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VIRTUAL ORGANIZATION BASED DISTRIBUTED ENVIRONMENTAL SPATIAL DECISION SUPPORT SYSTEMS: APPLICATIONS IN WATERSHED MANAGEMENT

By

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ABSTRACT

VIRTUAL ORGANIZATION BASED DISTRIBUTED ENVIRONMENTAL SPATIAL DECISION SUPPORT SYSTEMS: APPLICATIONS IN WATERSHED MANAGEMENT

By

Yi Shi

Watershed management as a consensus-building process demands a holistic integrative approach to consider the impacts of various human activities in a watershed on water resources and other related natural resources. The challenge of effectively integrating scientific information from different disciplines into watershed environmental decision making process remains an outstanding challenge for environmental practitioners. In this research, the author argues that a collaborative online Virtual Organization (VO) based Watershed Management Spatial Decision Support System (SDSS) capable of integrating distributed databases and computational models offers superior opportunities for holistic watershed management. This system can utilize the latest Grid computing technology and provide an effective way to embed science in the decision making process by improving the communication between the scientific and the policy sector and between decision-makers and involved stakeholders and translating often complicated modeling results into an easy to understand format for environmental decision makers. The requirement analysis for a VO-based watershed management SDSS is conducted first. A general Internet-based integration framework for the VO-based watershed management SDSS is then conceptualized based on the requirements specified. The implementation of an example VO-based watershed management SDSS within this framework for sediment runoff reduction in two watersheds in northern Indiana is

described in detail to illustrate the advantages of VO-based watershed management SDSS. The parallelization of a selected water quality model and subsequent performance analysis demonstrates how Grid computing technology can be utilized as underlying technical infrastructure for a VO-based watershed management SDSS. Finally, design, implementation and application of a new fundamental DEM-based flow analysis algorithm are reported and statistical analysis of application results are done to show its improvement over existing methods. The integration of this new algorithm into VO-based watershed management SDSS can benefit decision makers and other users immediately.

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Chapter 1. Challenges in Distributed Environmental Decision Support Systems

1.1. Introduction

This research addresses the long standing issue of effective integration of science and decision making in environmental management using the latest Virtual Organization (VO) based Grid Computing technology coupled with advanced geospatial technology within watershed management context. The related technical and organizational interoperability problems in distributed geoprocessing and modeling are also discussed in the watershed management context. Environmental managers have been increasingly calling on science to provide relevant information for environmental decision making (e.g., Browning-Aiken et al., 2004, 2006; NRC, 1999; Matthieset al., 2007). However, despite the recent remarkable growth in availability of relevant knowledge, data, and information in environmental science, how science can effectively support environmental decision making remains an unresolved question (Cash et al., 2003; Lee, 1993; Reichert et al., 2007; van der Sluijs, 2007).

The objective of this research is to extend the virtual organization paradigm to the context of watershed management, and to evaluate its effectiveness for that context. My hypothesis is that watershed management can benefit from VO if particular developments are realized:

- Integration of decision-making and communication into a web-based distributed environmental decision support system. For example, policymakers at multiple organizations should be able to work with one another remotely, sharing not only data and models, but also decisions.

- Distribution of environmental models. For example, actors in one location and agency should be able to execute watershed models with elements on remote servers in different organizations.
- Distribution of computing resources. Complex models require much processing time, and distributing those in a Grid-based manner may integrate model runs into real time or near-real time decision support.
- Modularity of environmental model components. For example, analysts should be able to plug different functions into a model and have it run seamlessly. A watershed model might have one flow accumulation algorithm replaced by another.

This dissertation presents my progress in each of these areas, with original contributions illustrating how VO can be utilized by organizations involved in watershed management. Furthermore, it evaluates the performance and efficacy of each contribution, to help identify whether the challenges of this model of decision-making are worth the effort.

This research is clearly within the realm of geography because it studies geographic phenomena and their relations within watersheds and human interactions with watershed environments. As Turner (2002) pointed out, geography has two basic identities: geography as a spatial-chorological approach and geography as the human-environment subject. The spatial-chorological branch of geography investigates the geographic phenomena and their relations within a particular region while the human environment branch deals with human environment interactions (Turner, 2002). By furthering our understanding of flow phenomena within watersheds and developing a coherent organizational and technical framework for integrating scientific knowledge into decision making process, this research conforms to both traditions of geography discipline.

The rest of this section describes the background of this research first and then defines the overall research approach. The second section of this chapter reviews distributed computing, geoprocessing and spatial decision support. The third section examines the various aspects of watershed management. The final section lists specific research objectives and lays out the organization of this manuscript.

Environmental systems are driven by various natural and human processes at multiple spatial and temporal scales (Steyaert, 1993). Even though science has been increasingly brought in to provide critical information for complex environmental decision making (Browning-Aiken et al., 2004, 2006; NRC, 1999; Matthies et al., 2007), our knowledge of complex environmental systems relative to the holistic nature of these systems, however, tends to be fragmented frequently resulting in narrowly-focused, or myopic, fragmented management approaches and strategies (Savory et al., 1999). Federal environmental statutes and permitting programs, many of which are implemented by state agencies, focus on one environmental medium at a time—the Clean Water Act, Clean Air Act, Resource Conservation and Recovery Act (RCRA), Superfund (CERCLA), and the Endangered Species Act to name but a few. Not surprisingly, then, environmental data are collected and stored in different formats by different agencies pursuing different missions. Different agencies also produce different computational environmental models that are often not interoperable. In addition to different agencies being responsible for different environmental media, there is limited vertical integration between federal, regional, state, and local government agencies. The vertical as well as horizontal range of agencies can be broad and extremely diverse.

In the case of the Great Lakes Basin, for example, many government agencies in the U.S. with environmental responsibilities are involved in data collection and other aspects of environmental management (See table 1.1).

Agency Name	**Agency Level**
Environmental Protection Agency	Federal
US Geological Survey	Federal
USDA Natural Resources Conservation Service	Federal
US Army Corps of Engineers	Federal
US Coast Guard	Federal
US Fish and Wildlife Service	Federal
National Park Service	Federal
US Forest Service	Federal
National Oceanic and Atmospheric Administration	Federal
Regional Planning Agencies	Regional
State Departments of Natural Resources	State
State Departments of Environmental Quality	State
State Departments of Agriculture	State
Soil Conservation Districts	State
Regional Great Lakes Commission	Regional
Great Lakes Fisheries Commission	Regional
International Joint Commission	International
Local (City, County, and Township) Governments	Local

Table 1.1 Agencies involved in Great Lakes Environmental Management

All of these agencies collect a myriad of environmental data in a variety of formats for purposes associated with their respective missions. Some of these agencies also sponsor or produce different computational environmental models or decision support systems for various environmental management purposes. But unfortunately, these models and systems are often difficult to use and don't work with each other so they are rarely used in the real world decision making process (Acreman, 2005; Cash et al., 2003; NRC, 1999).

There have been a number of recent discussions on how to best connect environmental science and decision making, so that science can generate useful information in the context of decision making (Cash, 2002;Cash et al., 2003; Dilling, 2007; Logar and Conant, 2007; McNie, 2007; Sarewitz and Pielke, 2007). While scientists often say their opinions have been ignored by policy makers, the latter have also indicated that critical information required for decision making is often not readily available or not presented in a usable form (Jacobs, 2002). So clearly a better interface and communication mechanism between science and policy is needed for improved environmental decision making (Parker et al., 2002). To deal with the management, data and modeling fragmentation issues mentioned above and improve environmental decision making with sound science, a holistic systematic approach is needed based on: 1) a coherent set of multi-institutional relationships and 2) technical consistency and quality (Chi & Holsapple, 2005; Castelletti and Soncini-Sessa, 2006,2007; Gaddis et al., 2007).

Multi-institutional coherence can be provided through strategic coordination and timely communication among those collecting and storing data, those doing modeling and decision support system work such as researchers, scientists and IT professionals, environmental managers and policy makers, and others (Castelletti and Soncini-Sessa, 2006,2007; Gaddis et al., 2007). Developing and understanding these multi-institutional and multi-disciplinary relationships is critical to building a common base of knowledge that supports well-informed, science-based environmental and natural resource management decisions (Castelletti and Soncini-Sessa, 2006,2007; Gaddis et al., 2007).

Technical consistency and quality and can be achieved through effective use of technology and modeling—particularly information technology, geospatial technology, and environmental modeling (Parson, 1995; Dilling, 2007; Xu et al., 2007). Recent advances in organizational theories, geospatial technology, and information management technology, grid computing in particular, have contributed to the development of new types of comprehensive decision support systems (DSS) (Birkin et al., 2005). These systems have the capacity to integrate multi-disciplinary, multi-institutional sets of diverse environmental data and computational models, and provide rapid translation of research results into practical methods to understand and manage complex environmental systems in a virtual organization context. A virtual organization is "an identifiable group of people or organizations that makes substantially more use of Information and Communication Technologies than physical presence to interact, conduct business and operate together, in order to achieve their objectives" (Sieber et al., 1998).

By combining Grid computing capacity with a virtual organization, a new paradigm is being created. This powerful paradigm takes advantage of multiple networked computers to form virtual computer architecture with the capacity to distribute process execution across a parallel infrastructure and produce greater computation throughput (Foster, 2003; Foster & Kesselman, 2003; Foster, 2005; Foster & Tuecke, 2005; Stockinger, 2007). Grid computing employs the resources of many computers located at different sites but connected through a digital network (the Internet, usually) to solve large-scale computation problems (Foster & Tuecke, 2005; Stockinger, 2007). The Grid computing approach reflects a conceptual framework rather than an actual physical structure. Using multiple physically and administratively-separated resources, Grid computing enables a single virtual organization to perform complex sets of computational tasks (Jacob et al., 2005). The one important aspect of Grid Computing is to emphasize and enable organizational interoperability first before engaging in detailed technical interoperability (Foster & Tuecke, 2005). This is exactly what the multi-organizational and multi-disciplinary environmental DSS needs. Grid computing can not only integrate system components across organizational boundaries, but it can also enable high-performance computing within the DSS.

A case study approach is used in this research to test the hypothesis stated above. This case study investigates the functionality requirements of a virtual framework based on an integrated grid computing network coupled with advanced geospatial technology for a comprehensive watershed management decision support system (DSS) at multiple watershed scales. Then an example VO-based distributed watershed management decision support system within this framework is built to demonstrate the benefits of VO for watershed management. Distribution of environmental models and computing resources including the technical and organizational interoperability issues in distributed environments are also discussed in this context. An innovative DEM based flow modeling algorithm for such a watershed management VO is also developed to show how modularity of environmental model components can help improve watershed management VO.

In the next two sub-sections distributed computing, spatial decision support and watershed management are reviewed in the context of this research.

1.2. Distributed Computing, Geoprocessing and Spatial Decision Support

1.2.1. Distributed Computing

The term *distributed computing* was used to describe a type of computing where different processing tasks and data are distributed among separate computers connected to a network (Attiya & Welch, 2004). Distributed systems today generally have following characteristics: (1) greater access to data and computing resources stored and managed on distributed servers on the network; (2) faster response time due to local computing; (3) tighter system security; (4) less complexity; and (5) in many cases, lower-cost computing solutions than more traditional mainframe or minicomputer solutions (Coleman, 1999; Attiya & Welch, 2004). Distributed systems are pervasive today throughout business, academia, government, and the home. They provide ways to share resources such as printers and scanners, and to share data and computational services. The concept of distributed computing often provides a better fit to the complex structures and often multidisciplinary nature of modern organizations and offers greater user involvement in information management activities (Coleman, 1999). The rapid advances of distributed computing technologies and the growth of high-speed Internet connections has resulted in an Internet-driven, online computing era (often referred to as Web 2.0). The software industry is moving towards the Internet platform while the new distributed technologies like XML and Web services have emerged to provide a solid foundation for this seismic shift (Spector, 2003). Internet-based software and Service Oriented Architecture (SOA) has globalized information and content while catalyzing formation of various online communities dedicated to a bewildering array of different topics and subjects (Dempsey, 2000; Purcell, 2006; Lawler & Howell-barber, 2007).

The emerging Grid computing technology is a result of natural evolution of distributed computing and the Internet. Grid computing is based on the notion of computational Grids (Foster & Kesselman, 2003) where computing resources are available as universally and as easily as electric power. Grid computing focuses on large-scale resource sharing, innovative applications, and, in some cases, high-performance orientation within a Virtual Organization (VO) (Foster & Tuecke, 2005; Stockinger, 2007). Grid computing is capable of linking multiple organizations through a network of shared data, software programs, and powerful processors. This capability is a function of integrated organizational and technical components. The degree of integration that a VO employing Grid computing technologies can achieve is unprecedented (Shi et al., 2002; Foster & Kesselman, 2003; Foster & Tuecke, 2005; Stockinger, 2007). Grid computing also has two major integrated technical components: distributed computing and parallelization of intensive computation. These two components are also very important for Geographic Information Technology (Coleman, 1999; Healy et al., 1997; Armstrong et al., 2005).

The Geographic Information Science (GIScience) community has long recognized the value of distributed computing technologies for societal use and diffusion of geospatial technologies (Coleman, 1999). The problems and applications addressed by GISs are particularly well suited to distributed computing (UCGIS, 1996, 1998, 2002; Coleman, 1999), and as a result, distributed computing is a research priority in the field of GIScience. Geographic information technologies allow demonstration of vital linkages between what otherwise appear to be unrelated activities. The identification of characteristics and attributes with a common geographic location has frequently led to more extensive sharing and integration between what were previously rigidly-separate organizations or parts of the same organization (UCGIS, 1996).

1.2.2. Geoprocessing and Spatial Decision Support

Geographic decisions supported by GISs often involve multiple stakeholder groups widely distributed across geographic locations and social strata. Stakeholders are also frequently located in different administrative tiers in an organization hierarchy. In the past, this distribution has precluded any integration or coordination (Shi et al., 2002).

Data sources and geoprocessing power residing in sophisticated software and hardware are often widely distributed. Geospatial operations and related decisions are frequently made in the field and thus require flexible access to remote databases and models. Computationally-intensive spatial applications with ever-finer data resolution often tax the capacity of single machines (UCGIS 2002, Shi et al., 2002, Xue et al., 2002; Armstrong et al., 2005; Wang et al., 2005).

Spatial Decision Support Systems (SDSS) are a type of computer systems that utilize both geospatial technologies and decision support system to assist decision-makers with problems that have spatial dimensions (Walsh 1993, Prato and Hajkowicz, 1999). SDSS have been used in a variety of applications such as flood prediction (Al-Sabhan et al., 2003), river water quality evaluation (Wang et al., 2005), conservation program management and best management practices assessment (Rao et al., 2007). But most of these applications are stand-alone ones that don't use distributed computing technologies. An early representative GIS application of distributed computing and spatial decision support system was a project called Sequoia 2000 that linked researchers throughout the

University of California system who were investigating global climate change via an integrated computer environment (Stonebreaker, 1995). Scores of earth scientists, atmospheric scientists, and computer scientists as well as industry representatives worked together and created a system to manage vast environmental databases that rapidly provide data and visualizations across a dedicated wide-area network.

The experiences of Sequoia 2000 and similar projects indicated the presence of both opportunities for and impediments to the distributed computing applications. Impediments may be either technological or organizational. Technological challenges include:

- Integrating data from different sources, stored in different databases
- Transmitting very large quantities of information over the network
- Developing flexible interfaces for different users
- Building high performance and, if necessary, parallel geoprocessing functions for real time applications and very large datasets with finer resolution.

Organizational challenges include:

- Combining members of highly disparate research communities like computer science, hydrology, agricultural and environmental engineering, earth science, etc.
- Communicating clearly research objectives and requirements
- Orchestrating linked but independent environmental models developed in different laboratories (Shi et al., 2002)
- Forging geographic information partnerships for local, regional, national, international, and global spatial data infrastructures.

The academic GIScience community, government agencies, and commercial GIS software vendors have worked diligently to address these challenges since the Sequoia project. A variety of GIScience initiatives (see e.g., OGIS, 2002; Hecht, 2001; UCGIS, 2002) were intended to improve the utility of distributed computing for geospatial applications. These initiatives focused on technical aspects although organizational challenges associated with large projects have long been acknowledged. Several U.S. initiatives have focused on building nationwide partnerships and data infrastructures (e.g., e-Government (eG), National Spatial Data Infrastructure (NSDI), The National Map (TNM), and GeoSpatial One-Stop (GOS)). These initiatives call for development of an "information highway" to connect diverse spatial data producers and users in the private sector, academic institutions, and all levels of government (UCGIS 2002; NSDI future directions, 2004; Crompvoets et al., 2004).

A critical issue related to applications of distributed computing in geospatial applications is how to achieve interoperability in a distributed environment. Interoperability refers to the ability to move easily from one system to another. Interoperability has been a serious concern for sharing of geographic information in GIScience since the late 1970s (Sondheim et al., 1999; Harvey et al., 1999, Riedemann and Kuhn, 1999). The explosive growth of the Internet and Web has facilitated the rapid advances in the interoperability research. As a result, ontology and semantics have become important topic in both general IT and GIScience community. Ontology has been viewed in GIScience as a standardization process through which easier semantic interoperability can be achieved between different information systems (Gruber, 1991; Chandrasekaran et al. 1999, Smith 1999, Fonseca et al. 2002, 2003). Semantics focuses on the study of meanings. Semantic interoperability is the capability of two or more computer information systems to exchange information and have the meaning of that information automatically interpreted by each other (Selvage et al., 2006). Because of the inherent indeterminacy and vagueness associated with geographic concepts and categories, no consensual shareable ontology for the geospatial domain has been produced even though some specific ontologies exist for certain applications (Agarwal, 2005; Fonseca et al. 2002, 2003).

