessed by using ArcHydro tools before being used as a base data set for virtual terrain. ArcHydro does this processing step by step. The steps in terrain processing include filling topographic depressions to map water flow. These depressions are called sinks and are natural occurrences in the landscape. GIS uses cell-based calculations for filling these sinks. ArcHydro is a GUI-based tool which is incorporated in ArcMap. The terrain processing is accomplished by choosing options from a pull-down menu. These options include filling sinks, calculating flow directions and flow accumulation, stream definition, and stream segmentation for delineating watershed. Figure 11 shows a pull-down menu for ArcHydro toolbar.
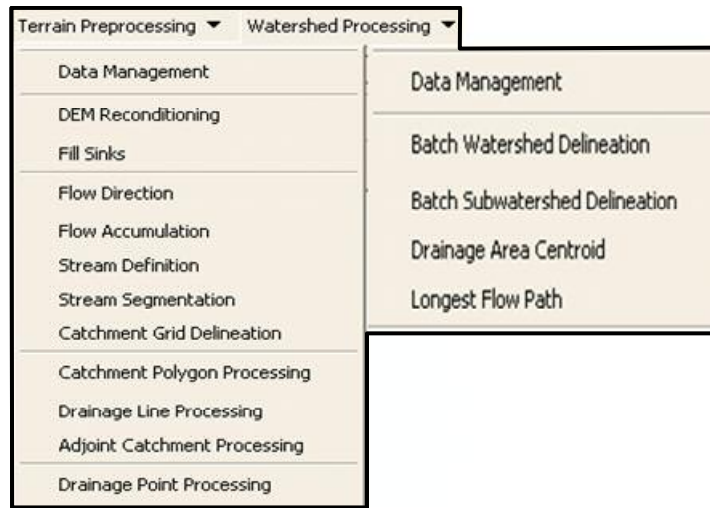
Figure 11. ArcHydro toolbar menu

Sinks are assumed to be errors in the DEM data. These errors are in the form of very low elevation values relative to the surrounding cells. Sinks are filled by raising the elevation of the pit cells so it is equal to the elevation of the lowest point of the surrounding cells. It is necessary to fill the sinks before getting flow directions, because water gets caught in these depressions and doesn't flow to the river, which gives errors while calculating flow accumulation and flow direction. Sinks are filled by clicking on "Fill Sinks" in the Terrain Preprocessing pull-down menu. The raw DEM is added as input for processing. By default, it will pick the DEM from the open map document. The output of Hydro DEM is "Fil" as shown in Figure 12. Select "OK" to continue processing.
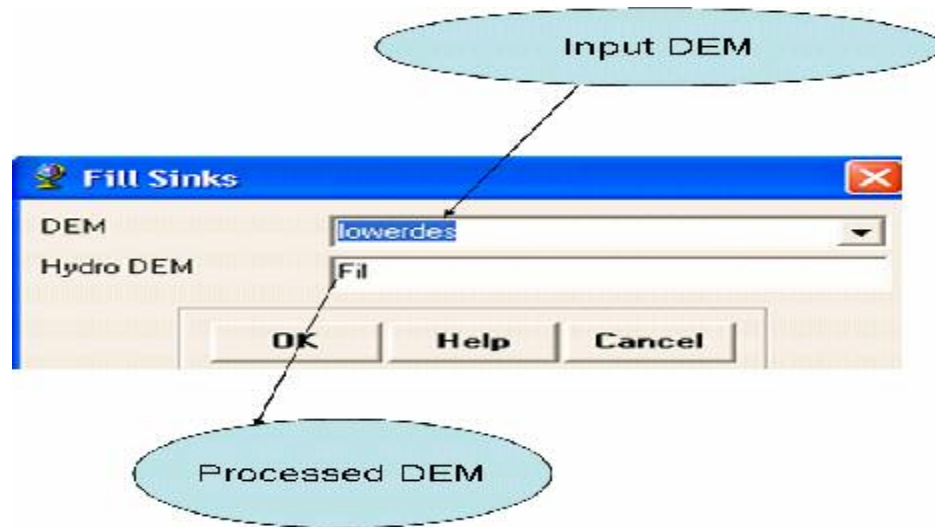
Figure 12. Filling sinks in ArcHydro

The next step is to determine flow direction, which is further used to find flow accumulation. The flow direction is defined as the direction in which flow moves to one from the eight neighboring cells (the D8 model) based on the cell that has the steepest slope. This is done by selecting "Flow Direction" in the Terrain Preprocessing pull-down menu and then inputting sink-filled DEM as "Hydro DEM" for processing. The user can then select "OK" to continue the processing, as shown in Figure 13.

Figure 13. Flow direction dialog in ArcHydro

The "Flow Accumulation Grid" is created by an accumulation of cells upstream of each cell (see Figure 14). After determining the "Flow Accumulation Grid," the next step is obtaining the stream definition. A selected minimum threshold value is used to

identify the stream network. This threshold value defines the number of cells that are

contributing to single cell to form a stream (see Figure 15). This is accomplished by

selecting "Terrain Preprocessing," then the "Stream definition" option and providing the

"Flow Accumulation Grid" as input.
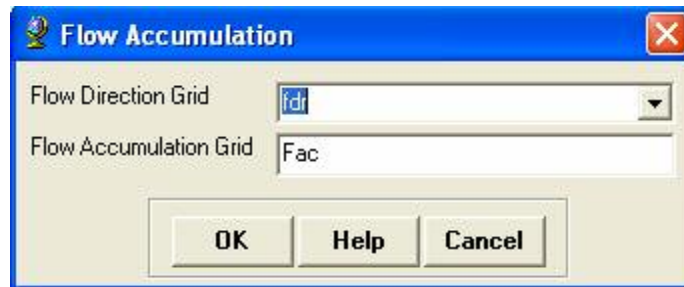
Figure 14. Flow accumulation dialog box
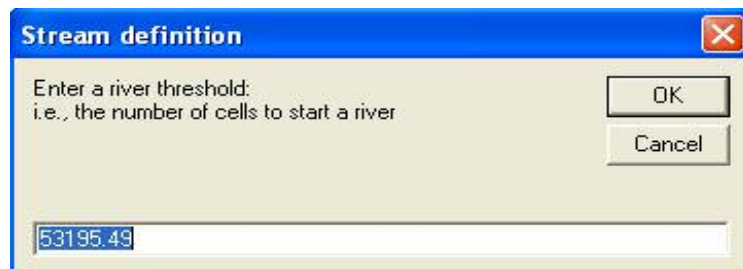
Figure 15. Stream definition dialog box

The next step is stream segmentation, which converts the stream into a vector

representation from the grid. This step is required for catchment grid delineation. The

catchment grid delineation can be defined as dividing the watershed into various sub-

basins based on topographic and hydrographic characteristics of the catchment. This is

done by selecting "Catchment Grid Delineation" from the Terrain Preprocessing pull-

down menu and providing input for the Flow Direction Grid and Stream Segmentation

Grid. The output from this processing (see Figure 16) is a catchment grid, as shown in

Figure 18.
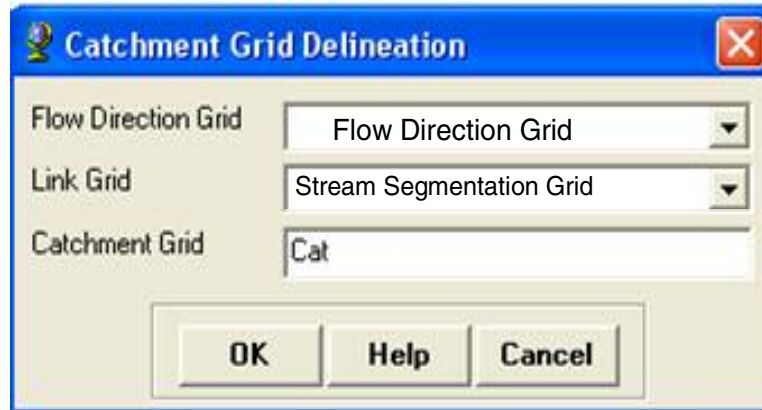
Figure 16. Grid delineation operation menu in ArcHydro

In order to covert this grid format into vector representation, polygon processing

is done on the watershed grid. The input for the watershed polygon processing is the

watershed delineation grid, which is converted into a shapefile representing the

delineated watershed. Figures 17 and 18 show the watershed delineation process and a

typical example for a delineated watershed, respectively. The Terrain Preprocessing tool

in the ArcHydro toolbar delineates the catchment area into sub-basins, which further

enhances the profound watershed analysis.

Figure 17. Watershed delineation operation
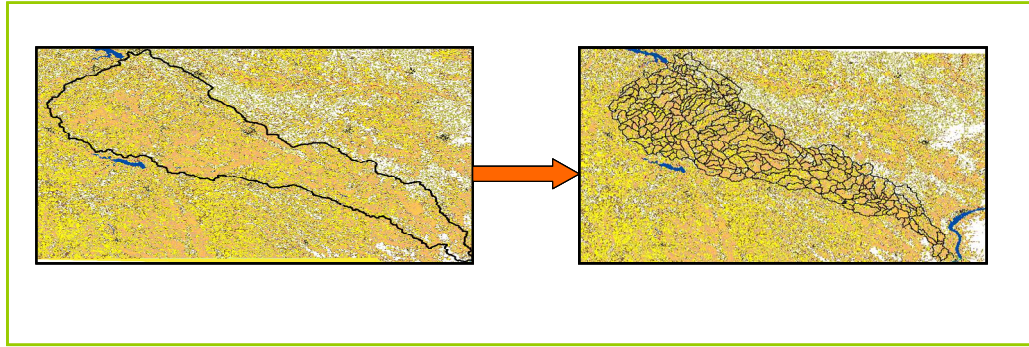
Figure 18. Typical example of a delineated watershed

3.5.3. Converting Grid to XYZ Text File

Virtual terrain is generated by connecting the X, Y, and Z values for a point. These X, Y, and Z values are obtained from the preprocessed DEM. The ArcGIS Spatial Analyst Extension is used to convert a 1000-meter by 1000-meter DEM to X, Y, and Z data. The first step is accomplished by setting up a mask of a concerned area. This is done by selecting Spatial Analyst→Options→Analysis mask (see Figure 19). The next step is to set up the cell size and the extent (meter) equal to the preprocessed DEM (see Figure 20).
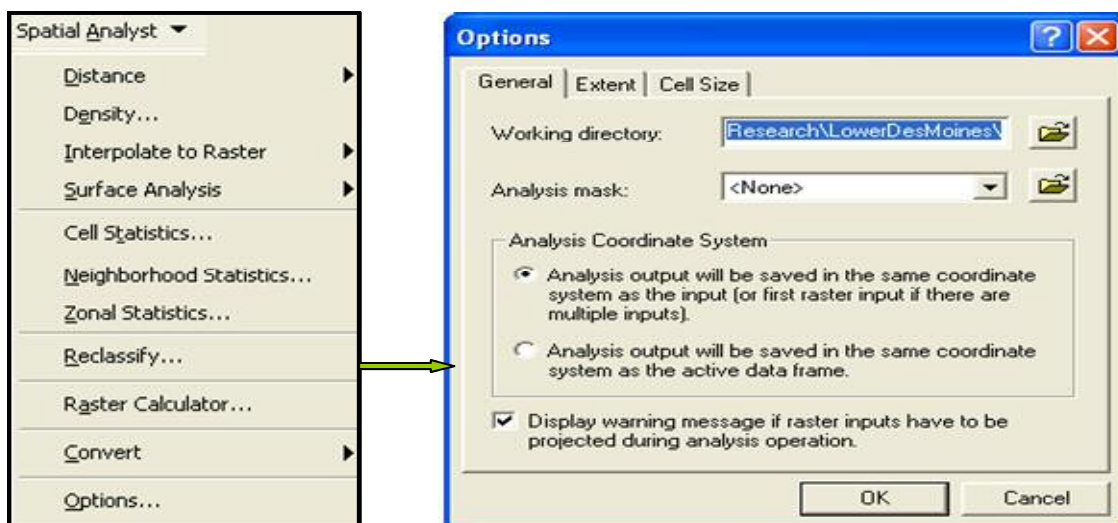
Figure 19. Setting the mask for analysis in Spatial Analyst Extension
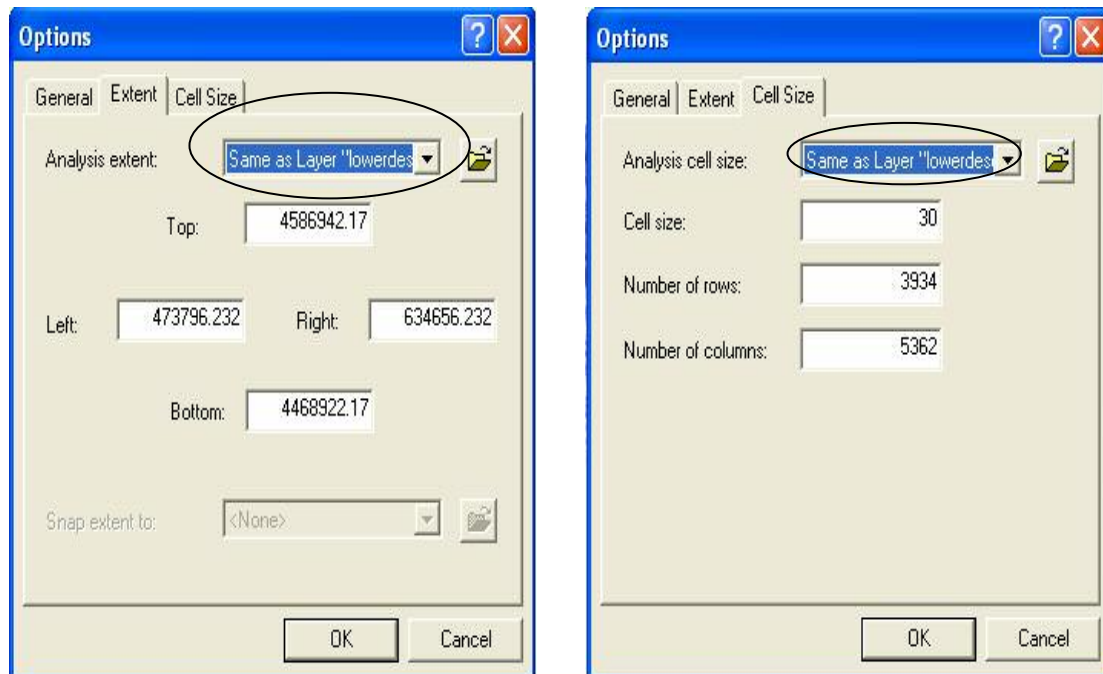
Figure 20. Setting the extent and cell size for analysis using Spatial Analyst Extension