GIS communities' interest in distributed computing and interoperability has historically focused almost entirely on sharing data. Effective sharing of geoprocessing methods and tools has a potentially higher return than sharing data because these methods and tools are generic with a broader range of users than a given set of data (Peng & Tsou, 2003). Over the past few years, major GIS software vendors have recognized the importance of the Internet as a computing platform, and they re-engineered their products for an Internet platform. This new generation of Internet-based GIS software products not only facilitates sharing of spatial datasets but also facilitates advanced geoprocessing functions across the Internet based on service oriented architecture (Smith & Sheahen, 2008).

1.2.3. GRID-based Geospatial Applications

The new generation of Internet GIS, however, has not met all the technical and organizational challenges cited in the previous section. New innovations in distributed computing are needed to tackle those challenges. The emerging Grid computing technology has great potential to solve these problems and challenges. In fact, the

GIScience and environmental sciences community in general have already recognized the importance of Grid computing technology and started to apply it in various geospatial applications (e.g., Shi et al., 2002; Wang et al., 2002, 2005; Armstrong et al., 2005). Beven (2003) realized the potential of GRID to change the way that environmental models are constructed and used. Hluchy et al. (2004) introduced a flood forecasting system in a Grid computing environment. Araújo et al. (2005) described a GRID-enabled Hydro-Meteorological Scientific Network. Zhang and Tsou (2005) presented a new framework for Grid-enabled GIService web portals to facilitate the building of high-level intelligent Internet GIServices. Shu et al. (2006) explored integrating OGC (Open Geospatial Consortium) web services and Grid technologies for geospatial data sharing. Several major research efforts that involve developing GRID enabled geospatial applications are listed in table 1.2.

Application Title	Application Type	State of Development
GEON	Online Portal w/ Access to Data, Tools & Applications	Ongoing
GISolve	Online Portal w/ Access to Data, Tools & Applications	Ongoing
WATERS	Online Portal w/ Access to Data, Tools & Applications	Ongoing

Table 1.2 Major GRID enabled Geospatial Applications

As a multi-disciplinary research initiative, GEON (GEOscience Network) was formed by earth and computer scientists in 2003 to build a cyberinfrastructure for the geosciences. In order to better understand the dynamics of complex earth systems, geoscientists need an integrative computational infrastructure to link, share and utilize massive multi-disciplinary data sets and tools they developed over the years. The main goal of the GEON is to provide the critical infrastructure necessary to facilitate collaborative interdisciplinary earth science research (Seber et al., 2003; Keller et al., 2003, 2005). By integrating datasets at semantic levels, GEON can provide users with information on datasets, tools and resources at the conceptual level and thus enable them to access and utilize data and tools from allied disciplines with minimal effort. However, construction of this cyberinfrastructure capable of integrating, analyzing, and modeling dynamic heterogeneous spatial information is not an easy task. Major obstacles include different characteristics of geoscience data formats, storage protocols, and computing systems and, most importantly, the differing conventions, terminologies, and ontological frameworks across disciplines (Seber et al., 2003). Because of these obstacles, many researches within the GEON project have been focused on ontology and semantic interoperability (e.g., Bowers & Ludaescher 2003, 2004; Lin & Ludaescher 2004; Sinha & Lin et al., 2005; Sinha & Zendel et al., 2006; Sinha & Lin et al., 2006; Brodaric &. Gahegan, 2006).

Grid technology is used in GEON to develop its cyberinfrastructure. Grids provide sustainable and distributed architecture to facilitate seamless data and computational resources access over the Internet using secure links and connections. The GEON grid and portal were built as open source platforms so the user community can develop their own tools and access mechanisms (Seber et al., 2003; Keller et al., 2003, 2005). A lot of development efforts within the GEON project are geared towards middleware development because it is the critical component for connecting different parts of the infrastructure (e.g., Bhatia & Memon et al., 2003; Memon et al., 2004; Bhatia & Chandra et al., 2005; Mueller, 2005; Youn et al., 2006). According to Carnegie Mellon Software Engineering Institute (1997), middleware is "connectivity software that consists of a set of enabling services that allow multiple processes running on one or more machines to interact across a network".

GEON's earth science research has been tested in two regions: the Rocky Mountains and the Mid-Atlantic region. Intracontinental deformation and terrane recognition and analysis were studied in each region, respectively (Seber et al., 2003). Most of applications developed within the GEON are centered on geological areas (e.g., Sinha et al., 2003; Salayandia et al., 2006; Rees et al., 2007) and LiDAR (Light Detection and Ranging) data distribution and processing (e.g., Crosby & Arrowsmith, 2004; Crosby et al., 2006; Jaeger-Frank et al., 2006). The future goals of GEON network include improving existing GEON systems and middleware infrastructure; building new useful tools on top of existing framework; encouraging software development and resource integration with partner sites; and integrating more data, more applications (Chandra, 2007).

As a problem solving environment, GISolve was created based on Grid architecture to provide grid services for computationally intensive geospatial information analysis. Many of GISolve projects are focused on the so-called geo-middleware development. The geo-middleware is a piece of software that sits between existing grid middleware and geographic information analysis applications to manage heterogeneous and dynamic resources on behalf of analysis applications. GISolve can also decompose certain parallel geographic information analysis problems into several sub-tasks that can be scheduled for processing using multiple Grid resources. Data transfer management and distributed task scheduling are all supported by GISolve. All functions in GISolve are exposed as grid services that are compliant with the open grid service architecture

(OGSA) through grid portal. Grid portal technologies provide access to Grid services for security management, remote data and job management, resource information access, application interface specifications, and access to collaboration services. The examples within GISolve include a computationally intensive spatial statistics application and spatial temporal data explorer etc (Wang et al., 2005).

WATERS (WATer and Environmental Research Systems) network was planned by CUAHSI (Consortium of Universities for the Advancement of Hydrologic Sciences) and CLEANER (Collaborative Large-scale Engineering Analysis Network for Environmental Research) project office in 2005. It is funded by National Science Foundation (NSF) Engineering and Geosciences Directorates. The main goal of the WATERS Network is to build a national capacity to better understand and predict processes at multiple spatial and temporal scales coupling water with natural and human systems. It's a bold environmental observatory initiative to transform water research through new investments in infrastructure. It recognizes that the advances in water-related sciences and engineering can only be based on new measurements (WATERS Network, 2008). According to its website, the WATERS Network will include the following elements:

1. "A national Observational Network of highly instrumented experimental facilities for testing hypotheses, with:
    - sensor networks within the natural, built, and managed environments for acquisition and analysis of high-frequency and spatially dense environmental data in real time
    - representative coverage of the diverse conditions of the United States
    - high-resolution characterization data"

2. "A Sensor and Measurement Facility to provide specialized instrumentation, support and training in instrumentation use to address WATERS Network questions. The Sensor and Measurement Facility will include:
   - specialized support personnel and facilities for sensor and measurement support
   - expertise on recent advances in environmental sensors, wireless communications and remotely sensed data"
3. "A Cyberinfrastructure, Modeling, and Synthesis Facility to provide a shared-use network as the framework for collaborative analysis, including:
   - an integrated model of the hydrologic system to support adaptive sampling
   - a digital watershed to access all available data (including those collected by other organizations and mission agencies)"

WATERS network cyberinfrastructure demo site include some preliminary applications such as hydrological data access system and streamflow analyst. A review of the project timeline at WATERS network website indicates that even though the WATERS network project office was established in 2005, the project is still at planning and strategy design stage as of 2008. Various planning documents regarding different components of the network such as sensors, cyberinfrastructure and modeling etc. can be found at WATERS network website.

All three major research efforts mentioned above attempt to develop cyberinfrastructure based on Grid technology in support of sciences. GEON is focused on facilitating collaborative and interdisciplinary research in geosciences. GISolve bridges the gap between computationally intensive spatial information analysis applications and the Grid environment. WATERS network strives to build a national capacity for advancing water-related sciences. But one thing worth notice is that all these research efforts have largely been conducted in the academia with very few linkages to environmental agencies and user communities. These linkages are considered critical in the research presented in this dissertation even though it also aims at applying Grid technology to build a better technical infrastructure for environmental decision making.

1.3. Watershed Management

1.3.1. Watersheds

Water is essential to life. The quantity and quality of water is critical to all human systems and those of other natural organisms. Every living organism on the Earth depends on water. Water, therefore, regulates population growth, affects world health and living conditions, and determines biodiversity (Newson 1992). Yet until the 1980s, most water management practices focused on solving singular, localized problems without considering the impacts of changes in human behaviors and the landscape on the biophysical, economic, and social dimensions of a watershed system (Schramm 1980). Over the past thirty years, a global consensus has emerged to treat watersheds as the appropriate units for the management of water and related aquatic resources (McDonald and Kay 1988; Koudstaal et al. 1992; Lee 1992; Newson 1992; Heathcote 1998; Gregersen et al., 2008).

A watershed is the area of land which drains runoff (from rain, snow, and flowing springs) to a body of water (Gregersen et al., 2008). In each watershed, water flows downward to a common receiving body such as a river, lake, wetland, or bay. Water travels across land surfaces used for farming, forests, suburban lawns and golf courses, city streets and other impervious surfaces before reaching a surface water body. Some water infiltrates the soil and becomes groundwater (Ward et al., 2003).

1.3.2. Watershed Management Process

Watershed management is the process of organizing and guiding the uses of land and other resources at a watershed scale to provide desired goods and services without adversely affecting water and related natural resources (Brooks et al., 1997). Watershed management recognizes the interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas. A watershed perspective drives the consideration of the multiple and cumulative effects of changes and actions in a biophysical area and the need to identify the nature, attributes, and characteristics of key linkages between terrestrial and aquatic ecosystems (Gregersen et al., 2008). Watershed management entails an integrated approach in which social, economic, and environmental factors are considered in determining appropriate actions to manage water resources (Heathcote 1998; Gregersen et al., 2008). This holistic approach requires consideration of the interaction of ground and surface water. Effective integrated watershed management is an ongoing, iterative process, and flexibility is needed to adapt management practices to the unique characteristics of each watershed as well as those changes in human populations and behaviors and changes on landscapes in a watershed over time (Brooks et al., 1997; Heathcote 1998; Gregersen et al., 2008).

Watershed management relies in large part on the active involvement of local agencies, economic interests, NGOs, and citizens. Bishop (1970) observes that water management planning is a process to achieve social change. As a consensus-building process, then, it is categorically not a one-dimensional pure scientific exercise. Davenport, an EPA watershed management expert with two decades of field experience, indicates that watershed management is mainly a process of working with people to solve identified problems (Davenport, 2002). An effective watershed management plan must reflect societal consensus regarding the value of water as a resource, social attitudes, and stewardship responsibilities, and the community's vision of an ideal watershed and water quality (Nickum and Easter, 1990; Davenport, 2002; Gregersen et al., 2008).

Practices associated with watershed management are directed at guiding changes in land use and vegetative covers as well as other structural and nonstructural actions to achieve water quality goals and objectives (Reimold, 1998). Management tools include nonstructural (vegetation management) practices as well as an array of structural (engineering) practices depending on specific conditions. Soil conservation practices and land use planning activities are tools that can be employed in watershed management. Land use practices include establishment of protected sensitive areas; regulations on road building, timber harvesting, and agro-forestry practices; storm water runoff management; and other activities (Reimold, 1998). The focus of these practices is their impacts on water resources and related aquatic resources in a watershed.

The institutional and policy framework of watershed management provides an integrative methodology to consider the impacts of various human activities in a given unit of land (the watershed) on water resources and related aquatic resources (Reimold, 1998). Management practices include the use of physical, regulatory, or economic tools and techniques to address identified and potential problems involving relationships between water resources and land uses. These tools and techniques are employed by farmers, foresters, soil conservation staff, engineers, citizens, and others. Watershed management requires active collaboration among specialists in a broad range of disciplines – engineering, biological sciences, hydrology, economics, sociology, law, institutional policy, and ethics – as well as government agencies, private industries, nongovernmental organizations, and the public (Brooks et al., 1997; Heathcote, 1998; Reimold, 1998; Gregersen et al., 2008).

The process of watershed assessment and management decision making requires biophysical, social, and economic information that ideally is augmented by local knowledge and insights. This process is built on stakeholder involvement, social capacity building, and adequate monitoring (Heathcote, 1998; Davenport, 2002; Gregersen et al., 2008).

1.3.3. A Four-phase Watershed Management Process and its Benefits

Davenport (2002) describes a four-phase watershed management process based on collaboration that responds to common, stated needs and goals. The four phases are assessment; planning; implementation; and evaluation. This watershed management process is multi-phase and iterative (Figure 1.1).

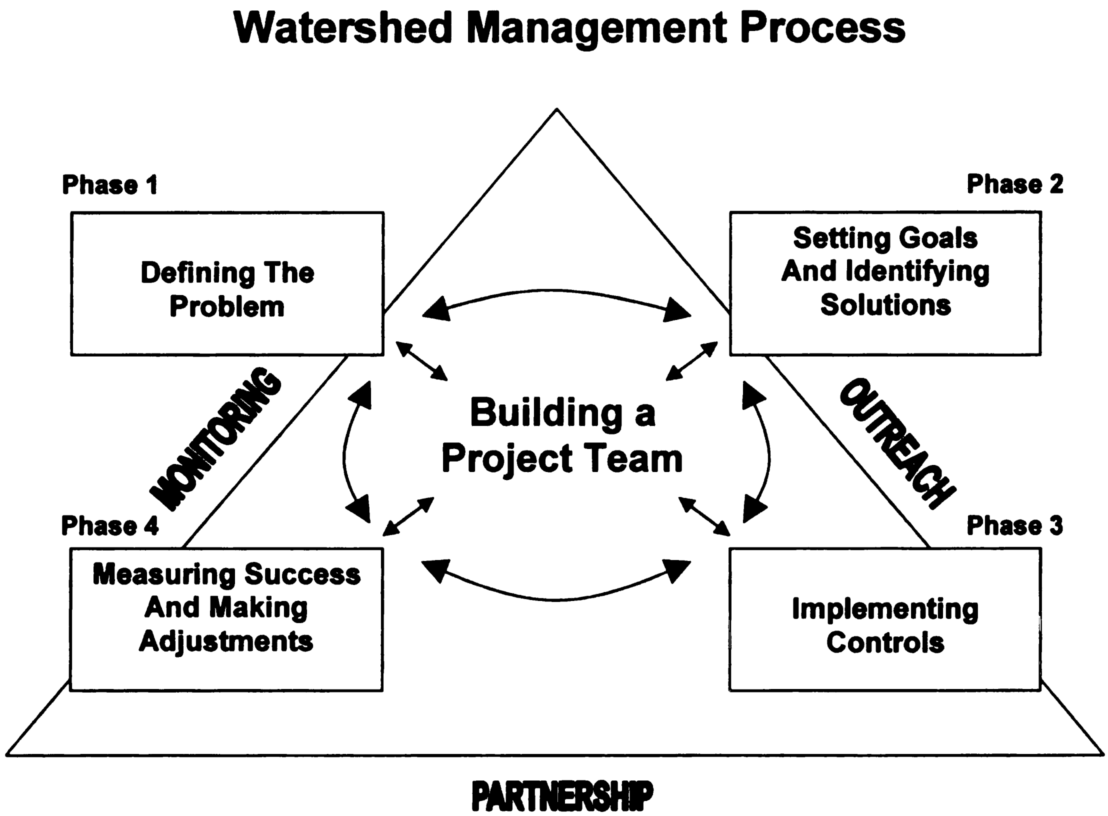

Figure 1.1 Watershed Management Process (Davenport, 2002)

In phase 1 of watershed assessment/problem identification, knowledge of the biophysical, economic, and social processes and interactions in and around the watershed is acquired, including stakeholder concerns and interests, institutional concerns and constraints, and socio-economic characteristics. This phase is subdivided into four components that include: (1) inventory/mapping; (2) obtain information and data analysis; (3) identify problems (stressors and their sources) based on the analysis; and (4) determine the overall goal (Davenport, 2002).

In phase 2, planning refers to development of an implementation strategy based on a diagnostic analysis that uses information from inventory assessments and stakeholder input. Selection of strategic options from among identified alternatives and documenting the decision making process is based on this analysis. To achieve a valid planning outcome, a mere document is not sufficient. An effective implementation strategy solves identified problems and resolves outstanding data needs. An effective plan is "bottom-up" rather than "top-down" (Davenport & Wilson, 2001). Prescribed actions are based on well-defined, water-quality standards, voluntary incentives, education and information, and regulation/enforcement (Davenport, 2002; Gregersen et al., 2008). It should be noted that a watershed management plan need not be completed before implementation begins. Problems identified with known solutions should be addressed immediately. With an early start in building a successful track record, success of the overall planning and management process is more likely (Davenport, 2002).

In phase 3, implementation represents the culmination of the initial assessment and planning efforts, organizing, and information/education activities – bringing together previous efforts and actually doing the work. Implementation actions include steps to address pollution prevention, pollution controls and reduction, and restoration of ecological quality and functions (Davenport, 2002). Implementation builds on the historic point source controls in which compliance with effluent discharge standards (maximum acceptable levels of pollutant loadings) achieved significant and even dramatic improvements in water quality with the reduction of pollutant loadings (Gregersen et al., 2008). Reducing nonpoint source pollution (as distinguished from "point" source discharges from industrial and municipal treatment facilities regulated by the National Pollution Discharge Elimination System [NPDES] under the 1972 Clean Water Act) has been a steep challenge given the diffuse nature of nonpoint pollution sources—farm fields, septic tanks, residential lawn fertilizers and pesticides, water runoff from streets and parking lots, and many other multiple small sources (Ritter and Shirmohammadi, 2000). Although the aggregate impact of nonpoint pollution is a highly significant cause of degradation of water quality, precise identification of the location of these highly diffuse sources has been extremely difficult (Nikolaidis et al., 1998; Ritter and Shirmohammadi, 2000; Zhang and Wang, 2002; Zhang and Jørgensen, 2005). Such identification is critical to targeting appropriate best management practices (BMPs) at those sources with the highest risks of generating pollutant loadings.

In phase 4, evaluation builds on assessment data and will continue after completion of the implementation phase. Evaluation provides indications of whether implementation has achieved stated goals and objectives. In addition, evaluations conducted during implementation can provide feedback to guide midcourse corrections (Davenport, 2002). Evaluations can also signal opportunities to celebrate accomplishments and this kind of positive feedback contributes to a sense of community ownership in the process of enhancing responsible environmental stewardship.

There are three categories of benefits for this watershed management process. First, it provides a context for multi-institutional integration by using a practical, tangible management unit. The size of the watershed addressed is tied to identified problems and local capabilities and interests. A process that includes a high level of stakeholder engagement facilitates focusing and coordinating federal and state efforts to address local problems (Davenport, 2002). Second, it promotes learning, understanding, and an appreciation of natural ecological functions and processes. Appreciating how natural processes and ecological functions benefit humans is critical to the identification and implementation of actions to protect and preserve valuable ecological functions

(Gregersen et al., 2008). Stakeholders learn to link the impacts human activities on ecological changes in water quality and quantity. Third, this process promotes better management (Davenport, 2002).

1.3.4. Watershed Partnership

The watershed planning process requires the creation of a partnership that manages this process to ensure stakeholder involvement, adequate monitoring, and an outreach program (Walters, 2000; Davenport, 2002). Stakeholder participation early in the process is critical. Extensive interaction with stakeholders is imperative to develop the most appropriate plan to manage the watershed and fulfill stakeholder goals (CTIC, 1995; Born and Genskow, 1999). Since stakeholders' opinions on watershed issues frequently diverge or clash, negotiation and compromise may be necessary to agree on appropriate actions. Effective compromises depend on the active involvement of multiple stakeholders with easy access to accurate data and information (CTIC, 1995). Active stakeholder involvement creates a context in which consensus and support needed to implement watershed management plan can be obtained (CTIC, 1995; Born and Genskow, 1999). It is obviously true that information is power. And distributed information can provide a mechanism to disseminate information across conventional barriers and enable effective democratic decision making (Voinov and Costanza 1999).

A partnership is critical to the process of developing an effective watershed management plan (Walters, 2000; Davenport, 2002). A partnership is defined here as a collection of agencies, organizations, and individuals associated in a geographically-based undertaking as shareholders and/or partakers to address specific problems or issues.

Watershed partnerships embrace a place-based focus and rely in large part on science to support decision making (Born and Genskow, 1999; Walters, 2000; Davenport, 2002). A partnership bridges the capabilities, assets, and resources of multiple agencies, organizations, and individuals. The development and implementation of a watershed plan by a broadly-based partnership creates local ownership in the watershed and provides an effective mechanism to reach consensus (Davenport, 2002). A partnership may also provide a means for more efficient use of financial resources; more creative and acceptable ways to manage and protect natural resources; and a broad commitment to the protection and preservation of natural resources (Walters, 2000; Davenport, 2002). A partnership-building process includes the identification and engagement of interests with a stake in the management of the watershed, establishment of an organization, determination of a goal and plan for the watershed, implementation of the plan, and evaluation of its impact (Davenport, 2002). Davenport (2002) describes four characteristics for successful watershed management partnerships: one, a clearly-stated goal; two, a strong management plan with identified outcomes; three, leadership representing multiple interests, and four, local support. Holdren et al. (2001) identifies key institutional characteristics of a successful watershed organization that include full-time staff; office space and equipment; a water-quality monitoring program; public outreach program; access to water quality information; concern for water quality; and a commitment to citizen participation.

There is no single organizational model for watershed partnerships. The form and structure of a watershed partnership can range from an informal organization to a complex, formally-organized structure. Davenport (2002) recommends a minimum organizational structure that includes steering, planning, technical advisory, citizen advisory, and operations committees. A steering committee provides leadership for the overall watershed management effort and identifies program resources available to address watershed management needs. A planning committee develops the watershed management plan working closely with a technical advisory committee (TAC). A TAC conducts the watershed assessment to provide a technical basis for the watershed management plan. A planning committee determines watershed plan objectives after identifying the resource issues and concerns in the watershed. A TAC uses these objectives to identify possible solutions to the identified problems and meet the objectives. A TAC is typically comprised of 20-25 professionals and interested stakeholders from nonprofit, nongovernemental organizations (NGOs), local governments, state and federal agencies, and public and private universities. A TAC is interdisciplinary with expertise in biology, hydrology, etc. to perform the assessment/problem identification and formulate alternative strategies (Davenport, 2002). Some watershed partnerships have a citizen advisory committee (CAC) to provide advice. A CAC provides input, influence, and active involvement of watershed residents. An operations committee is responsible for implementation, evaluation, outreach, and monitoring. Depending on the scope and complexity of implementation activities, various operations teams or workgroups may be formed to focus on specific activities. A planning committee determines the primary outreach message, and an outreach team identifies target groups and appropriate communications strategies (Davenport, 2002). An important part of the outreach component is convincing stakeholders that they are stakeholders (Walters, 2000; Davenport, 2002). Outreach must also be coordinated with

TAC and planning committee activities (Davenport, 2002). A document/information repository should be created to house completed studies, reports, and other information and be made available to the public. An operations committee should be responsible for the repository (Davenport, 2002).

Watershed management partnerships have organizational and technical needs that correspond to the capacity of VO-based watershed management DSS. An Internet-based infrastructure can provide critical support in forming partnerships and subsequent collaboration and ongoing networking. A watershed management VO extends the utility of internet partnerships in two general areas: first, it offers a much more powerful knowledge-sharing mechanism, and second, it provides a natural extension to the decision-making functionality of traditional watershed partnerships. Even though many researchers have utilized the web and Internet for environmental DSS development (e.g., Watson et al., 2002; Cheng et al., 2004; Dymond et al., 2004; Hluchy et al., 2004; Xie and Yapa, 2006; Wang and Cheng, 2007), only a few realized the value of VO and associated Grid computing technology (e.g., Hluchy et al., 2006). A VO-based watershed management DSS can effectively function to integrate information from multiple organizations and disciplines. It can also assist in providing watershed inventories, assessments, problem identification, modeling, and analyses of alternative scenarios for stakeholders so they can understand issues at hand. This system can be used as a communication tool and assist dissemination of project results to maintain active public engagement and support. By providing access to anyone at any time, in, any location with a computer, a powerful tool is created. Development of VO-based watershed DSS may result in a distributed system that participants can continue to use across multiple locations over time, as demonstrated later in this dissertation.

The next section describes the specific objectives of this research and the outlines of the dissertation organization.

1.4. Objectives and Organization

A case study approach is used here to test the hypothesis that VO model can benefit watershed management by providing effective ways to integrate science and decision making and to operationalize a multi-organizational and multi-disciplinary, comprehensive, watershed management SDSS. Given its multi-organizational structure and multi-functional management nature, the integrated watershed management SDSS has multiple information and analysis requirements. It also requires intensive computing capabilities that both Grid computing and geospatial computing provide. The multi-organizational nature of the system also demands organizational theories like Virtual Organization and Actor Network Theory (ANT) for requirement analysis.

The main goal of this research is both to conceptualize a watershed management VO and to discuss certain implementation aspects of this concept, including exploring technical issues related to hydrologic modeling within the context of such a VO.

The specific objectives include:

- Conduct a requirements analysis for a VO-based watershed management DSS;
- Conceptualize, partially implement and evaluate an Internet-based integration framework for VO-based watershed management SDSS;
- Parallelize a water-quality model to utilize distributed processors; and

- Develop and evaluate a new DEM-based flow analysis algorithm.

The following chapters focus on different issues and objectives outlined above. Chapter 2 discusses VO and ANT organizational theories and applies them to a requirements analysis for a VO-based watershed management SDSS. Chapter 3 discusses Grid computing technology and the conceptualization, partial implementation and evaluation of an Internet-based integration framework for the VO-based watershed management SDSS. The parallelization of a water-quality model is also developed to demonstrate how to utilize distributed computing resources. Successful watershed management depends not only on organizational aspects described in the previous section, but also technical aspects such as data sampling, modeling, monitoring etc. In this research, a detailed study on fundamental DEM (Digital Elevation Model) based flow modeling algorithms is also conducted. Reviews of various flow modeling algorithms and details of this study can be found in Chapter 4. As a result of this study, a new flow routing algorithm based on principles in fluid mechanics called FlowNet is created and evaluated. This new FlowNet algorithm is applied to 21 watersheds in three different physiographic regions along with two other algorithms for comparison purposes. It is also validated against wetland data available for Michigan watersheds. The comparison and validation results in Chapter 4 show advantages of the FlowNet algorithm for watershed modeling. This algorithm can clearly be integrated into the modular VO-based watershed management SDSS to provide better information for decision making. Chapter 5 presents conclusions on the research and future research recommendations.

Chapter 2. Requirement Analysis for a VO-based Watershed Management SDSS

2.1. Introduction

Water is a renewable but finite resource. It's an important resource necessary for sustainability of all socio-economic development activities including industry and agriculture. When water and land become limited resources, competition among various stakeholders for use of fresh water is bound to increase (CTIC, 1995). To ensure long-term sustainability, watershed managers recognize the need for a holistic watershed management approach that involves coordination among different organizations and collective decision-making based upon information from different sources (Gregersen et al., 2008). As indicated in Chapter One, the ultimate goal of watershed management is to improve watershed ecosystem health and support economic developments such as agricultural production on a sustained basis (Brooks et al., 1997; Heathcote 1998; Gregersen et al., 2008). Therefore, the needs and impacts of every stakeholder on the natural functions of a watershed need to be understood for making decisions regarding resource management and sustainable development (Davenport, 2002). There is also a need for a clear identification of the steps involved and the detailing of the requirements that adhere to specific policies all of which are a requirement for an effective management plan. So a key to effective water management is to have in place an enabling framework at a watershed/river basin scale and multi-stakeholder partnerships at all levels (Walters, 2000; Davenport, 2002). This framework should reinforce the fact that nothing happens in isolation and that everything is connected by the land and water within the watershed. Given the relationships and interdependencies that exist between land, water, and various stakeholders, a comprehensive, all-inclusive approach to considering the factors affecting water and other natural resources within a watershed needs to be clearly understood (Gregersen et al., 2008). Any decisions regarding water resource management must be done in a socially, environmentally, and economically sustainable manner (Chander 2005). Davenport's partnership driven four-phase watershed management approach described in Chapter One clearly meets all these requirements.

A critical aspect of implementing the above framework is an application of a dynamic integrated assessment system. The system should contribute to provide methodological support to deal with the general problem of integrated watershed management implementation. In particular, the system should support the management of large amount of multi-sectoral and multidisciplinary information, and the communication between the scientific and the policy sector and between decision-makers and involved stakeholders (Chen et al., 2004). The system should also support public participation and social learning. Social learning here refers to the growing capacity of a multiple actors network (those concerned by the watershed) to develop and perform collective actions related to integrated watershed management (Pahl-Wostl et al., 2007).

Integrated Watershed Management is a social-relational activity (interests, water practices, information, knowledge, funds are spread over many actors) and a complex technical task; both cannot be separated (Gregersen et al., 2008). Social learning corresponds both to this participatory social/technical process as well as to the outcomes of this process. This collective problem solving approach requires that the actors meet each other, develop relational practices. The quality of these relational practices is fundamental from a social learning perspective: it is based on reflectivity, reciprocity and respect for diversity (Bandura, 1977; Pahl-Wostl et al., 2007). The quality of these social interactions is supposed to determine the awareness for interdependencies between the participants and the acceptance of a diversity of interests, of mental frames, of knowledge. The different stakeholder groups in a basin have to understand that a complex issue such as integrated watershed management can be better resolved in a collective way, relying on disseminated information and knowledge (Pahl-Wostl et al., 2007).

Considering the huge number of people concerned by integrated watershed management, traditional interactions between experts and decision-makers are not sufficient any more and other additional relational mechanisms have to be considered to go across geographical and organizational scales, including the public at large (Maurel et al., 2007).

In this context the author argues that a Virtual Organization (VO) based watershed management Spatial Decision Support System (SDSS) capable of linking multiple organizations, databases and modeling at the watershed or sub-watershed level can play a crucial role to support the implementation of the enabling framework and the social learning dimension of public participation through two-ways communication processes for the integrated watershed management. A sub-watershed is a smaller basin of a larger drainage area that all drains to a central point of the larger watershed (Gregersen et al., 2008). But as indicated by Zimmerman and Nardi (2006), requirement analysis for a multi-sited, multi-user cyberinfrastructure can be a difficult task. Therefore, both organizational and technical elements are used in this chapter to tackle the requirement analysis for a VO-based watershed management SDSS.

In the following sections, Actor Network Theory (ANT), Virtual Organization (VO) concept and Spatial Decision Support System (SDSS) are introduced first. Essential elements of ANT, VO and SDSS are described and then applied to the requirement analysis of a VO-based watershed management SDSS. Both organizational and technical requirements are analyzed. An example watershed management VO is employed to facilitate the organizational requirement analysis based on ANT and VO concept. The integration of Grid computing technology with various components of SDSS is discussed for technical requirement analysis. Other technical requirements are also identified. Please refer to Figure 2.1 for the organization of chapter two.

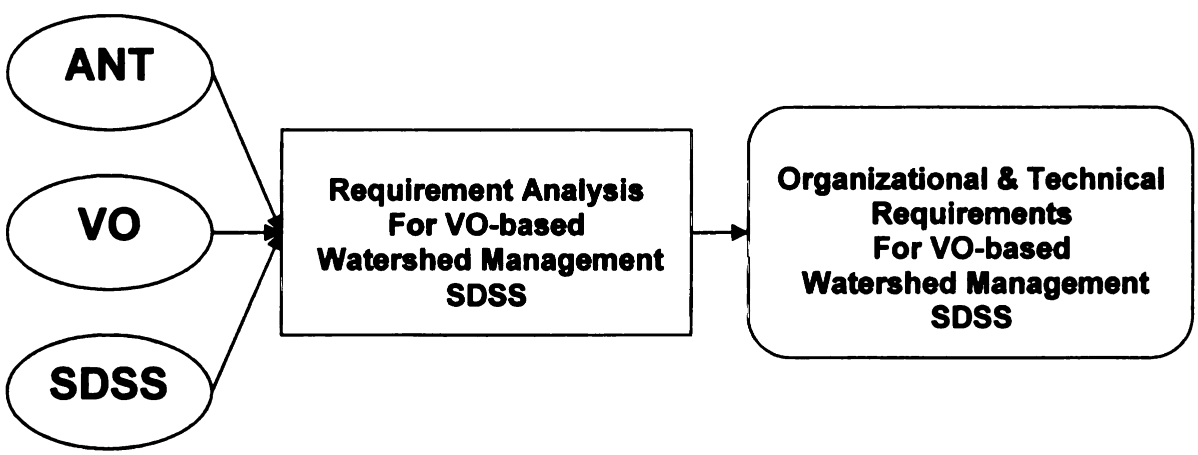

Figure 2.1 Chapter 2 Organization

The goal of this chapter is to collect requirements for a VO-based watershed management SDSS to guide the conceptualization and partial implementation of an Internet-based integration framework for the VO-based watershed management SDSS in the next chapter.

2.2. Actor Network Theory (ANT)

ANT is a social theory and a framework for investigating society-technology interactions that evolved from the work of Michel Callon and Bruno Latour. ANT is very useful for analyzing and understanding the social and technical nature of the watershed management process. The ANT framework was developed by tracing heterogeneous networks of actors and their interactions involved in the production of science and technology (Latour, 1987, Callon *et al.,* 1996). ANT offers explanations of how technology becomes acceptable and is taken up by groups in society. It suggests how technology is socially constructed. ANT provides a fine-grained approach to analyze the mechanism by which social action shapes technology and technology shapes social action. The primary focus is on actors and how they are involved in the shaping of technology. ANT considers the whole world as patterned networks of heterogeneous entities containing both human and non-human elements (Latour, 1999). An actor network is a network where elements of any kind may be included: humans, technological artifacts, organizations, institutions, etc. ANT denies purely technical or purely social relations. It describes the society as heterogeneous. ANT considers both social and technical determinism to be flawed and proposes instead a socio-technical account in which neither social nor technical positions are privileged. Since all interactions between humans are mediated through objects of one type or another (Law, 1992), ANT accepts humans, non-humans and their intermediaries as actors and considers all actors equal (Latour, 2005). An actor is any entity that interacts with other actors or serves as an intermediary between actors. By removing the analytical divide between humans and objects, the ANT framework enhances researchers' ability to examine the nature of interactions that are the building blocks of networks both within and beyond organizations (Latour, 1991, 1992; Law, 1992; Martin, 2000). The ANT framework is very useful for analyzing the partnership-driven watershed management process and the requirements for a VO- based Watershed Management Spatial Decision Support System.