After setting the properties for Spatial Analyst Extension, the Raster Calculator is used to calculate the X, Y, and Z values from the DEM. The Raster Calculator provides a geo-processing tool that enables users to convert data (e.g., converting a shapefile to a geo-database feature class), overlay data (by union or intersection of two or more datasets), extract data (by clipping a subset from the dataset), and manage data (by joining fields, and relating, merging, and dissolving datasets). The "SAMPLE" command (ESRI, Redlands, California) in the Raster Calculator converts cell values to a XYZ text file. The input dataset defining the locations to be sampled can be an ASCII point file or raster. Output from sampling is a text file stored at the location defined in the Spatial Analyst toolbar, having three columns showing X, Y, and Z values (see Figure 21).
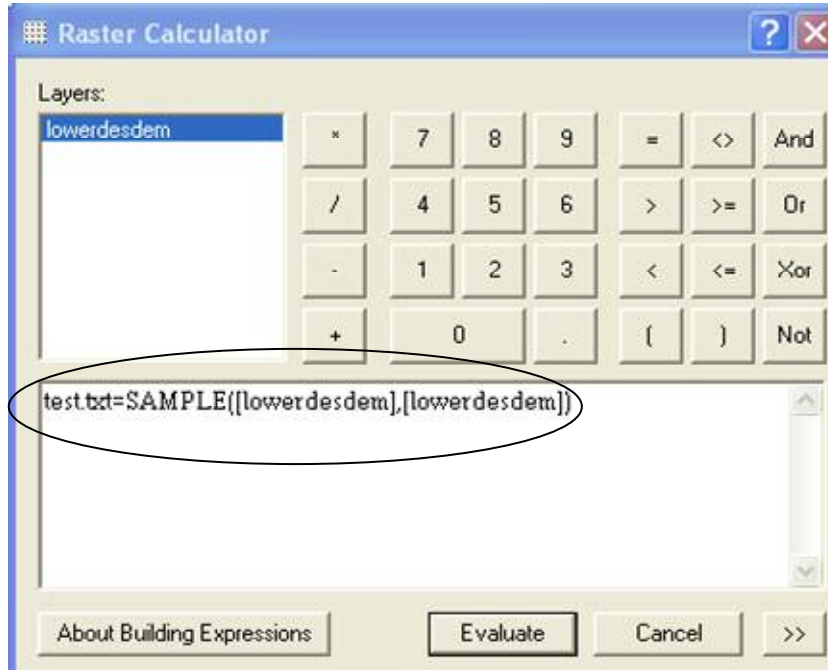
Figure 21. Converting DEM to X, Y, Z values using the Raster Calculator in Spatial Analyst Extension

3.5.4. Development of 3D Primitives

One main objective of my research involves the development of a 3D low-immersive desktop-based VE for ecological applications. The procedure for creating the VE is accomplished by using various libraries including OpenGL, Voce, GLUI, and GLUT programmed with C++. Each of these libraries and their roles in the VE are described below.

3.5.4.1. OpenGL

Open Graphics Library (OpenGL) is an Application Programming Interface (API) for the development of 2D and 3D graphics applications. OpenGL was developed by Silicon Graphics and has found popular applications in games and virtual interactions. It is widely used for developments in Computer Aided Designing (CAD), VR, and scientific visualization. Coupled with graphics hardware, OpenGL consists of about 250

commands that can be used for drawing geometric primitives and specifying operations

to produce interactive 3D objects. These geometric primitives are developed into

innovative application by incorporating rendering, texture mapping and orientation by

using OpenGL. Scientists and developers can apply OpenGL in diverse fields for the

development of a wide range of innovative and immersive applications to boost research

and development processes.

3.5.4.2. GLUT

GLUT is a Windows-based system-independent OpenGL Utility Toolkit designed

for writing OpenGL programs. It is a simple windowing API for OpenGL. GLUT makes

it considerably easier to learn about and explore OpenGL programming. GLUT provides

a portable API for writing a single OpenGL program that is platform independent.