Interactions between actors are the primary building blocks of actor-networks and their many forms are called 'translations' (Callon, 1985; Latour, 1987; Latour, 1997; Latour, 2005). Between human actors, the translation of interests is roughly similar to persuasion and the negotiation of common interests. Between humans and objects, translation occurs during design stage when the object is given with its purpose, program or script in how it interacts or affects other actors (Akrich 1992). Further translation takes place between the object and the actors it encounters as the initial program or script is changed through interaction.

When actors and their interactions are taken together, they form a network. Latour (1997) cautions about the differences between an ANT network and technical or social networks. Social networks exclude non-human actors just as technical networks exclude the human. ANT networks incorporate both with the linkages consisting of stabilized translations and interactions between actors. Actor-network theory assumes the heterogeneous nature of these linkages and seeks to understand the reasons for this heterogeneity (Law, 1992). This uneven distribution in networks requires two types of consideration: temporal and spatial. The temporal considers the durability of the network and its effects and the spatial considers the nature of circulation within a network. Both of these characteristics become central focuses in the tracing or delineating networks.

Interaction and circulation by four action intermediaries: control, money, people's abilities and information, can be utilized to delineate relationships among actors (Martin, 2000).

Convergence is the degree to which the processes of translation and circulation lead to agreement (Callon, 1991). Convergence is a special case of translation that aligns the elements in a network. Alignment and durability can lead to punctualization, a point where the network supporting an actor disappears from view. This takes place when the network components that are responsible for the production of objects or performance of functions are summed up in symbols or artifacts that encapsulate the network (Callon, 1991). In the case of technology, punctualization takes the form of a 'black box' (Latour, 1987).

Actor Network Theory has been widely used in information system research to study the implementation of information systems and in other situations involving technological innovation. Adams and Berg (2004) used ANT to show how reliability of health information sites on the Internet is currently being negotiated. They described some of the central actors and initiatives, including certification schemes, portals, and rating systems, and attempts to analyze which issues are at stake, and what reliability in this novel setting ultimately comes to mean. Faraj et al. (2004) described the evolution of the Web browser technology in the context of commercial actor-networks of innovation. They attempted to take the actor network as a unit of analysis and thus reject the subject-object distinction. In the GIS area, Martin (2000) applied ANT to study conservation GIS implementation in Ecuador. Later in this chapter, ANT will be employed to analyze the social technical watershed management process in assistance of requirements analysis for a VO-based watershed management SDSS.

2.3. Virtual Organization (VO)

As defined in Chapter One, a Virtual Organization is "an identifiable group of people or organizations that makes substantially more use of Information and Communication Technologies than physical presence to interact, conduct business and operate together, in order to achieve their objectives" (Sieber et al., 1998). The VO is a powerful model for accomplishing group objectives in a dynamic manner independent of the geographic location of group members (Palmer & Speier, 1997). A typology proposed by Shao et al. (1998) identifies four characteristic features of a virtual organization:

- Connectivity, which establishes linkages where none previously existed
- Purpose, which creates a common incentive for agents in the virtual organization
- Technology, which enables connectivity
- Boundary, which separates those who are part of the VO from those who aren't

The role of trust is critical, since decisions must be made without the same degree of face-to-face interaction in more traditional settings, and because data, strategic decisions, and objectives must be shared with semi-independent participants in the VO. Because of this greater autonomy, VO participants tend to be more equal, with greater independence than is typical in a hierarchical organization.

The VO paradigm has been highly useful for certain business activities, particularly those that are technologically oriented and require flexibility and rapid adaptation (Jägers et al., 1998). It has also been adapted in academic settings at large and small scales. At large scales, it is common for multidisciplinary research teams with members in several academic institutions to collaborate on projects. At small scales, multiple-authored papers are typically developed in concert, with portions of work done by different authors in physically different places. In either case, electronic transmission of documents and data, as well as ideas, keeps the work coordinated between multiple parties. The network enables the rapid flow of communication, which is critical for the virtual organization. Strader et al. (1998) indicated that an information infrastructure based on the Internet and Intranet technology can support the communication required for effective virtual organization management.

In the business world, because of the growing demands of the global market, small and medium sized business enterprises see virtual organization type of collaboration between companies as a powerful option to give companies new, successful opportunities and ways to stand the pressures of global competition.

Hannus et al. (2005) listed a number of benefits of VO for business enterprises:

- Companies can easily access and use competencies not available internally.
- As consequence, a virtual organization can go for larger, more complex and thus higher value opportunities, than individual companies.
- The VO can more flexibly balance bottlenecks.
- The risks for the projects are effectively shared among the participating companies.
- In trustful relationships there is a strong incentive for joint problem solving and customer satisfaction.

- VO members can have access to very different (international) markets or customers bringing in new opportunities.
- The combined mass of companies allows stronger market presence, e.g., on trade fairs or through advertisement than an individual company.
- VO serves as a very good training ground for management skills. People become more aware of different working practices across the companies, develop an outlook for new opportunities, and sharpen their skills in collaboration and project management.
- VO also enables companies to align investment decisions, strengthening their core competencies or production facilities, while relying for other facilities on other partners. This can significantly increase efficiency of investments and utilization of resources.

They also mentioned significant risks and hurdles for the build-up of a VO:

- Customers often like to have a single company being liable for an order – and also many banks to do not yet have experiences in financing such projects.
- Companies need to build the trust to rely on cooperation.
- The competence mix and market orientation of a VO needs to be carefully evaluated and jointly defined.
- Setting-up and running VOs and projects for business opportunities requires managerial skills – up to the point that the level of managerial competence can be assessed by the level of activity in such networked organizations.

In order to use the benefits and avoid the hurdles, the VO needs to be well planned and implemented. Required competencies and skills as well as methods, processes and conditions need to be understood. Lawson et al. (2005) investigated a virtual organization for Australian tool making industry and indicated the trust is a crucial underlying aspect of successful collaboration. Joia and Neto (2004) studied the implementation of virtual enterprises for government agencies in Brazil and identified security, organizational culture and training as critical success factors for such endeavor. Dunne and Browne (2005) examined four virtual organization cases and found the main reasons for their failures are: insufficient emphasis on initial planning; informal and unstructured sourcing and selection methods for potential partner identification; communication barriers and inadequate information technology support.

The VO theory proves beneficial not only for the business community, but also for the environmental management community. Araújo et al. (2005) presented a virtual Hydro-Meteorological Scientific Network that connects data, computing power and human expertise together in a productive way. Hluchy et al. (2006) described a virtual organization for flood forecasting. Their VO includes computation cycle providers, storage providers, data providers, experts, developers and end users. It utilizes the computational grid to run a large cascade of meteorologic, hydrologic and hydraulic models for flood forecasting purpose. Visualization and workflow management functions are also available in the grid environment to facilitate modeling process. The user friendly graphical interface allows users to interact with the system without knowing anything about grid. One important fact about this system is that it is designed to be used solely by meteorologic and hydrologic experts within the VO. But in a watershed management VO, a variety of users such as decision makers, experts and members of the public etc. have to be considered. The VO theory can certainly help to further our understanding of different needs of these users. For this reason, it will be applied later in this chapter for the requirement analysis of VO-based watershed management SDSS. The above mentioned benefits and hurdles of VO clearly shed some lights on how to build successful Watershed Management VOs.

As indicated in Chapter One, an important technical aspect associated with VO is the Grid Computing technology. It will be explored in more details in the requirement analysis section.

The ANT and VO theories described above form a solid organizational foundation for the requirement analysis of a VO-based Watershed Management SDSS. In the next section, Spatial Decision Support System, a major technical component for a VO-based Watershed Management SDSS, will be discussed.

2.4. Spatial Decision Support System for Watershed Management

2.4.1. Overview

Walsh (1993) defined Decision Support System (DSS) as a computer system, hardware and software, designed to support decision makers interactively in thinking about and making decision about relatively unstructured problems. A DSS provides a framework for integrating modeling capabilities with database resources to improve decision-making processes. Decision makers can interact with the system using intuitively designed easy-to-use graphical user interfaces. Historically, development of the DSSs can be attributed to the ineffectiveness of the old-fashioned Management Information Systems (MIS) available in the 1960s and 1970s. They were data oriented, most of which simply retrieved data from large databases on selected queries. The demand for better modeling facilities and a greater degree of interaction with solution processes spurred development of the new tool known as the DSS (Armstrong et al. 1990). Decision support systems have progressed from tools that simply provide users with the resources to formulate, assess, and compare alternative solutions to applications that educate users about the problem context and how the problem has come into existence (Bellamy et al., 1996). With education as the primary focus, managers and planners can more easily adapt to changing situations through understanding of the causal relationships of the situation at hand (Climaco et al., 1995; Bellamy et al., 1996).

Spatial Decision Support Systems (SDSS) are a type of computer system that combine the technologies of GIS and DSS to assist decision-makers with problems that have spatial dimensions (Walsh 1993). Spatial Decision Support Systems (SDSS) are developed to integrate data, knowledge, and modeling results to identify, evaluate, and recommend alternative solutions to spatially distributed problems (Djokic, 1996; Bellamy et al., 1996; Prato and Hajkowicz, 1999). A SDSS focuses on a limited problem domain, utilizes a variety of data, and brings analytical and statistical modeling capabilities to solve the problems. It further depends on graphical displays to convey information to the users. It can be adapted to decision-maker's style of problem solving, and can easily be extended to include new capabilities as needed (Densham et al. 1989, Armstrong et al. 1990). Leipnik et al. (1993) defined SDSSs as integrated environments, which make use of the databases that are both spatial and non-spatial, models, decision support tools like expert systems, statistical packages, optimization software, and enhanced graphics to offer the decision makers a new paradigm for analysis and problem solving.

Densham et al. (1989) suggested the following three key characteristics of effective decision processes, which can be used to guide the identification of the goals of a SDSS.

- "Iterative: Decision problem is iterative because decision makers generate and evaluate a set of alternative solutions, gaining insights which are input to, and used to define, further analyses."
- "Integrative: Integration occurs because decision-makers, who hold the expert knowledge that must be incorporated into the analysis with the quantitative data in the models, evaluate alternatives across a broad range of pertinent criteria, making value judgments that materially affect the final outcome."
- "Participative: The participation by decision-makers returns control over the decision-making process to them, enhancing the quality of that process."

Based on Geoffrion's (1983) suggested five distinguished styles in a DSS design, Densham et al. (1989) further simplified them as the following six characteristics of SDSS.

- SDSSs are designed to tackle semi or ill-structured problems where either the problems or the objectives or both are not fully and coherently specified.
- They often adopt interactive and recursive ways of system development known as multipass approach, which contrasts the more traditional serial approach involving clearly defined phases like requirements specifications, detailed design, programming, testing and implementation.
- The designs place high value on the flexibility of system use and ease of adaptation to the evolving needs of the users.

- They strive for a genuine integration of data sources and models, including appropriate interfaces to transaction processing and database management systems.
- Users are of prime importance during DSS design. The underlying technology comes second. That is why much emphasis is given on the interface to be user-friendly.
- The users should be able to generate a series of possible solutions by running different 'what-if' scenarios in the models.

In natural resource management, SDSS have proven to be effective in a variety of applications such as flood prediction (Al-Sabhan et al., 2003), river water quality evaluation (Wang et al., 2005), conservation program management and best management practices assessment (Rao et al., 2007). Al-Sabhan et al. (2003) listed issues associated with stand-alone or GIS based hydrologic modeling practices: difficult interface; GIS knowledge requirements; platform dependency; programming knowledge needs; customization difficulty; limited accessibility by non-experts and the public; lack of collaboration support; and finally, costly data acquisition and communications. They further argued that a web-based hydrologic modeling SDSS can help solve most of these problems. They indicated such system can offer openness, user friendly interface, transparency, interactivity, flexibility, and fast communication and be directly accessible to a broad audience including decision makers, stakeholders and the general public. Using a regional river water quality model from EPA and web-based GIS software, Wang et al. (2005) created a web-based river water quality SDSS with similar advantages.

Even though a lot of effort, time, and money were spent on their development, the adoption and success rates of decision support systems and spatial decision support systems have been relatively low (Uran and Janssen, 2003). Newman et al. (2000) attributed this lack of adoption to the complexity and quantity of data inputs, limited computer ownership, and a lack of understanding by potential users of the underlying modeling theory (Newman et al., 2000). Uran and Janssen (2003) examined five spatial decision support systems for coastal zone and water management and found that difficulties in specifying alternatives, complexity in navigation resulting from a large number of options, and lack of adequate support to the decision process are major reasons for the low adoption rates. Furthermore, they indicated that a closer involvement of users during development process would potentially lead to higher adoption rates in the future. An important observation made by the National Research Council's Committee on Watershed Management (1999) is that the difficulty in developing a DSS is not a lack of available simulation models, but rather making these models available and understandable to decision makers. Over the past few decades, federal government agencies have spent millions of dollars on model development. These simulation models are used extensively in research settings, but they are rarely incorporated into the decision-making process in an easy to understand and easy to use fashion.

2.4.2. Components of SDSS

Spatial Decision Support Systems are created either by writing the entire program from scratch, or by linking existing applications that provide the necessary tools (Djokic, 1996). Since writing the application from scratch is complex and often reinvents procedures to provide required functionality, SDSS shells are usually developed by integrating existing applications (Djokic, 1996). In a watershed management context, Spatial Decision Support Systems typically include a user interface, geographic information systems, hydrologic simulation models, and database management systems (Sugumaran, 2002; Densham, 1991; Fedra, 1991). In an actor network, all these components can be considered as actors.

In a watershed management SDSS, linkages are often made between hydrologic/water quality simulation models, a GIS, and a relational database management system which provides an efficient means to store, analyze, and visualize results from the model (Yoon, 1996).

2.4.2.1. User Interface

Historically decision support system research has focused on data, procedures, rule sets, text, forms, and spreadsheets associated with the problem decision domain (Sankar et al., 1995). However, the user interface has been considered to be the most important aspect (Sprague and Carlson, 1982) because acceptance of decision support systems is largely dependent on their ease of use (Uran and Jassen, 2003), which is often determined by the user interface. The user interface controls the communication between the user and the application. A good dialog should be error tolerant and provide user help as carefully phrased informative messages (Molich and Nielsen, 1990). The user interface should be easy to learn, allow graceful shifting from one task to the next, and provide a high level of guidance and feedback based on a user's interactions while giving the user the sense of being in control (Holsapple and Whinston, 2001).

2.4.2.2. Geographic Information Systems

Geographic Information Systems are used as integration platform for Spatial Decision Support Systems. GIS can incorporate data from a variety of sources addressing multi-ownership, infrastructure, and economic concerns. GIS offers the functionality to explicitly model the spatial heterogeneity in landscapes, pasture utilization, and distribution of management units (Bellamy et al., 1996; Bellamy and Lowes, 1999) and effectively analyze non-point source pollution problems (Fraser et al., 1996; Yoon, 1996; Fraser et al., 1998; Guertin et al., 1998; Basnyat et al., 2000).

As indicated in Chapter One, the GIScience community has long been interested in integrating distributed computing capability into GIS. In the past few years, commercial GIS vendors have developed server based GIS software products capable of utilizing Internet technology. This new breed of server based GIS has the potential for rapid increases in the efficiency and effectiveness of the ways in which we share geographic data and geoprocessing capabilities (Peng & Tsou, 2003).

GIS are widely used in watershed management for reporting and technical analysis. It can also be used to support public participation. Specifically in a watershed management context, GIS can be used to identify legitimate stakeholders; manage shared geo-information; communicate geo-information; support GIS-based watershed modeling; collect and communicate public knowledge, perceptions and comments; and bring people together.

2.4.2.3. Hydrologic Simulation Models

Hydrologic models have long been used in watershed management. They provide an important tool for evaluating and assessing hydrologic systems, and environmental managers are increasingly reliant on this technology to support decision making. The classification, application, and development of available models have been reviewed in great detail by others (see Singh, 1995; Maidment, 1993). The majority of models applied today perform simulations using methods derived in the early 20th century.

Even though the first watershed-scale, computer based simulation model was developed almost forty years ago in the Stanford Watershed Model (Crawford and Linsley, 1966), simulating watershed scale processes continues to be an extremely challenging activity, in spite of recent advances in data quantity and quality, and technologies to manage the spatial attributes of watersheds. The National Research Council (1999) recommends that tools be developed to facilitate the transfer of simulation modeling technology, which will provide modeling results to managers for decision making in an easy to understand fashion even when they are based on imperfect information.

Recently GIS has been utilized widely in hydrologic modeling to develop parameter sets and visualize simulation results. Sui and Maggio (1999) identified four approaches for integrating models and GIS: embedding GIS in the hydrologic model and vice versa, and loose and tight coupling between the components, with each approach having advantages and disadvantages. Embedding the GIS functionality in the hydrologic model provides the most flexibility for application design, eliminating dependencies on previous GIS data structures, but most hydrologic modeling packages do not have the visualization capabilities of commercial geographic information systems (Sui and Maggio, 1999). Embedding hydrologic modeling functionality in GIS has recently been conducted by vendors such as ESRI and Intergraph, but the modeling capabilities are usually simplistic and calibration and verification must be conducted outside the GIS (Sui and Maggio, 1999). Loose coupling is completed using "stand alone" GISs and hydrologic models that exchange data using an ASCII or binary data format. Loose coupling relies on existing components, therefore reducing the programming required to develop these technologies, but data conversion between the components can be tedious sometimes (Sui and Maggio, 1999). The final approach, tight coupling embeds a hydrologic model within a commercial GIS utilizing its customization capability with scripting languages such as VB Script, ESRI Avenue or AML etc. (Sui and Maggio, 1999).

These approaches have produced numerous applications that utilize a combination of loose or tight coupling methods (Sui and Maggio, 1999). The Automated Geospatial Watershed Assessment Tool (AGWA; Miller et al., 2002; Miller et al., 2006) uses a hybrid between the loose and tight coupling where specialized routines are created using ESRI's Avenue programming language to prepare input files, but the communication between the GIS and hydrologic models are performed using an ASCII text format. A similar approach was used in developing a generic object-oriented modeling framework (McKinney and Cai, 2002) and integrating GIS into Agricultural Nonpoint Source Pollution Model (AGNPS: He, 2003; He et al., 2001), Better Assessment Science Integrating Point and Nonpoint Sources (BASINS: Lahlou et al., 1998), Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS: De Roo et al., 1989), and the Soil and Water Assessment Tool (SWAT: Srinivasan and Arnold, 1994). The US Army Corps of Engineers also used a loosely coupled approach integrating GIS and their Hydrologic Engineering Center River Analysis System (HEC-GeoRAS: Ackerman, 2002). AGNPS and ANSWERS were integrated into open source GRASS (Geographic Resources Analysis Support System) GIS system as extra modules (Srinivasan & Engel, 1994; Rewerts & Engel, 1991). A SWAT/GRASS interface was built into the earlier version of SWAT package (Srinivasan and Arnold, 1994). Special routines for soil erosion/deposition modeling were developed in GRASS by Mitasova and others (Mitasova et al., 1996; Mitas & Mitasova, 1998). Other hydrologic models such as KINEROS, TOPMODEL, FEA and CASC2D were also incorporated into GRASS as add-on modules (see Woolhiser et al., 1990; Chariat & Delleur, 1993; Vieux et al., 1990; Saghafian, 1993).

Internet-based hydrologic modeling applications such as Michigan State University's Online RUSLE and Purdue University's L-THIA have also been realized (Ouyang and Bartholic, 2001; Choi et al., 2005). Cate et al. (2007) also implemented DOTAGWA, the web-based AGWA tool for a selected pilot watershed. These applications offer several advantages over traditional stand-alone computer applications. A typical Internet application offers a centralized simulation model that does not require installation on local computers and provides access to the latest version of the data and software at all times. Internet applications do not require advanced software or hardware for the end user, since these applications operate through a web browser, with most of the processing conducted on the server. However, deploying applications over the Internet may alienate user groups since access to the Internet is not ubiquitous.

2.4.2.4. Relational Database Management Systems

A relational database management system is a database management system based on the relational model in which data is stored in the form of tables and the relationships among the data is also stored in the form of tables (Rob and Coronel, 2006). The relational database management system for a SDSS must support integrated spatial data storage, spatial query, spatial analysis and cartographic display. Because the data requirement for SDSS can be very large, relational database management systems are considered better than the traditional flat-file database systems in a SDSS. Most GIS and database vendors today provide strong spatial data support in mainstream relational database management systems (Zlatanova and Stoter, 2006).

2.5. Requirement Analysis for a VO-based Watershed Management SDSS

In the previous sections, Actor Network Theory (ANT), the Virtual Organization (VO) concept and Spatial Decision Support System (SDSS) technology have been introduced separately. In this section, they are applied together to the requirements analysis for a VO-based Watershed Management SDSS. Both organizational and technical requirements are investigated.

2.5.1. Organizational Requirement Analysis

2.5.1.1. Overview

The complexity and uncertainty of current water resource issues require new forms of governance that replace the traditional control-oriented hierarchical systems by participatory and flexible systems, based on experimenting and social learning between multiple actors (Doppelt, 2000; Gregory, 2000; Tabara, 2003; Woodhill, 2003). This social learning approach supposedly can contribute to a more integrated and sustainable way of managing water resources on a watershed basis. Integrated Watershed Management is the process of formulating and implementing a course of action involving natural and human resources in a watershed, taking into account social, economic, political and institutional factors operating within the watershed and the surrounding river basins to achieve specific social objectives (UNESCO, 1993; Falkenmark, 2002).

Integrated Watershed Management involves multiple stakeholders and the public at large. Stakeholders include all individuals, groups or organizations that are directly concerned by actions that others take to solve the problem/deal with the issue (Gray, 1989). Green (2003) distinguished the following criteria for identifying stakeholders in watershed management:

- Those whose actions can significantly promote or inhibit the achievement of watershed management in the case of a particular watershed.
- Those who have knowledge or experience that can contribute to that achievement.
- Those who will be affected in one way or another by the outcome of the particular choice (including those who will bear the costs).
- Those who have an interest in the watershed in question.

Typical stakeholders involved in watershed management include: professionals, authorities and elected officials, local groups and non-professional organized entities (broken down into groups focusing on a place such as a group resident association, and those focusing on an interest, such as fishermen), individual citizens, farmers and companies representing themselves and finally, the experts (government and water authority staff, academics, private consultants, etc.). The main challenge for watershed management can be formulated as follows: how can different stakeholders learn to take joint decisions related to water and other resources in a watershed, in which each has a specific stake and interest, in order to arrive at collective sustainable solutions? So the key is about people learning how to deal with each other and their interdependence, while they are learning together to deal with the interconnected issues of their watersheds (Pahl-Wostl et al., 2007).

To help people understand the complex dynamics of the environmental system in a watershed, efforts need to be devoted to developing appropriate spatial decision support systems for decision makers, citizens and lay people. Information contained in the system should be timely, comprehensive, meaningful, and uncertainties must be clearly expressed. The system should have the capability to integrate knowledge from different disciplines about an environmental problem along the whole chain of causes and effects to provide useful information for decision makers. Integrated Watershed Management often involves the following disciplines:

- biophysical sciences: hydrologists, soil scientists, geologists, agronomists, etc.
- engineering sciences: civil, environmental, mechanical, etc.
- computational sciences: GIS specialists, numerical modelers, etc.
- social, political and economical sciences
- managerial sciences

Such a system should support and facilitate the critical communications among various stakeholders with different backgrounds, so they can better understand each other's view on the watershed. Actually in all areas of environmental policy making, including land use and water resources management, the call for improved communication between scientists and decision makers is ubiquitous (Callahan et al., 1999; Schiller et al., 2001; Siepen and Westrup, 2002).

Therefore, the first essential requirement for a watershed management SDSS is to support multi-organizational and multi-disciplinary integration and communication.

According to Actor Network Theory, all stakeholders and technical components of a SDSS involved in a watershed management context can be equally treated as actors in a watershed management actor network. Based on their relationships and the connectivity under the common watershed management goals, they also form a watershed management VO. Figure 2.2 describes the general structure of a watershed management virtual organization that is applicable to any watershed management context.

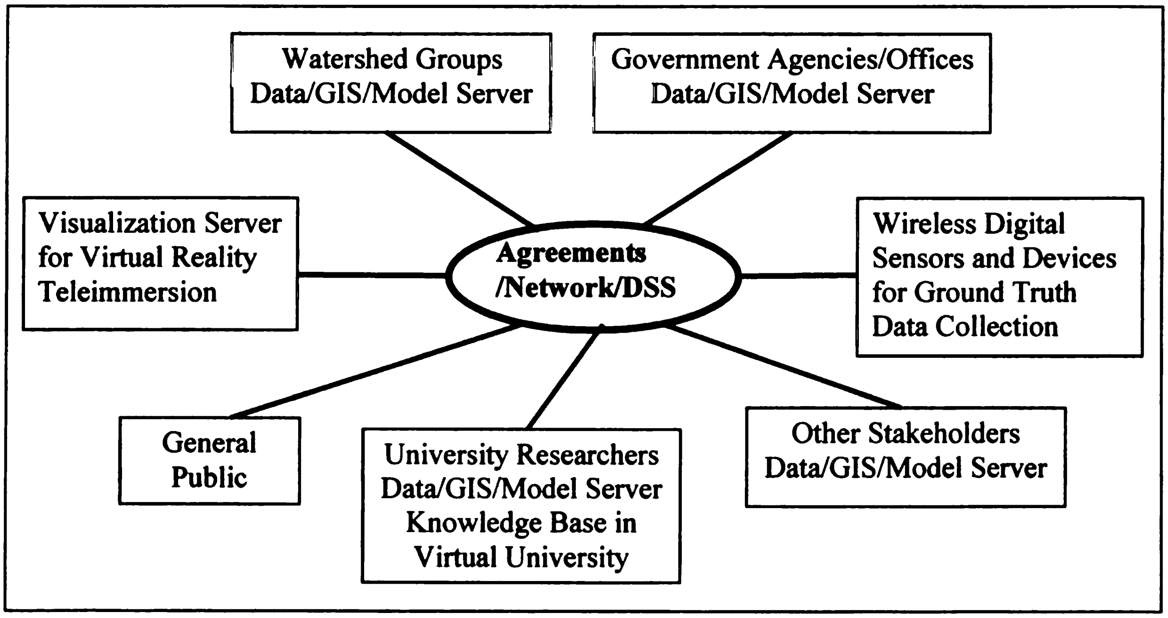

Figure 2.2 Watershed Management Virtual Organization Diagram

This diagram includes both organizational and technical elements of a watershed management VO. The central circle defines the different connectivity between any elements and it does not imply a central power that controls the relationships. A combination of organizational agreement, technical network such as the Internet and distributed decision support system can be used to define the relationship between any two members. In the meantime, any member is an independent entity and can provide its own services to watershed management. But as we know, understanding the inter-relationships among different stakeholders is the key to successful watershed management. So such VO focusing on connecting different organizational and technical elements can be very beneficial to watershed management. The purpose of this general VO structure is to provide comprehensive support for watershed management practices. What flows across the lines in the diagram could be any combination of action intermediaries such as control, skills/abilities, money or information. An example watershed management VO is described in the next section with Actor Network Theory applied to it to identify actors and their relationships.

2.5.1.2. Organizational Requirement Analysis for an Example Watershed Management VO

The Midwest Partnership for a Watershed Management Spatial Decision Support System was created in April 2002. The goal of the partnership is to develop, promote, and disseminate web-based spatial decision support systems to help manage watersheds in the Midwest region. In particular, the main objective is to make these systems freely available via the Internet to local officials, natural resource managers, and the general public. The major organizations involved in the partnership include EPA Region 5, EPA Office of Research and Development, Michigan State University, Purdue University and the Wisconsin Department of Natural Resources. Because of the nature of this partnership, it can be considered as a typical example of watershed management VO.

Figure 2.3 describes the actor network for this example partnership watershed management VO.

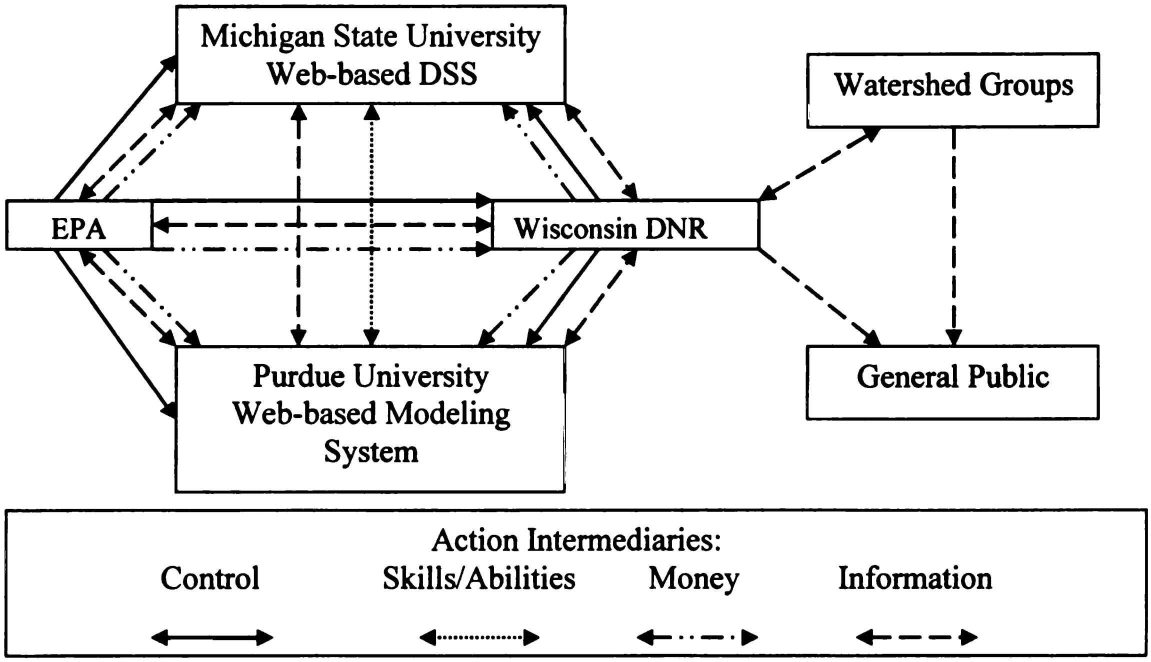

Figure 2.3 Actor Network for the Midwest Partnership for a Watershed Management Spatial Decision Support System

As illustrated in the diagram, all partnership members can be treated as actors and they all have different roles. Public Universities - Michigan State University and Purdue University - lead the main effort in tool development. EPA Region 5 and the EPA Office of Research and Development are responsible for planning the efforts and the general search for funds. The main task of the Wisconsin DNR is outreach and capacity building.

The relationships among partnership actors are described by four action intermediaries in the diagram. EPA as a regulatory and funding agency provides grant money and associated controls to the two universities and the Wisconsin DNR. It also provides environmental information and modeling tools as an information action intermediary. The two universities can share information and people's skills/abilities. The Wisconsin DNR as a state governmental organization may also provide grant money and associated controls to the two universities. Information also flows both ways among the EPA, the universities and the Wisconsin DNR. As a major outreach/education partner, the Wisconsin DNR provides information to watershed groups and the general public for capacity building and outreach. In the meantime, it also collects user evaluation and feedback information that tool developers can use to improve their products. Of course, EPA and the two universities also have outreach/education capabilities and they too can provide information to watershed groups and the general public, even though these are not explicitly described in the diagram. Watershed groups may also provide important local information to state and federal government agencies and the universities. The following example helps to explain the relationships among partners in this VO. The partnership was recently funded by EPA to enable watershed quality information to flow between state and federal government agencies, based on web services technology. In this grant, the Wisconsin DNR is the main funding receiver from EPA. The two universities are subcontractors of the Wisconsin DNR to carry out major developmental work. The end results, such as a water-quality information query and reporting tool and integrated modeling functions, will be made available to watershed groups and the general public.

Strong alignment between actors is the key for success and sustainability of any actor network. In the case of the Midwest Partnership for a Watershed Management Spatial Decision Support System, strong financial and technical alignments and sharable credits among actors helped its steady growth over the past few years.

In terms of a general Watershed Management VO, sharable common goals and credits are the most important factors that determine the sustainability of the VO. An expandable computational infrastructure that can meet watershed management computing needs is also critical. The relationship between VO members can be defined by physical network protocols and organizational agreements. Grid computing technology is an excellent fit to achieve this goal. Of course, steady, diverse funding sources also lead to longevity of watershed management VO.

For a VO-based Watershed Management SDSS, the most important requirement is the capability to support the partnership-driven watershed management process. It's obvious that considerable information and communication technological infrastructure is critical for the Watershed Management VO, especially as more advanced communication forms are enabled. Grid computing, as an emerging information technology, can provide such infrastructure.

2.5.2. Technical Requirement Analysis

2.5.2.1. Grid Computing

The Grid Computing concept is intended to enable coordinated resource sharing and problem solving in dynamic, multi-organizational virtual organizations. The basic idea is to provide computation power to everyone who can access it, like the power grid providing electricity. In this view of grid computing, computing becomes ubiquitous and individual users (or client applications) gain access to computing resources (CPUs, storage, data, applications and so on) as needed with little or no knowledge of where those resources are located or what the underlying technologies, hardware, operating system, and so on are (Foster & Kesselman, 2003). The key values of Grid computing are in the underlying distributed computing infrastructure technologies that are evolving in support of cross-organizational applications and resource sharing - in a word, virtualization - including virtualization across technologies, platforms, and organizations (Joseph et al., 2004; Jacob et al., 2005). Use of open standards is critical in this kind of virtualization, because it enables interoperability among heterogeneous resources and platforms. Grid Computing involves an evolving set of open standards for Web services and interfaces that make services, or computing resources, available over the Internet (Foster and Kishimoto et al., 2005; Baker et al., 2005).

The sharing in the computational grid refers to not only file exchanges, but also to direct access to a spectrum of computers, software, data, and other resources, as is required by a range of collaborative, problem-solving and resource-brokering strategies emerging in industry, science, and engineering. This sharing is necessarily highly controlled, with resource providers and consumers clearly and carefully defining just what is shared, who is allowed to share, and the conditions under which sharing occurs (Foster & Kesselman, 2003; Stockinger, 2007).

Grid Computing enables organizations (real and virtual) to take advantage of various computing resources in ways not previously possible. They can take advantage of under-utilized resources to meet user requirements while minimizing additional costs

(Foster, 2003). The nature of a computing grid allows organizations to take advantage of parallel processing, making many applications financially feasible, as well as allowing them to complete sooner (Foster & Kesselman, 2003).

Grid Computing makes more resources available to more people and organizations while allowing those responsible for the IT infrastructure to enhance resource balancing, reliability, and manageability (Jacob et al., 2005).