GLUT is designed for constructing small- to medium-sized OpenGL programs.

GLUT is simple, easy, small, and well-suited to learning OpenGL and developing simple

OpenGL applications; however, it is not a full-feature toolkit. Large applications

requiring sophisticated user interfaces are better off using native window system toolkits.

The GLUT library exists with C, C++, FORTRAN, and Ada programming bindings and

its source code distribution is portable to nearly all OpenGL implementations and

platforms. This GLUT toolkit supports the following functionality: (1) support OpenGL

rendering multiple windows, (2) event processing through callbacks, (3) a variety of input

devices, including keyboard, mouse, tablet, dial and button box, joystick, and space ball,

(4) an "idle" routine and timers, (5) support for creating simple, cascading pop-up menus,

(6) facility to generate various solid and wire frame objects, (7) support for bitmap and

stroke fonts, and (8) additional functionality provided by GLUT includes window

management functions, resizing of dynamic video, and full-screen support for game-oriented applications.

3.5.4.3. GLUI

GLUI is a GLUT-based C++ user interface library that provides controls such as buttons, checkboxes, radio buttons, and spinners to OpenGL applications. Being platform independent, GLUI relies on GLUT to handle all system-dependent issues, such as window and mouse management. Features of the GLUI User Interface Library provide

- incorporation with GLUT toolkit,

- creation of a new user interface window, and

- multiple user interface windows.

Standard user interface controls include buttons, checkboxes, radio buttons, editable text boxes, spinners, static text fields, panels, and separator lines. These controls can generate callbacks when their values change, and variables can be linked to controls and are automatically updated when the value of the control changes (i.e., live variables).

3.5.4.4. Voce

Voce is a speech synthesis and recognition library that was developed by Tyler Streeter at ISU's VR Application Center in Ames, Iowa (Voce). This is a cross-platform library which is accessible from Java and C++. A set of static methods is used to initialize Voce, which gives users access to the main speech interaction components. These methods are exposed to other programming languages through the Java Native Interface. This library has an ability to recognize and synthesize speech. In order to synthesize speech, Voce takes strings of text from applications and passes them to freeTTS

synthesizer (a free open-source speech synthesis library) which converts these strings to audio output. Then, a microphone from Sphinx4 (an open-source speech recognition library) listens to incoming audio data from the user's audio hardware and constantly processes this data, adding recognized strings to an internal queue that can be queried by application. The recognized strings are queried from grammar files. There are 120,000 words in the entire dictionary, but since most of the applications use a small subset, these grammar files are application-specific and are written by an application developer. Voce is an open-source library that provides a conceptually simple architecture to develop applications for speech synthesis and recognition.

CHAPTER 4. EXAMPLE APPLICATION

This chapter describes the developing of a VE for investigating land use and land cover dynamics in the Lower Des Moines River Basin area which is encompassed within the Upper Mississippi River Basin (UMRB). The chapter begins with an overview of the study area chosen to develop this VE and discusses the existing environmental problems arising from the changing land use in the study area. This is followed by the steps and procedures involved in developing the low-immersive desktop visualization environment and the medium-immersive environment for exploring land use changes. The chapter concludes with a discussion on the results obtained by using VE.

4.1. UMRB

4.1.1. Characteristics of UMRB

As shown in Figure 22, the UMRB is located in the north-central region of the United States. It extends from the source of the river at Lake Itasca in Minnesota to a point north of Cairo, Illinois. The entire UMRB covers a drainage area approximately 491,700 km^2. The Upper Mississippi River flows roughly 2,092,147.2 m through Iowa, Wisconsin, Minnesota, Missouri, and Illinois, draining an area approximately 489,507.7 km^2. Most of the regions in this basin are under intensive agriculture, with 60% in cropland or pasture (Umbria). Due to the high percentage of cropland, the UMRB has been implicated as the primary source of nitrate entering the Gulf of Mexico. An excessive amount of nitrate load exported from the UMRB is believed to have led to the depletion of seasonal oxygen concentration in the Gulf of Mexico, a condition referred to

as hypoxia. This hypoxic zone occupied up to 20,000 km^2 of the Gulf of Mexico in 1999

(Rabalais et al., 2002) and is continuously growing. Most of the nitrate load is accredited

to nonpoint sources.

Figure 22. UMRB and Lower Des Moines watershed

Agriculture is considered to be the main source of nonpoint source of nitrate-

nitrogen pollution. Runoff from rainfall or snowmelt picks up pesticides, fertilizers, and

pollutants resulting from human activity from these croplands and transports them into

the Mississippi River. Goolsby et al. (1999) estimated that UMRB discharged 39% of the

total Mississippi nitrate load into the Gulf between 1980 and 1996. About 35% of the

total load originated from tributaries in Iowa and Illinois (Goolsby et al. 2001). Despite

Iowa occupying less than 5% of the UMRB's drainage area, it contributes about 25% of

the nitrates that the Mississippi River delivers to the Gulf of Mexico (Iowa DNR). The

nonpoint source pollutant export from the Iowa watershed has come under close scrutiny

(Iowa DNR). Therefore, in this study it was considered critical to examine the effects of

agricultural management within Iowa's primary watersheds on the export of nutrients to

the Mississippi River. Immersive visualization of the areas which are producing a high rate of runoff could provide those interested with a better basis for decision making and landscape planning. The visualization environment developed in this research is used to describe how to enhance the planning of best management practices (BMP) by using a low-immersive VE.

4.2. Application of a VE for Evaluating Land Use Dynamics for the Lower Des Moines Watershed

The VE developed in Chapter 3 consists of two main subsystems, namely the geospatial data processing system and the VE. This section describes the way these subsystems can be used to explore land use changes and their impacts in the UMRB and Lower Des Moines watershed. In order to develop this virtual system, a series of steps were followed. The first step was preprocessing data sets using geospatial data acquisition and processing systems. After this, the development of the VE is described in Section 4.2.3.

4.2.1. Geospatial Data Acquisition and Processing

Getting the data from different data warehouses was the initial step for creating this VE. The most important data sets for developing a VE are shapefiles, topographic data, land use, and soil. The topographic data was in the form of a 30-meter by 30-meter grid that was downloaded from the United States Geological Survey (USGS) website. This data was downloaded individually for the states of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. The land use data was also downloaded for all five states from the USGS website. The soil data (SURGO: Soil Survey Geographic Database), which is

prepared by the United States Department of Agriculture (USDA), was downloaded from

the Natural Resource GIS library of the Iowa DNR. The shapefile and other

meteorological (climatic) data were obtained by using Better Assessment Science

Integrating Point and Nonpoint Sources (BASINS) developed by the U.S. Environmental

Protection Agency.

Since topographic and land use data were downloaded separately for the five

states, the initial step was to combine all the datasets for different states into one raster

file. The Mosaic tool from ArcCatalog was used to combine the DEM and the land use

data for all five states. The next step of geo-processing operation was to clip the

combined data to the boundary of the Upper Mississippi watershed area. This was done

by using the Extraction tool from ArcCatalog. The data was extracted from the primary

data by using the mask as a shapefile for the concerned watershed (i.e., UMRB and

Lower Des Moines). Before extracting the data for the watershed, all the datasets were

projected into a common coordinate system. The data for UMRB was projected into the

GCS_NORTH_AMERICA_1983 coordinate system, and the projection coordinates for

Iowa were set to Universal Transverse Mercator (UTM) zone 15. After assigning the

projections, the data sets were stored in a database.

4.2.2. DEM processing for Development of Virtual Terrain

Creating the terrain was the major component in the VE. DEM coverage for the

U.S. Midwest was used for development of the UMRB terrain. In order to reduce the

memory allocation, the DEM was converted from a 30-meter by 30-meter grid to a 1000-

meter by 1000-meter grid by using the ArcGIS Spatial Analyst Extension. The 1000-

meter by 1000-meter grid was used for extracting X, Y, and Z data points using the
Raster Calculator as described in Section 3.5.3.

4.2.3. Development of the VE

This section describes the development of VE for investigating land management
issues. A 3D scene was generated using geometric primitives and textures. The geometry
and the texture data were acquired from different resources and were used to develop the
real-world scene using the methodology described earlier. OpenGL was used to organize
and to optimize the graphics in the VE. It provided many useful tools for development of
a complex scene. The application was build with C++, which provided object-oriented
coding. The desktop-based VE was designed to include the following aspects: (1)
displaying terrain, stream, and attribute data such as land use, (2) providing multimodal
interaction with an environment using a mouse, keyboard, and voice, and (3) displaying
outputs of modeling.

4.2.3.1. Developing geometric primitives for visualization

The geometric primitives can usually be constructed in two different ways: (1) by
using available 3D modeling software, such as 3D Studio-Max and Maya, or (2) writing
code using 3D graphic libraries. The first approach is considered to be much easier and
quicker. However, this approach provides limited approaches for interactive editing of
the component features inside the VR environment. The second approach involves more
work.; however, there is no compromise on actual representation of geo-referenced data
and information. Considering these issues, the second approach was chosen to create the
virtual scene.

OpenGL was coded using C++ to accomplish the development of the VE. All the geographic and geo-referenced data was represented as points, lines, and polygons in this 3D environment. The terrain for this VE was developed from the topographic data that existed in the grid format (DEM). The grid was segregated into spatial attributes (X, Y, and Z) using the Raster Calculator in the Spatial Analyst Extension, as described in Section 3.5.3 of Chapter 3. Each geo-referenced point was connected to the adjacent point to form the triangles. The "GL_TRIANGLES" function from the OpenGL library was used to form the wire mesh of triangles (see Figure 23). This wire mesh, having parameters of the location and elevation, resembles the original terrain for UMRB and Lower Des Moines (see Figure 24).
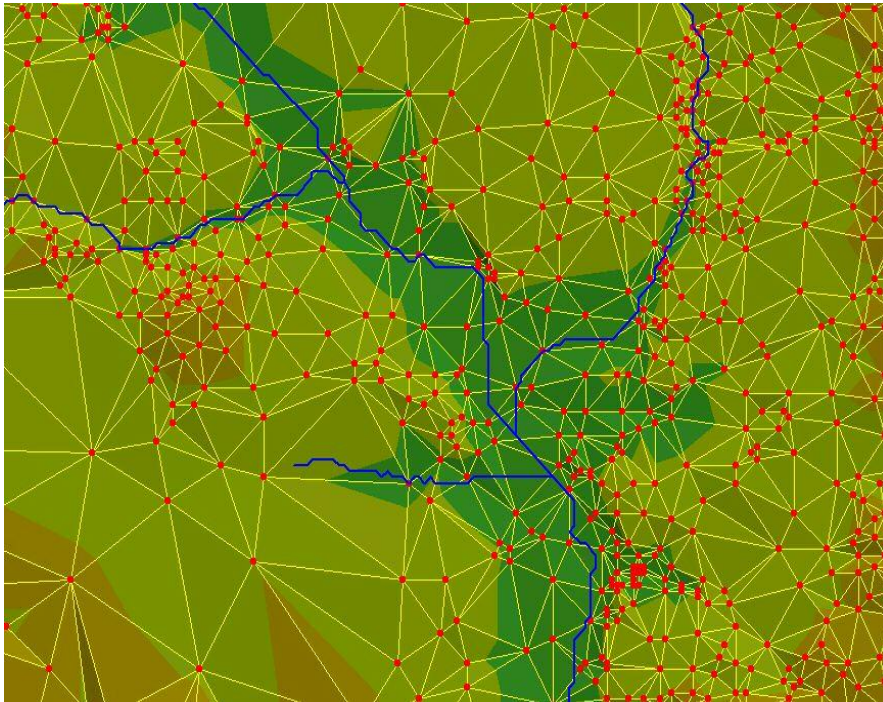
Figure 23. Generation of terrain using GL_TRIANGLES
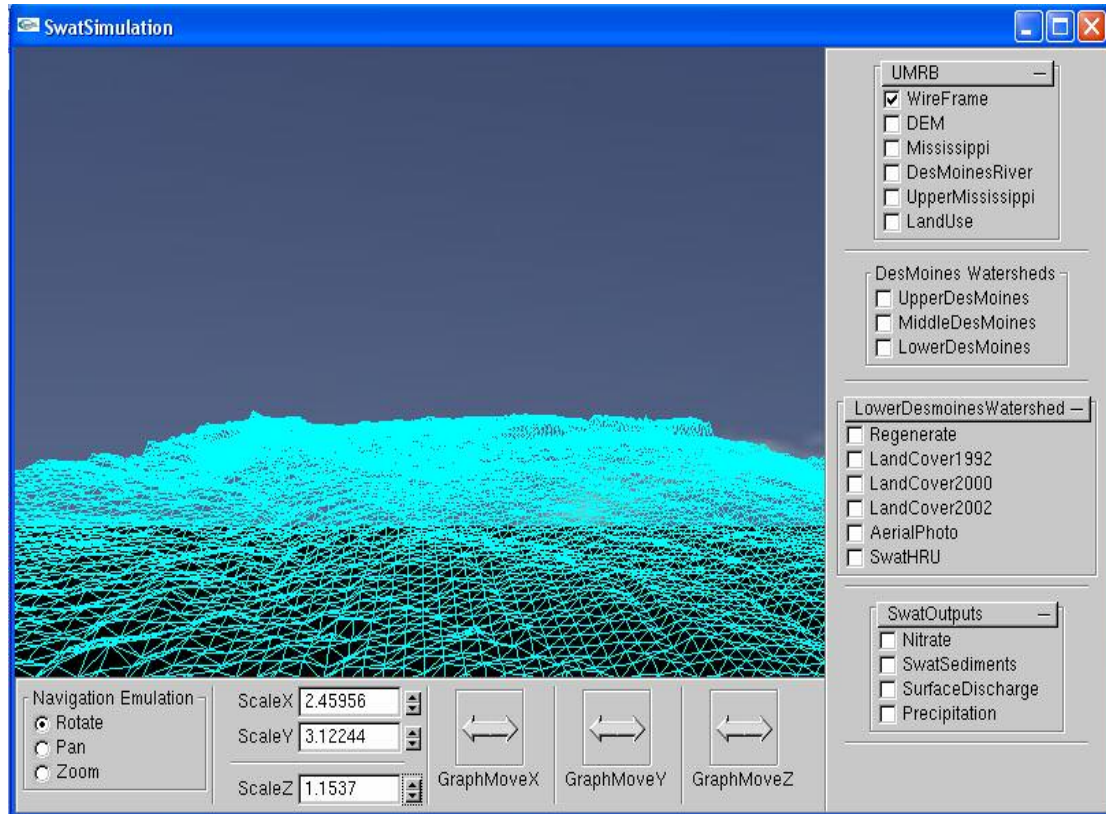
Figure 24. Wire mesh generation from spatial attributes (X, Y, Z)