Since its emergence in 1997, Grid Computing technology has grown rapidly. Scientific communities around the world have built numerous Grid systems for scientific applications. Araújo et al. (2005) built a virtual Hydro-Meteorological Scientific Network based on Grid technology. Hluchy et al. (2006) created a flood forecasting application using a computational grid. Major commercial software vendors like IBM and Oracle offer Grid solutions for various industries. Organizations such as The Global Grid Forum have been formed to define specifications for Grid Computing. Grid technology is also being converged with Service Oriented Architecture (Foster and Tuecke, 2005). Foster (2005) also described the notion of service oriented science based on Grid technology.

To support VO-based watershed management SDSS, Grid technology has to integrate with different components like GIS, Hydrologic Models, RDBMS and User Interfaces.

2.5.2.2. Grid Computing & GIS

The notion of Grid Computing matches very well with the argument that GIS will finally become part of the urban infrastructure and real-time delivery of data and GIS functions through the network will be passed from professional use to lower level routine use (Batty, 1999). How to utilize Grid Computing technologies for geospatial applications is a new and challenging topic in Geographic Information Sciences. The UCGIS has identified pervasive computing as a major research priority in the Geographic Information Sciences (UCGIS 2002). Since Grid Computing deals with the integration problem from both organizational and technical aspects, research on its utility for geospatial applications is also beneficial for two other research priorities in Geographic Information Sciences identified by UCGIS: GI Partnering and Institutional GIS (UCGIS 2002). Shen et al. (2004) analyzed the weaknesses and problems of traditional GIS and proposed methods to solve these problems with the technology provided by Grid Computing and web services. Wang and Armstrong (2005) demonstrated a Grid-based, problem-solving environment for computationally intensive geographic information analysis based on geo-middleware. Wang and Zhu (2008) indicated that coupling Grid-based cyberinfrastructure and GIS can facilitate computational thinking to analyze massive quantities of spatiotemporal data rapidly and economically. As described in Chapter One, researchers involved the GEON network also published a series of papers on the Grid-based cyber infrastructure for the earth sciences. Data interoperability issues within a Grid environment and integration problems with ESRI software components such as ArcIMS and ArcWEB services have also been studied (Arrowsmith et al., 2004; Memon et al., 2004). The GIS industry is well poised to utilize the potential of Grid Computing because of its mature, web-service culture, interoperability data standards, a process-oriented environment, high performance computing needs and the characteristics of spatial data. But Grid Computing technology has not been widely adopted by commercial GIS software vendors yet.

2.5.2.3. Grid Computing and Hydrologic Models

Hydrologic modeling is a powerful technique of hydrologic system investigation for both the research hydrologists and the practicing water resources engineers involved in the planning and development of an integrated approach for management of water resources (Gregersen et al., 2008). The availability of remotely sensed and other geospatial data provide very useful input data required for physically based hydrological models (Bhaskar et al., 1992; Browne, 1995; Fortin et al., 2001). The use of remote sensing and GIS facilitates the analysis of large scale, complex and spatially distributed hydrological processes (Maidment, 1996; Sui and Maggio, 1999).

The complex, distributed watershed models often require intensive computational resources, particularly when the resolution of the underlying data keeps increasing. This is where Grid technology can provide viable solutions. The high performance computing capability of Grid can help speed up the modeling process. But the parallelization of hydrological models has to be done first. Shi et al. (2002) experimented with the parallelization of a soil erosion model in a Grid environment. Hluchy et al. (2006) used Grid-based parallelization techniques to solve problems of precise flood prediction and potential damage assessment.

Another area of hydrological modeling that can benefit from Grid Computing is uncertainty analysis. For example, a Monte Carlo simulation for a hydrological model can be run on hundreds of computers within a Grid and, hence, increase the speed of the whole process. As an example, Lei et al. (2006) utilized Grid technology for reservoir uncertainty analysis.

2.5.2.4. Grid Computing and RDBMS

RDBMS (relational database management system) is a type of database management system (DBMS) that stores data in the form of related tables. An important feature of relational systems is that a single database can be spread across several tables. Relational databases are powerful because they require few assumptions about how data is related or how it will be extracted from the database. As a result, the same database can be viewed in many different ways (Allen and Creary, 2003). Today, almost all full-scale database systems are relational.

The performance and scalability requirements of relational databases have always been critical for end users. Grid technology can improve both the performance and scalability of a database (Segal, 2003). In fact, the commercial relational database providers like Oracle and IBM have realized the benefits of Grid Computing and have integrated Grid technology into their products. Sterck et al. (2007) integrated database and Grid technology for a bioinformatics application.

2.5.2.5. Grid Computing and User Interfaces

The user interface is the aggregate of means by which users interact with a particular machine, device, computer program or other complex system. The user interface provides means of input, allowing the users to manipulate a system, and output, allowing the system to produce the effects of the users' manipulation (Galitz, 2007). Many technological innovations rely upon User Interface Design to elevate their technical complexity to a usable product. Grid technology is no exception. The idea behind the GRID IT environment is to make the complicated inner workings of the system transparent to the end users. The user interface is obviously the key here. Wood et al. (2004) have presented a Graphical User Interface for Grid Services.

2.5.2.6. Other Technical Requirements

Besides the VO support requirement, other user requirements were collected based on reviewing the literature, the watershed management decision-making process and discussions with watershed groups and government officials. Based on these inputs, the following requirements were identified.

- *The system must support multiple organizations and public participation in a watershed management VO.*

  The social and technical nature of watershed management demands technology that can support communication and collaboration among multiple organizations. Public participation implies public communication. That means that government agencies, at a minimum, have to inform the public at large about issues concerning water and watershed management. Every higher level of participation, such as consultation, etc. implies ever higher demands on the quantity and quality of the information to be given. It implies also that this communication becomes more bi-directional and interactive. Nevertheless, it is all but evident to decide in which way and to what extent the public has to be informed (Webler and Tuler, 2001). A VO-based watershed management SDSS has to support all these communication and collaboration needs. A Grid-based IT infrastructure can provide such support.

- *The system must provide interactive spatial data display services.*

Users of the system require extensive interaction with spatial data through an appropriate user interface. The required operations should include zooming in and out, panning, and toggling spatial layers on and off (Densham, 1991). This provides users with basic data-viewing functionality found in typical GIS applications.

- *The system must provide interactive non-spatial data display services.*

  Users of the system require extensive interaction with non-spatial data through a proper user interface. The required operations should include table data and text displays (Djokic, D. 1996).

- *The system must provide distributed data access and geoprocessing capabilities.*

  Users of the system require access to distributed data and geoprocessing methods made available by different organizations as web services and the capability to display data and use methods locally (Dangermond 2007). This is very important in an increasingly serviced-oriented IT environment.

- *The system must provide access to simulation models.*

  Users of the system require access to different simulation models and the capability to run them for scenario analysis. These models could be watershed-based hydrological models such as SWAT, AGNPS, etc. or economic analysis models. These models should be integrated with the system in a proper way so users can use them through a uniform interface (Sui and Maggio, 1999).

- *The system must provide alternative scenario generation and analysis functions.*

  Users of the system require the capability to generate alternative scenarios and analyze the pros and cons of each output (Choi et al., 2005).

- *The system must be extensible, so new data and models can be easily added incrementally.*

  The system should be extensible and scalable. As new data and models become available, it should be possible to integrate them into the system without causing major changes to the existing architecture (Walsh, 1993).

- *The heterogeneous components within the system must be interoperable with each other and with external systems.*

  The components within the system, such as GIS, models and databases, should be interoperable. The system should also be interoperable with external systems based on existing standards (Densham, 1991).

- *The system must provide a user-friendly interface.*

  Users of the system require an intuitive interface that can help them learn to use the system easily and heuristically (Densham, 1991; Walsh, 1993).

- *The system must be web-enabled and easily accessible.*

  The system must be web accessible to users. The Internet provides an excellent platform for technology transfer (Lane et al., 1999).

2.6. Conclusions

As illustrated in this chapter, the social/technical nature of watershed management demands a multi-organizational and multi-disciplinary VO-based Watershed Management SDSS. Such a system should support the management of large volumes of multi-sectoral and multidisciplinary information in a distributed environment, and the communication between the scientific and policy sectors and between decision-makers and involved stakeholders. The system should translate often complicated modeling results into an easy-to-understand format for environmental decision makers.

This chapter suggests that Grid Computing, combined with advanced geospatial technology, can provide an effective organizational and computational architecture for such a VO-based Watershed Management SDSS. After a conceptual watershed management VO was described, an existing watershed management VO was used to facilitate the requirements analysis for a medium-sized, VO-based Watershed Management SDSS incorporating actor from federal and state government, academia and environmental groups. Concepts of Actor Network Theory were applied to the requirements analysis process and they proved to be very useful for such an endeavor. Detailed requirements were specified in the previous section. The integration of decision making and communication into a web-based environmental decision support system within a watershed management VO presents the best opportunity for effectively integrating sciences into real-world watershed management decision-making processes because of the social/technical nature of watershed management. In the next chapter, the requirements defined in this chapter will be used to guide the design and partial implementation of a Grid-based integration framework for the VO-based Watershed Management SDSS.

Chapter 3. Grid Computing and VO-based Watershed Management SDSS

3.1. Introduction

As indicated in Chapter Two, the multi-organizational and multi-disciplinary nature of watershed management demands an enabling decision support framework that can assist such cross-organizational and cross disciplinary integration and collaboration. The Grid Computing technology based on the Virtual Organization model clearly meets this requirement. In fact, Grid technology and the VO concept have been used in a variety of environmental applications. For example, Araujo et al. (2005) described a successful Grid Empowered Hydro-Meteorological Scientific Network to support a cascade of models that simulates the behavior of the atmosphere, hydrographic basins, aquifers and reservoirs. Hluchy et al. (2006) presented a Grid based flood prediction VO. The Earth System Grid (ESG) project targeted their efforts toward the problems faced by the climate modeling community (Bernholdt et al, 2005; Williams et al., 2007). Kendall et al. (2008) built a web-enabled collaborative climate visualization application within the ESG. But one important limitation of all these research efforts is that they have largely been conducted in the academia with very few linkages to environmental agencies and user communities and the applications built within these endeavors are mostly used by experts and researchers only.

In this chapter, the author addresses this limitation by conceptualizing a grid based integration framework with connections to government agencies and broad user communities for the VO-based Watershed Management SDSS. The implementation of selected components for this framework is also presented in a project context for the Army Corp. of Engineers. The main goal of this project is to create a sediment runoff analysis SDSS for two local watersheds in northern Indiana by combining and customizing existing online tools from Michigan State University and Purdue University. The author is responsible for overall system architecture design and development of the modeling system on MSU's end.

Section 3.2 describes the details of the integration framework. The design and implementation of an example VO-based watershed management SDSS within the framework is reported in section 3.3. Section 3.4 explains the parallelization of a water quality model in a grid environment. Section 3.5 concludes the chapter.

3.2. A Grid based Integration Framework for the VO-based Watershed Management SDSS

The social and technical characteristics of watershed management demand a SDSS that can support Virtual Organization environment and provide high performance computing capabilities. Based on the requirement analysis for VO-based watershed management SDSS done in Chapter Two, the author designs the following conceptual Grid based integration framework for the VO-based Watershed Management SDSS (Figure 3.1) as a general architecture for such a system.

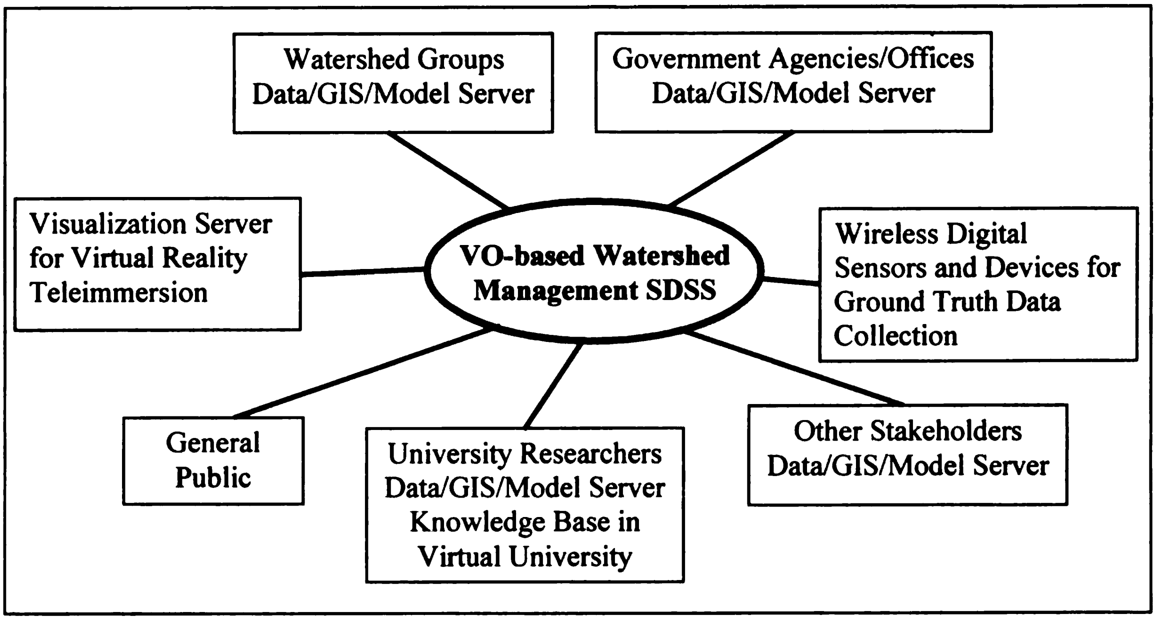

Figure 3.1 Grid based Integration Framework for Watershed Management VO (Derived from Figure 2.1)

In this conceptual framework, all components except for the box labeled 'General Public' are connected as a loosely coupled extensible, interoperable and scalable hierarchical VO-based spatial decision support system for watershed management. Every square box except for the General Public one can be considered as a VO member with its own spatial decision support system. The General Public is also a VO member but without its own spatial decision support system. So this framework is actually a system of systems in a distributed network environment. Technically all these systems are made interoperable with one another through web services or Grid protocols. The specific interoperability capabilities are developed incrementally for different user needs and requirements within the VO. This framework connects different watershed management related organizations in a watershed management VO. These organizations participate in the VO by different means.

University researchers usually have strong technical capabilities so they may contribute both database and modeling services. They may also provide training services because of the educational nature of the university. The university researchers are often domain experts too so they can also provide applied consulting services. The government agencies are typically responsible for public environmental information dissemination so they often provide database services. Some government agencies such as USGS or EPA may also make various environmental models available to the public, but in general these models are not provided as online web services for various reasons (EPA, 2008; USGS, 2008). Of course the government agencies are also charged with other non-technical responsibilities such as policy making and enforcement etc. Watershed groups are grass-roots organizations founded and maintained by citizens or nonprofit groups for the purpose of protecting particular watersheds (Davenport, 2002). Some watershed groups may have their own spatial decision support system but most of them don't have the technical resources to maintain an online system that can provide services to other entities in the watershed management VO (Davenport, 2002). Therefore most watershed groups are pure end users of the system within the VO. Even though watershed groups may not contribute technical resources, they often play a very important role in building essential organizational connections among actors within the VO. Other stakeholders with their own interests in watershed management may also have their own database or modeling services for others to use. And at the meantime, they are end users of the system as well. The wireless and digital sensors within the system are used for field data collection purposes. These data may be used to calibrate model or as model input. The visualization server is used for data and model result visualization to help people understand issues at hand better. The General Public within the VO is often viewed as people who just want to access public information. Anyone can connect to the system through a user-friendly interface that provides a single entry point to the whole system. And the system architecture is transparent to the end users so they may not realize that they are utilizing different computing resources within the system from different organizations in the VO.

3.3. An Example VO-based Watershed Management SDSS

To further illustrate this conceptual framework, let's take a look at an example watershed management SDSS designed and developed by the author at Michigan State University's Institute of Water Research. This system has the potential to be Grid-enabled. It's also part of the Midwest Spatial Decision Support System described in Chapter Two. The system is called Digital Watershed (DW). The DW system connects federal agencies; universities, state government and other organizations to form a very effective watershed management VO. The goal of this VO is to develop, promote, and disseminate web-based spatial decision support systems to help manage watersheds in the Midwest region. In particular, the main objective is to make these systems freely available via the Internet to local officials, natural resource managers, and the general public.

Digital Watershed provides a user-friendly spatial decision support system that utilizes the national 8-digit watershed database within the EPA BASINS program. Watersheds are delineated by USGS using a Hydrologic Unit Code (HUC) system based on surface hydrologic features. This system divides the country into 21 regions (2-digit), 222 subregions (4-digit), 352 accounting units (6-digit), and 2,262 cataloging units (8-digit) (Seaber et al., 1987; USGS, 2007). An 8-digit watershed is one of these 2,262 cataloging units. This comprehensive 8-digit watershed database contains all regulated facilities, river networks, DEM, state soils, and other relevant data layers. The overall system architecture of DW is illustrated in Figure 3.2.

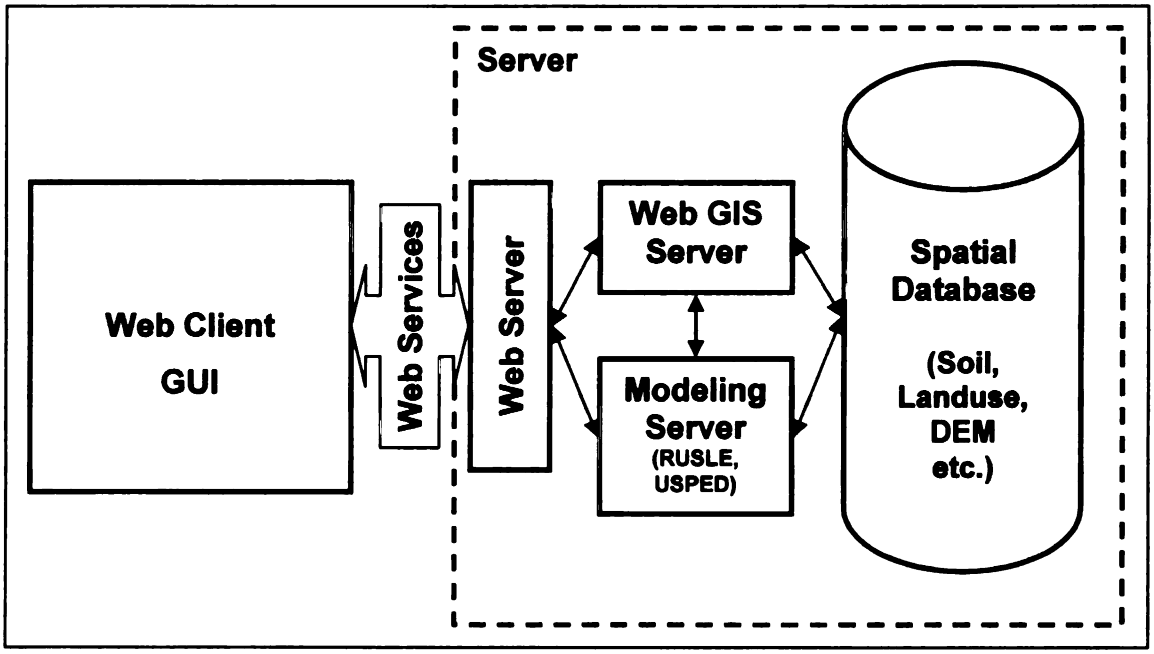

Figure 3.2 Digital Watershed System Architecture

The Digital Watershed system provides end users with three forms of access to an interactive GIS for specific 8-digit watersheds. The address-based entry allows users to locate their watersheds with a street address or by clicking on a location on a regional map. The search entry allows users to search for their watershed by name or Hydrologic Unit Code (HUC) code. The interactive GIS provides basic spatial functions such as zoom and pan. A visualization function allows end users to generate a 3-D view of any 8-

digit watershed. Using the USPED modeling function, one can run an erosion and deposition model to calculate erosion and deposition pattern in a watershed. USPED stands for Unit Stream Power - based Erosion Deposition, a simple model predicting the spatial distribution of erosion and deposition rates for a steady state overland flow under uniform rainfall excess conditions (Mitasova et al. 1996, Mitas and Mitasova 1998). The system also includes a precalculated 10-meter resolution sediment data layer based on the SEDMOD model for the selected watersheds in the Midwest region to help end users identify areas at high risk of erosion. SEDMOD, an acronym for Spatially Explicit Delivery MODel, calculates a Sediment Delivery Ratio (SDR) which can be useful to calculate the amount of eroded material that would be available for transport and that is deposited along hillslopes and streams (Fraser 1999). Total amount deposited along hillslopes and streams is equal to the amount transported. The interoperability features of Digital Watershed include seamless links (a single click) to the TerraServer (Barclay et al., 2000) for aerial imagery and Google Earth and Maps (Google, 2008). The TerraServer Web site developed by Microsoft and USGS is one of the world's largest online databases, providing free public access to a vast data store of maps and aerial photographs of the United States (Barclay et al., 2000). The link to TerraServer is done via OGC WMS (Open Geospatial Consortium Web Map Service) protocol. The link to Google Maps and Google Earth is implemented by passing watershed boundary data to the Google Mapping interface and generating a KML file from the same watershed boundary data. KML is the data format Google Earth uses for spatial data. The system is also connected with Purdue University's online L-THIA modeling system through web services. L-THIA, Long-Term Hydrologic Impact Assessment, is designed to help these people to quantify the impact of land use change on the quantity and quality of their water. This tool employs land use and soil characteristics from the user along with thirty years of precipitation data to determine the average impact that a particular land use change or set of changes will have on both the annual runoff and the average amount of several non-point source pollutants (Engel et al., 2003).

The DW system is extensible because new data layers and new models can be added over time. It's also designed to be interoperable with other online SDSS systems within a VO as mentioned above. The system provides scalability in that it contains a hierarchical database for watersheds at different spatial scales. A recently completed project by Michigan State University and Purdue University involving the author for the US Army Corps of Engineers can help illustrate more details about how a loosely coupled distributed Spatial Decision Support System of multiple online systems might actually work.

The major goal of the project is to develop a fully Web-based watershed management SDSS for two critical watersheds in Indiana, the Burns Ditch and Trail Creek watersheds, on the southern end of Lake Michigan for erosion and sediment control purposes. Erosion is a major environmental concern in the areas surrounding Great Lakes waters in the United States (and Canada). Great Lakes Tributary Modeling Program was established by the U.S. Army Corps of Engineers (USACE) to develop computer modeling tools for Great Lakes watersheds to facilitate management planning by various stakeholders to reduce erosion and associated water quality problems. This web-based SDSS was developed as part of the program. The management system is fully Web-based and was built by linking two existing Web-GIS applications hosted separately at Purdue University (the Long-Term Hydrologic Impact Assessment, L-THIA, Web modeling tool) and Michigan State University (Digital Watershed Web mapping tool). Interoperability between the two systems was implemented by extending both systems and passing dynamically re-projected vector GIS data and modeling results between the two sites. The integrated system takes advantage of complementary data and modeling capabilities from both applications to construct a complete SDSS to facilitate management decision making for erosion and nonpoint source pollution reduction. It allows end users to browse GIS data, dynamically delineate watershed boundaries, make changes in land use and/or apply Best Management Practices (BMPs) within a watershed, and run hydrologic and erosion models to assess different management scenario impacts on hydrology, water quality, and sediment yield. It also allows preliminary sizing and cost estimation for building a number of erosion and sediment control structures. The Web-GIS was advocated as a spatial decision support system (SDSS) to support state and local measures that are designed to reduce tributary loadings of sediments and pollutants. The purpose of this work is to help USACE reduce the need for, and costs of, navigation dredging, while promoting actions to delist Great Lakes' area of concerns (AOCs). According to the user survey results (see Table 3.1 in section 3.3.5), the system was well received during a stakeholder workshop for its user-friendly graphical user interface (GUI) design and usefulness in potential local level management efforts to combat erosion and nonpoint source (NPS) pollution in Great Lakes region.

Specific objectives of the project include: 1) extend two existing systems to allow BMP application and erosion modeling; 2) establish interoperability between MSU's Digital Watershed system and Purdue's watershed modeling system to allow seamless integration of the various mapping and modeling components for the resulting watershed management system; and 3) disseminate the integrated modeling system through workshops and evaluate the system based on user feedback.

Since MSU's DW system was already described above, here only a general description of Purdue's SDSS is given. The overall system architecture of Purdue's SDSS is illustrated in Figure 3.3.

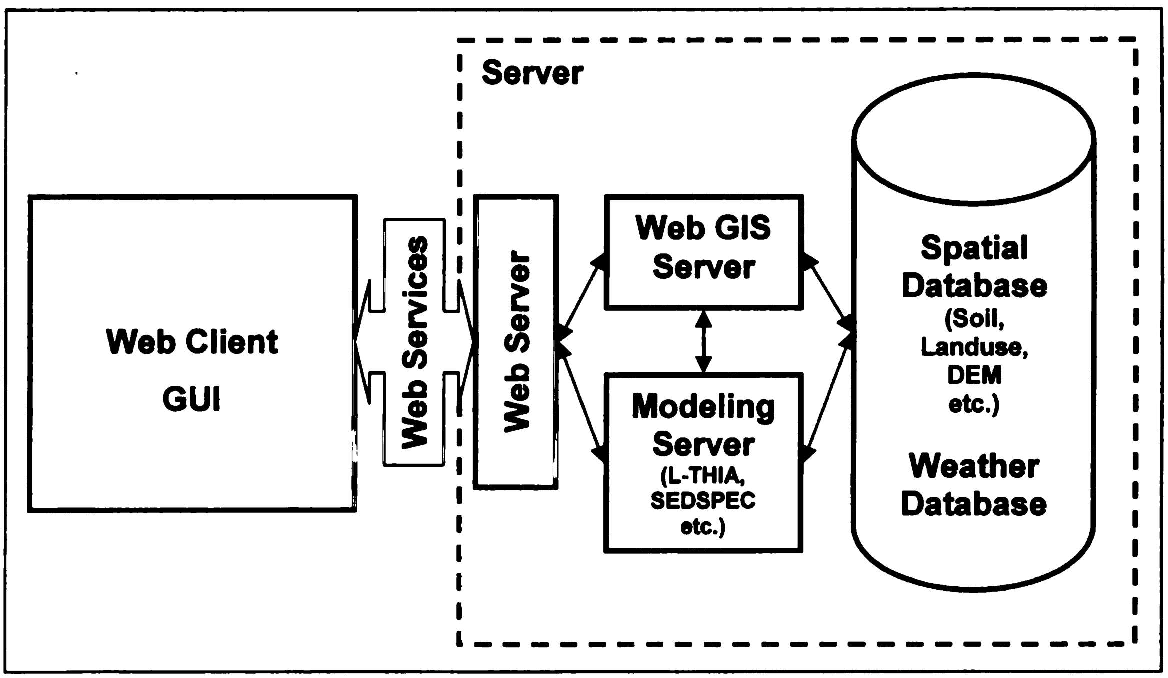

Figure 3.3 Purdue SDSS System Architecture

Purdue University's Web-GIS based spatial decision support system (SDSS) encompass the following modeling tools: 1) Long-Term Hydrologic Impact Assessment (L-THIA) model for small watersheds (Engel et al., 2003); 2) Sediment and Erosion Control Planning, Design and SPECification Information and Guidance Tool (SEDSPEC, Tang et al., 2004); and 3) the real-time watershed delineation and land use change impact assessment system (Engel et. al., 2003, Choi et al., 2005) that includes two additional tools for estimating imperviousness and peak runoff. The Purdue SDSS's geo-database covers the five states in US EPA region 5 (Indiana, Illinois, Michigan, Ohio, and Wisconsin). Data include aerial photos, digital elevation model (DEM), land use, topographic maps, soils, streams, and other civil features. These modeling tools are introduced below.

The L-THIA model uses long term (30+ years) daily weather, soil type, and land use data to simulate runoff volumes and loadings in the runoff for 13 NPS pollutants including nitrates, phosphorus, heavy metals, and fecal coliform. Long-term daily outputs are presented in terms of loadings for each land use type and the probability of exceedance curves. Details of the model were described previously (Engel et al., 2003).

The SEDSPEC model estimates small watershed peak runoff that can be used for the preliminary design of hydraulic and erosion control structures. For peak runoff estimation, two standard hydrologic models (the Rational Method and TR-55) were implemented to simulate short-term peak runoff based on site-specific hydrologic soil groups and land uses. The hydrologic models estimate peak runoff using storm data stored in a database. SEDSPEC can be used to design or provide recommendations for the structural dimensions of channels, culverts, grass-lined channels, level terraces, low water crossings, runoff diversions, sediment basins, and storm water detention basins. Estimates of construction costs for these structures are also provided. Details of the model were described previously (Tang et al., 2004).

The above-mentioned modeling tools and a tool that estimates imperviousness using the mean imperviousness of each land use type in percentages and the overall imperviousness in a watershed or area of concern were integrated into a Web-GIS based SDSS (Choi et al., 2005). The online SDSS allows users to delineate a watershed, extract land use, soil, and weather data from backend databases to form model inputs, and run hydrologic models and analyses results based on land use changes. Delineation of watershed boundaries can be done with a user-specified drainage point on a stream segment, flow accumulation, and flow path derived from a digital elevation model (DEM).

It is noteworthy that both Purdue's and MSU's Web-GIS systems have been widely used by local, state government agencies, as well as environmental consulting professionals (Watermolen, 2008).

The following three sections provide detail on particular system components: how they functioned to model important hydrologic elements, and how these components were integrated for the project.

3.3.1. Erosion modeling

To estimate soil erosion, sediment yield, and the impact of implementing BMPs, the Revised Universal Soil Loss Equation model (RUSLE) was chosen. RUSLE is an erosion prediction model that estimates long-term average annual soil loss resulting from the detachment of soil due to raindrop splash and overland runoff from field slopes in specific cropping and management systems and from rangeland (Renard et al., 1997; Renard and Ferreira, 1993). RUSLE is a replacement for the Universal Soil Loss Equation (USLE) and retains its six factors in that equation, as shown below.

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where **A** is the long-term average annual soil loss (ton acre^{-1} yr^{-1}), **R** is rainfall erosivity in [(hundreds of ft-ton) inch acre^{-1}hr^{-1}yr^{-1}], **K** is the soil erodibility in [ton acre^{-1} (hundreds of ft-ton)$^{-1}$inch^{-1} acre hr], **LS** is the dimensionless slope length and steepness factor, and **C** and **P** represent the dimensionless impacts of cropping and management systems and of erosion control practices, respectively (Renard et al., 1997). The RUSLE model was first developed by the USDA-Agricultural Research Service and was first released in 1993 (Renard et al., 1997). It has been widely used by USDA-Natural Resources Conservation Service (NRCS) nationally, and it has been adopted internationally as well. There is a wealth of information and data available for its application for many locations (see e.g., Ouyang and Bartholic, 1997, 2001; Nyakatawa et al., 2001; Angima et al., 2003; Fu et al., 2006; Nyakatawa et al., 2007; Schiettecatte et al., 2008).

The RUSLE model predicts long-term average annual erosion (Renard et al., 1997). In this project, however, the desired erosion related estimate is the sediment yield. Soil erosion refers to the soil dislodged from its original location due to rainfall and/or overland runoff. Not all of the dislodged soil, however, is transported in runoff water to a nearby stream or lake. A portion of the eroded soil is deposited at lower points in the watershed whenever runoff slows down. The amount of eroded soil that actually reaches a stream or other water body is called sediment (Fraser, 1999). Hence, for a given watershed, the long-term average annual sediment yield can be estimated by multiplying the long-term average annual soil erosion potential by a sediment delivery ratio. The sediment delivery ratio is the ratio between the actual lost sediment to the total erosion (detached soil) potential from a watershed (Novoty, 1980). The sediment delivery ratio varies between 0 and 1. There are different ways to determine sediment delivery ratio for a watershed. In this project, a relationship between watershed size and sediment delivery ratio is used. In other words, the sediment delivery ratio for a watershed is determined as a function of the watershed size (Roehl, 1962; Renfro, 1975).

In this project, the RUSLE equation is applied to a watershed by way of multiplying the raster (or grid) data layers (10 meter resolution) for the factors in the RUSLE equation in a watershed. Then, total watershed soil loss is calculated by summing up soil loss from all cells in the watershed. Finally, the sum is multiplied by the sediment delivery ratio for the watershed to arrive at the sediment yield value in tons yr^{-1}.

The erosion BMPs considered for this project include both structural and non-structural BMPs. Non-structural BMPs include no till, reduced till, and conservation tillage on agricultural field and riparian buffer strip. No till refers to the total cover (100 percent) of soil surface with crop residue. Conservation tillage leaves at least 30 percent of the soil covered by crop residues. Reduced tillage is an in-between tillage type. Structural BMPs include sediment basins and grassed waterways. To represent the different types of BMPs in the RUSLE equation, the **C** and **P** factors are adjusted for each of the BMPs accordingly.

3.3.2. Web-GIS based SDSS for erosion and water quality management

The overall architecture of the Web-GIS SDSS is shown in Figure 3.4. There are three common components in any Web-based modeling system: the user interface, backend server databases and modeling programs, and the Web server situated in between handling Hypertext Transfer Protocol (HTTP) connection and Web Service calls.

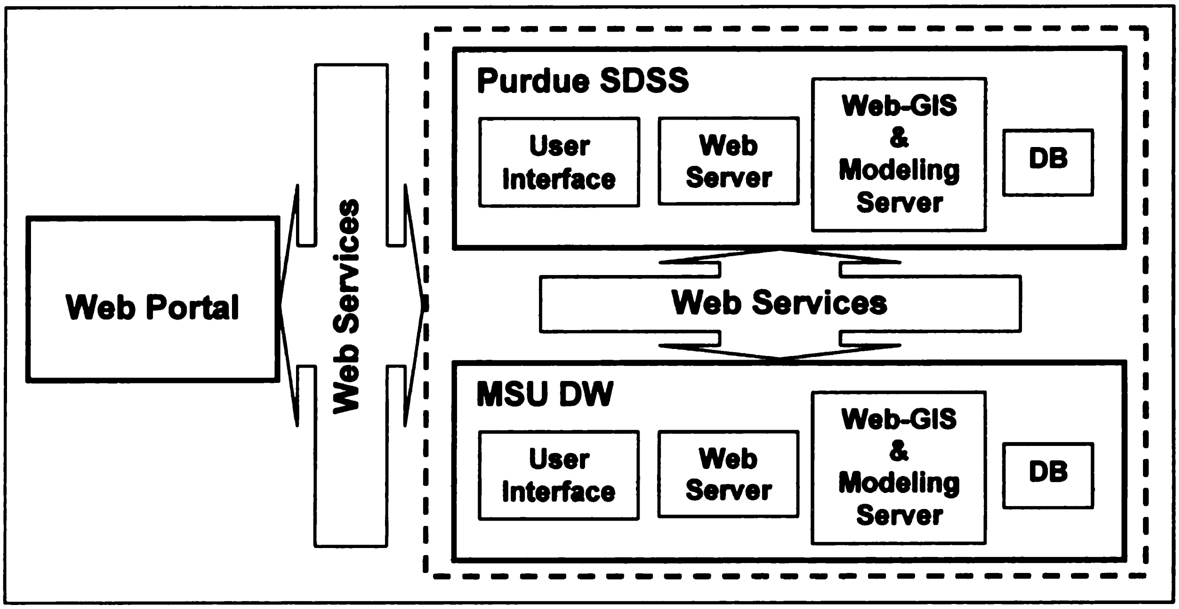

Figure 3.4 Burns Ditch Trail Creek Web-based SDSS System Architecture

The development team includes the author and Tong Zhai of Purdue University. The author is the overall designer of this architecture and developer of the modeling system on MSU's end. Tong Zhai is responsible for interface and BMP parameterization implementation on Purdue's end.