The terrain generated from the X, Y, and Z points acts as a base for displaying other datasets such as land use, orthographic image, and stream data. These datasets were overlaid over terrain using texture-mapping techniques in OpenGL, as shown in Figure 25. The geo-referenced Mississippi and Des Moines Rivers were drawn over the watershed by converting the stream data (in vector format) from grid format to XYZ coordinates using the Raster Calculator.
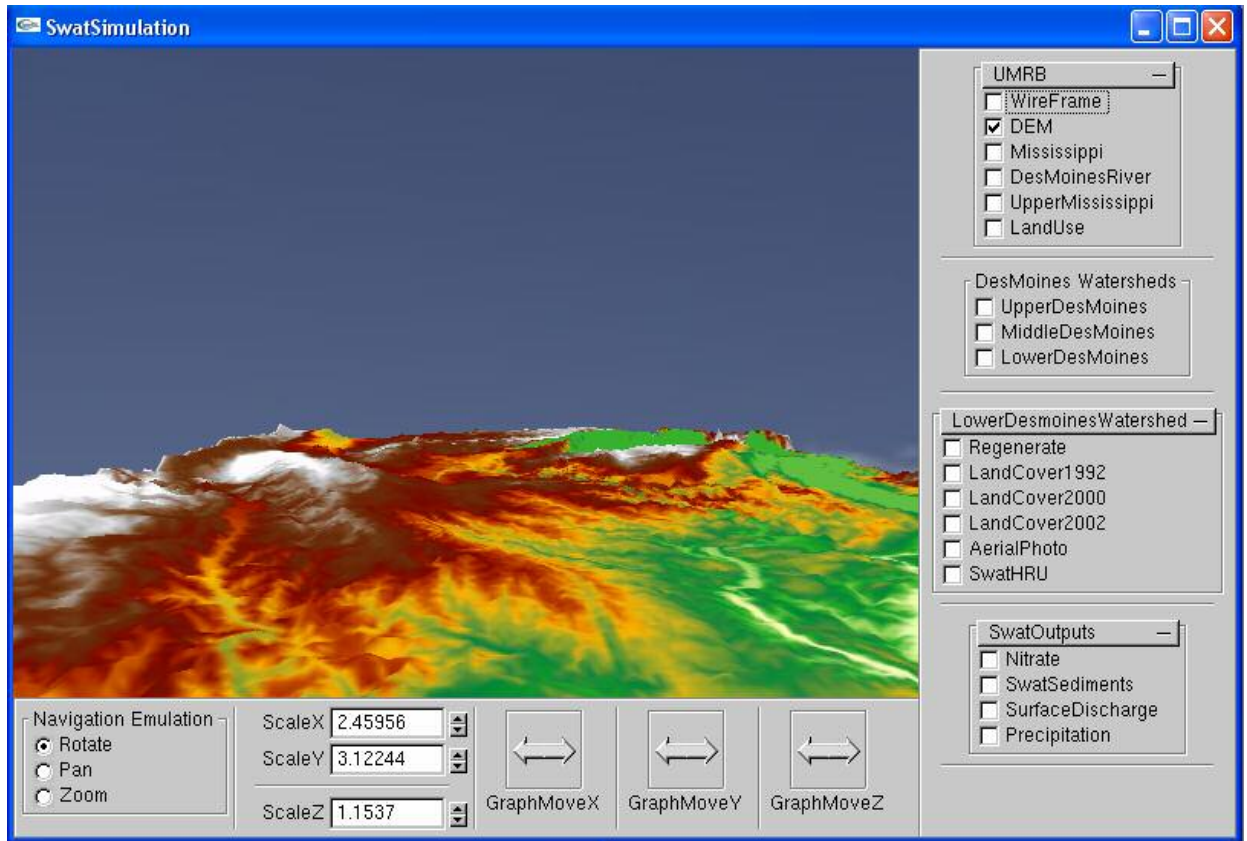
Figure 25. Development of terrain for UMRB

Another important feature in the VE was the UMRB watershed boundary, which was drawn by converting a shapefile (vector data) into a grid format and then converting the grid to X, Y, and Z values. After drawing the UMRB in VE, focus was shifted to the Lower Des Moines watershed area located in Central Iowa. The Lower Des Moines River and watershed area was drawn using the same procedure as described earlier. The major areas of concentration were the junction points where the flow from subbasins of the Lower Des Moines merges into the Des Moines River. An outlet point was chosen manually at the end of the watershed where discharge from all the subbasins of watershed was accumulated. This point was selected to have an idea of hydrologic contribution of Lower Des Moines to the Mississippi River. The graphs at the outlet gave the amount of

flow and chemical contribution by the Lower Des Moines watershed to the Mississippi

River, which is quite useful in understanding the influence of changed land use in Des

Moines on the Mississippi River.

In order to understand the changes in land cover and their effects on the ecology

of watershed, the original land use type was overlaid on the terrain. This was

accomplished by exporting the land use types as an image file (bmp) and texture mapping

them on the top of the terrain. Using a similar texture mapping technique, an aerial

photograph of the Lower Des Moines watershed was also texture mapped on the terrain

to give a realistic view of the watershed. The results obtained from the SWAT model for

the 2002 land use data were converted into text files. The bar graphs were created in the

VE by reading these text files and then drawing the graphs using OpenGL. The user can

then perform "what if" questions in relationship with the land use changes and its impacts

on the hydrology and ecology of the watershed, while still being immersed in a low- and

medium-immersive VE.

4.2.3.2. Visualization interfaces for land cover dynamics

Two visualization environment systems were developed according to the level of

immersion. The desktop visualization environment was developed so as to provide

planners and decision makers with readily available tools for investigating land cover

changes and their potential impacts on terrestrial and aquatic ecosystem. This was done

using the drawing routines of OpenGL and developing a user interface using GLUI and

GLUT libraries.

4.2.3.2.1. Low-immersive desktop-based visualization interface

The desktop visualization interface was developed using GLUI and GLUT libraries (see Figure 26). The terrain data, stream data, and graphs were drawn using techniques described in Section 4.2.3.1. GLUI and GLUT libraries were used to develop buttons, checkboxes, rollouts, and to provide interaction with the interface. The user was given a number of options to visualize different geospatial datasets. Other options provided to the user include navigation capabilities using mouse, keyboard, or voice. The user could pan, zoom in or out, and move left or right inside the scene using a keyboard, mouse, or his voice. Various "what if" analyses can also be performed inside the interface. The user can choose the land use type and then display the output graphs from SWAT to analyze changed land use patterns and their impact on the hydrology and ecology of the watershed.
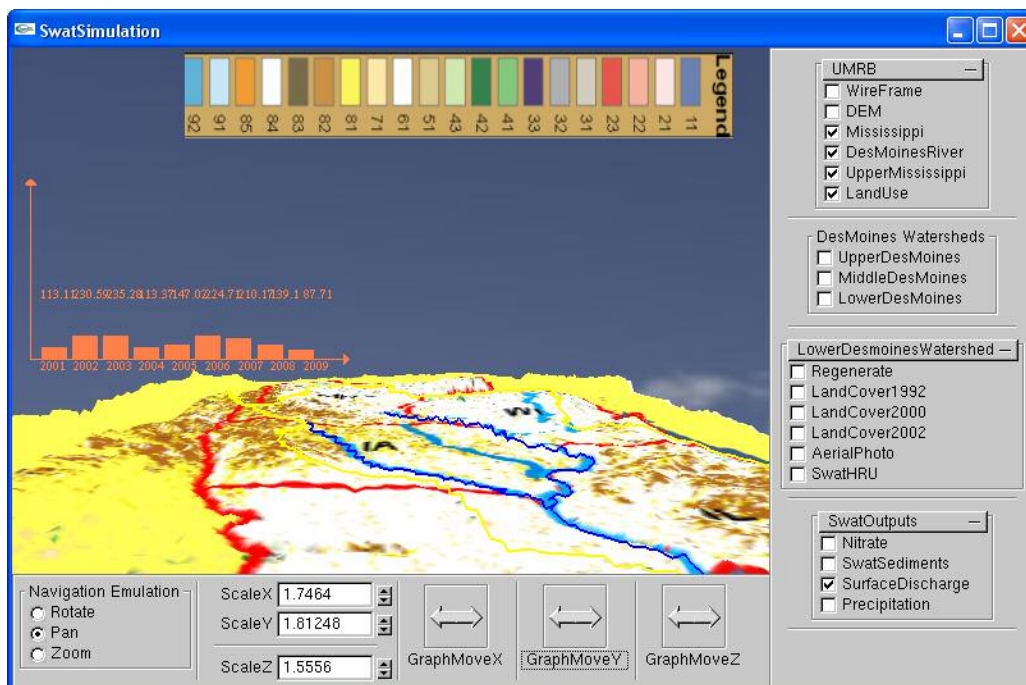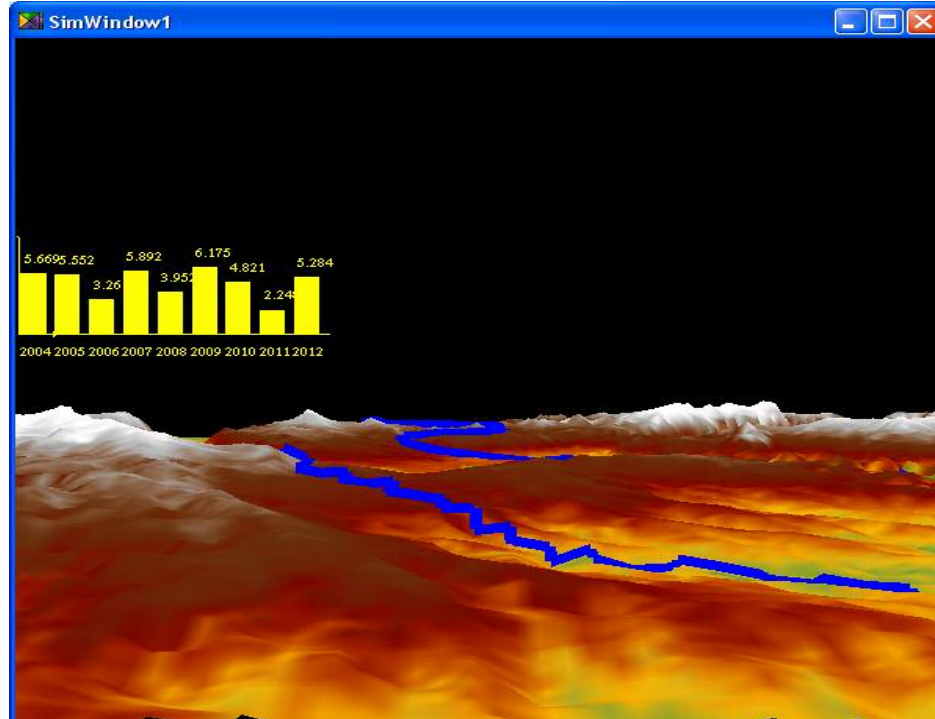

Figure 26. Hydrologic data analysis on the desktop-based low-immersive system

4.2.3.2.2. Medium-immersive VE

A medium-immersive environment was developed using a virtual workbench at ISU. VR Juggler was used to transfer the application to the workbench and to provide the user interaction inside a medium immersive environment. VR Juggler is a C++ class library that provides a platform for VR application development. This component allows a user to run an application on almost any VR system. Any application programmed with Juggler is extendable from simple desktop systems, like PCs, to complex multi-screen systems running on high-end work stations and supercomputers.

An immersive environment was developed for evaluating land use and land cover dynamics in the UMRB and Lower Des Moines watersheds. The main steps for the development of this VE included reading data files, loading textures in the initialization function, and optimizing the drawing and rendering of the geometric primitives in each frame. The data files that contained the geo-referenced geometric parameters for the drawings were obtained by using the Raster Calculator, as described in Section 3.5.3 of Chapter 3. These data files were stored as text files, and the values from these files were read and used to draw the geometric primitives, as described in Section 4.2.3.1 (see Figure 27).

Figure 27. Hydrologic data analysis on the semi-immersive system

CHAPTER 5. SUMMARY AND CONCLUSIONS

Humankind stands at the threshold of a new revolution in science, engineering, and technology. The rapid advancements in information technology, high-performance computing, and mobile and wearable technologies have not only provided the potential to increase the nation's productivity but also an infrastructure to address regional, national and global priorities, including the improved ability to (1) understand the impact of global climate change, (2) protect our natural environment, and (3) respond to the societal impacts of natural hazards. In the field of hydrological sciences, the combination of computing, information, and communication technologies have significantly enhanced the characterization of hydrological phenomena at various spatial and temporal scales and increased the level of user interaction with large volumes of hydrological data for improved and timely decision-making. In particular, VR technology and other tools for human-computer interaction have significantly enhanced the visualization of massive amounts of environmental data for assessing the interactions between complex human and natural systems.

This research focused on the development and implementation of a VE that combines disparate data and technologies to enhance the assessment of coupled human-natural systems. The VE was developed in this study using the SWAT and the geospatial tools and techniques of ArcView GIS (including Spatial Analyst and ArcHydro). ArcHydro and ArcView GIS were used to preprocess, analyze, and manipulate the datasets. The datasets created by the geospatial data processing system were used by the SWAT model to study hydrological and land use characteristics of the watershed. The

results produced by the model were then visualized on the desktop-based visualization

system and medium-immersive workbench environment. The Lower Des Moines

watershed was used as an example to explain the utilization of these VEs. The

visualization of spatial data for Lower Des Moines through these environments enhanced

decision making for this area, which has been prone to frequent land cover change in the

past few years and is also the area providing maximum loading to Des Moines River.

Development of this VE represents an example that is advanced from traditionally

static environmental modeling towards an improved infrastructure that supports dynamic

simulation modeling and visualization of complex environmental systems. Through this

VE resource, planners are able to perform almost all of the operations of a traditional

GIS-based environmental model within low- and high-immersive VEs, with better

control and added navigational abilities, including virtual fly-bys and zooming into a

particular area of the landscape to perform analyses at finer spatial scales. The user is

able to (1) simulate the effects of changes in land cover and land use on Non Point

Source flow and (2) develop a better understanding of the responses of managed

landscapes to a specific hydrologic event. There is also the ease and effectiveness with

which "what-if" scenarios related to land use changes can be evaluated using the VE.

5.1. Future Direction

The initial example application results hint at this prototype's great potential, but

there is plenty of work still to be done on this topic. Ongoing enhancements for this

environment will be concentrated on incorporating real-time data with the geospatial data

analysis system, environmental modeling, and VE components to enhance land use

management decisions in 3D and real world–looking environments. Multi-dimensional ecological modeling, geospatial analysis, and VR technologies are emerging as new tools for improving our understanding of how human activities define, perturb, and dominate the natural environment and are used extensively for timely and cost-effective decision-making. It seems likely that these new tools and associated methodologies, when fused with real-time remotely sensed data on earth surface processes, will open new frontiers in the analysis of complex environmental systems. This includes interactions between human and non-human biota.

In addition to having real-time linkage between data sources and systems, a future development of this environment will be to utilize the distributed nature of the internet to create an internet 3D-GIS portal for environmental impact assessment. This could be accomplished by generating a more generic interface that could take different formats of DEM files as inputs and, as a result, generate a 3D environment on the web browser. This environment would provide users with the ability to browse to different texture files to be loaded over this environment in order to analyze the geospatial data in the 3D environment. Users could load a map or spatial data from any PC by using a web browser and then can make several queries on these data using mouse, keyboard, and voice as modes of interaction with the environment. Another area where this research can be expanded is by incorporating models like ArcHydro into an internet 3D-GIS portal. This can be done by writing scripts using ArcObjects. ArcObjects is the development platform for the ArcGIS. By using ArcObjects, a full range of functionality similar to ArcMap can be achieved. This would provide lower-level modeling capabilities within the 3D environment. The user could perform spatial analyses like watershed delineation, flow

direction, and flow accumulation on an internet browser within the 3D environment. This would lead to better BMPs, as all the users (e.g., farmers, planners, and researchers) with access to the internet can perform these analyses and make better decisions.

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