The Purdue Web-GIS interface is built using the open source MapServer (http://mapserver.gis.umn.edu/) software with a Java applet front end. It handles watershed delineation based on a user-specified outlet point and user digitization of areas within a delineated watershed for land use change or erosion BMP implementation. Its hydrologic models, introduced earlier, can provide before and after land use change hydrologic impact assessment for the delineated watershed.

The MSU Digital Watershed Web-GIS system is built using Internet Mapping software from ESRI. It stores the raster data layers for the **K**, **LS**, and **C** factors for RUSLE simulation for the project area. The default **P** factor is assumed to be 1.

Web portal page provides all different entry points to the system. Through the interoperable approach, described in the next section, watershed and BMP area boundaries are first delineated by the Purdue Web-GIS system and sent to the MSU Digital Watershed system, which are used to clip raster layers of the erosion factors. BMP type specific **C** or **P** factors are then incorporated into the corresponding raster data layers for the user-defined areas. Then, the RUSLE model is run for the watershed to calculate total erosion, which is then modified by a sediment delivery ratio to arrive at long-term average annual sediment yield for the watershed. The results are then displayed back in the user's Web browser.

3.3.3. Interoperability

The interoperability operations of data passing and other related operations between the Purdue Web-GIS and MSU's Digital Watershed are carried out behind the scenes without the need of explicit intervention by the user. This ensures seamless integration of the two Web-GIS systems. The integrated SDSS links the two physically separate Web-GIS systems by passing dynamically re-projected vector GIS data and modeling results between them, as shown in Figure 3.5.

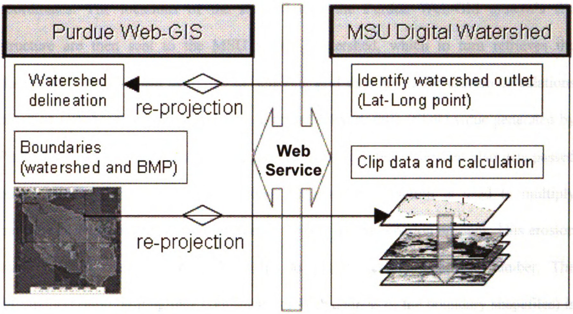

Figure 3.5 Interoperability

As shown in Figure 3.5, users first identify a drainage outlet point on a stream line within the MSU Digital Watershed Web-GIS environment. The outlet point's latitude and longitude coordinates are sent to the Purdue Web-GIS system, where they are re-projected to the Universal Transverse Mercator (UTM) Coordinate System, Zone 16 coordinates for the project area. Then, the Purdue Web-GIS uses the point to delineate a watershed based on DEM derived flow accumulation and flow path data. Users can also initiate watershed delineation starting from the Purdue Web-GIS system. Either way, a watershed will be delineated, upon which a summary of land use and soil group of the delineated watershed is displayed within the Purdue Web-GIS system. After reviewing the watershed land use and soil summary, users can proceed to digitize areas within the watershed to assign land use changes and/or apply erosion BMPs. The boundaries of the watershed and the digitized areas are saved on the Purdue Web-GIS as ESRI shapefiles first. Then, they are re-projected from UTM zone 16 coordinates to Latitude-Longitude coordinates. The locations of the shapefiles in the Purdue Web-GIS system's file structure are then sent to the MSU Digital Watershed, which in turn retrieves the shapefiles and uses them as masks for clipping grid data layers for erosion calculations based on GIS-based RUSLE model. A sediment delivery ratio (SDR) value generated by Purdue Web-GIS system based on the area of the delineated watershed also gets passed on to MSU's Digital Watershed system. Map algebra function is used to multiply multiple RUSLE factor grid layers together to get the final erosion amount. This erosion value is then multiplied by SDR value to get the actual sediment number. The information (latitude-longitude coordinates or Web address of the boundary shapefiles) is passed through web service calls on programs that reside on destination Web Servers. This description of interoperability also illustrates the distributed modeling process.

3.3.4. Burns Ditch Trail Creek Watershed Management VO

To further explain this example VO-based Watershed Management SDSS, all stakeholders involved are put into different boxes in Figure 3.6 for illustration purposes.

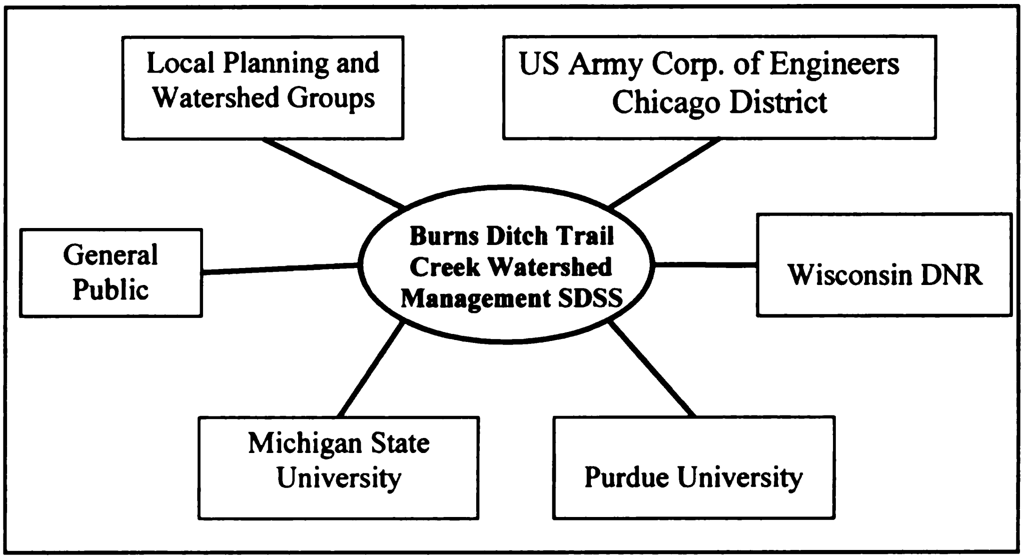

Figure 3.6 Stakeholders Involved in Burns Ditch and Trail Creek Watershed Management SDSS

As shown in Figure 3.6, multiple institutions are participating in this Virtual Organization for the common objective of reducing sediment runoff in the two watersheds. US Army Corp. of Engineers (USACE) provides funding sources and control for the project. The two universities are responsible for the development of the watershed management SDSS. Specifically, Michigan State University brings resource development expertise and perspective while Purdue University introduces engineering expertise and perspective into the system. Previous user evaluation and feedback information on Digital Watershed and L-THIA collected by Wisconsin DNR provides valuable input and validation for system development. Local planning and watershed groups are primary users of the system and they can also help with outreach and education.

3.3.5. Use Case

The implemented watershed management system for the Burns Ditch and Trail Creek watersheds is available online at http://danpatch.ecn.purdue.edu/~eqip/erosion/. This system fulfills most of the functional requirements specified in Chapter Two. Users can access the SDSS from either the Purdue Web-GIS interface or MSU Digital Watershed interface based on their preferences. Both ways will lead to the same system capability.

The general procedure for watershed management using the SDSS is shown in Figure 3.7 (a-d). This figure contains screen shots from the actual system. From the initial entry page, either from Purdue Web-GIS or MSU Digital Watershed, the user would zoom in to identify the area of interest and nearby stream, and then initiate watershed delineation by a single click on the stream (Figure 3.7a). A watershed is delineated in approximately ten seconds based on the user specified outlet point and underlying DEM data. The user can then activate the online digitizing interface to either manually digitize areas for BMPs or allow the system to determine the contributing areas in the case of grassed waterways or sediment basin structural BMPs. Then, the user specifies the type of BMP for the digitized area using the land use/BMP dialog box (Figure 3.7b). For grassed waterways, the user also needs to digitize a line inside the contributing area to define the location of the waterway. Tillage BMPs can only be applied to agricultural land uses. Once the changes are made and saved by the online digitizing tool, a before and after land use and BMP summary is given, along with a modeling toolbox for hydrologic and erosion modeling (Figure 3.7c). The available models can then be used to obtain a quantitative estimate of the impact from the land use changes made or BMPs applied (Figure 3.7d). The whole process can be repeated for the same delineated watershed as many times as the user would like. This allows multiple management scenarios to be evaluated and compared.

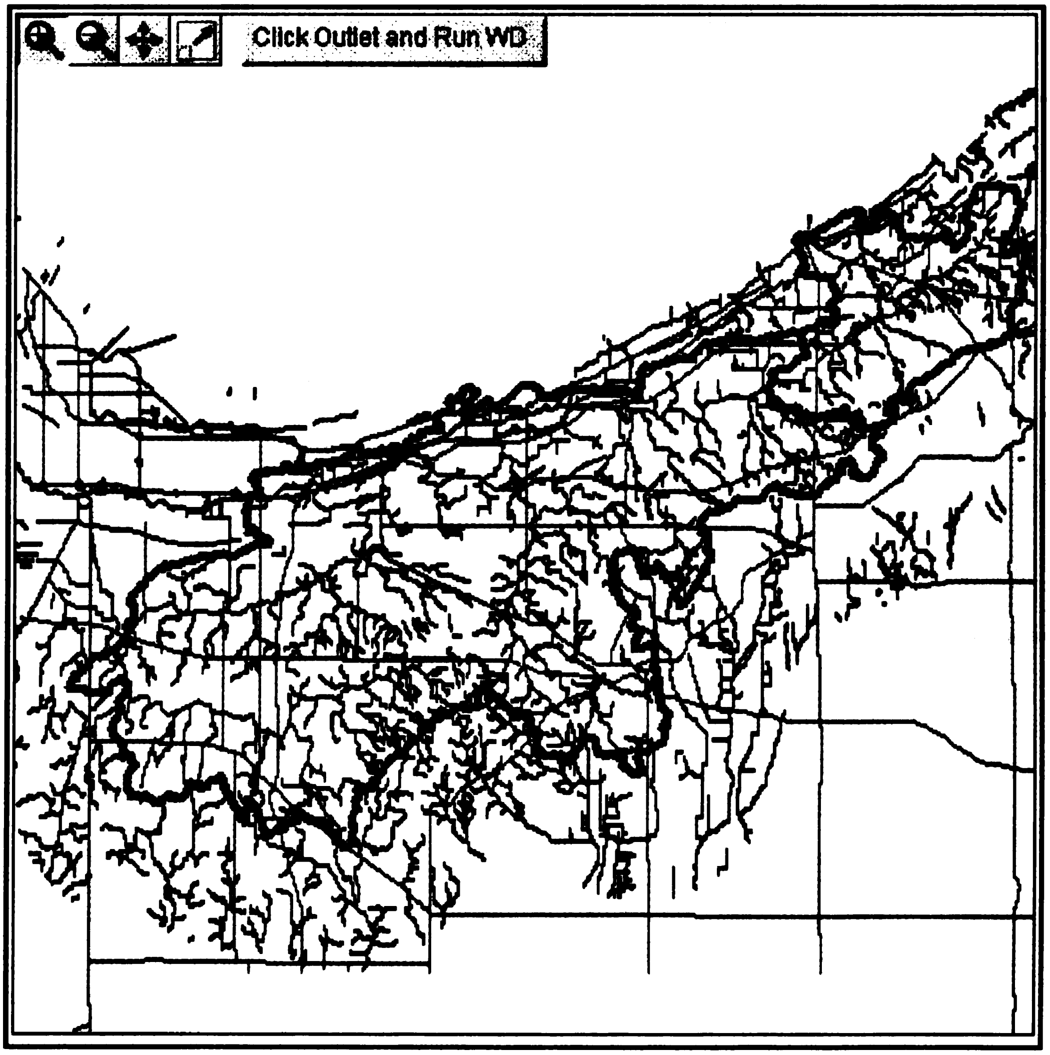

Figure 3.7a Use Case Part A

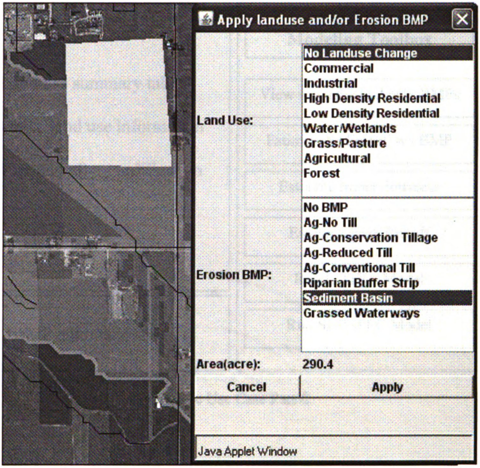

Figure 3.7b Use Case Part B

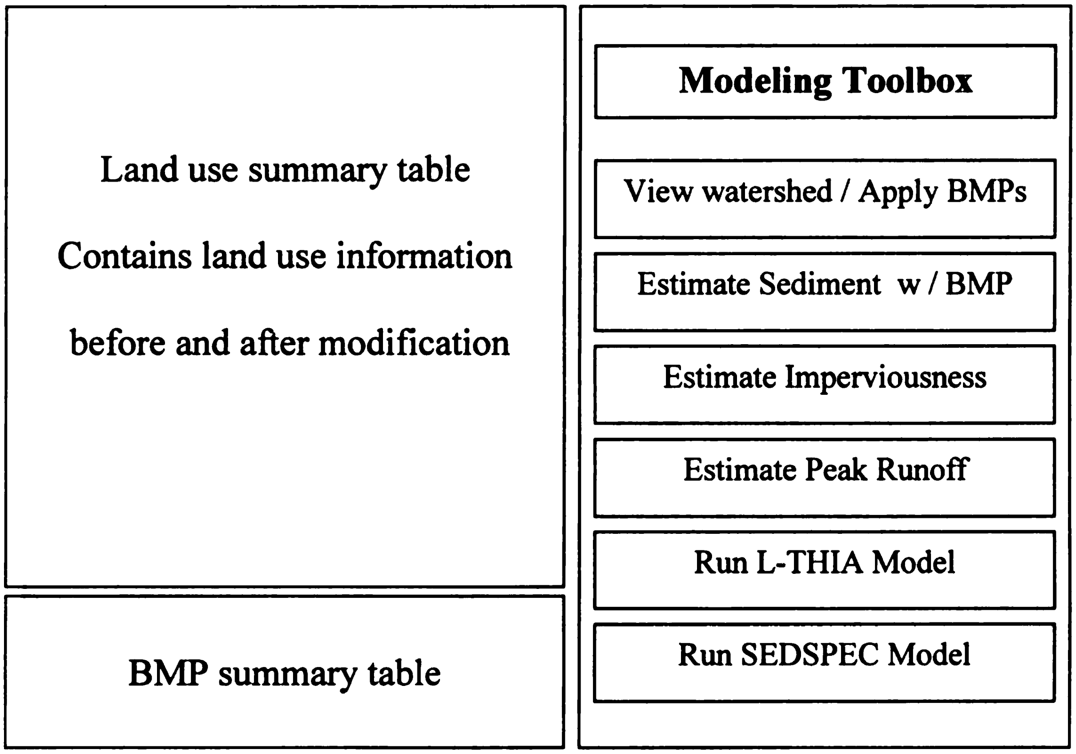

Figure 3.7c Use Case Part C

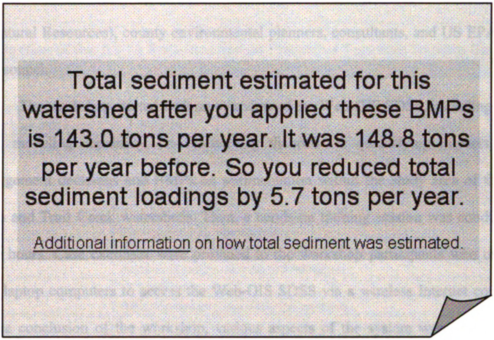

Figure 3.7d Use Case Part D

3.3.6. Training Workshop

The Web-GIS based watershed hydrologic and sediment modeling SDSS was delivered at a stakeholder workshop on December 19, 2006 at the Northwestern Indiana Regional Planning Commission (NIRPC) building located in Portage, Indiana. The workshop was organized and conducted by Army Corp. of Engineers and Great Lakes Commission (Bucaro, 2006). The Great Lakes Commission was directly contracted by Army Corp. of Engineers for workshop arrangement and coordination (Bucaro, 2006). Participants of the workshop represented a diverse set of stakeholder groups, including local water resource managers (Save the Dunes Council, Great Lakes Commission, Little Calumet River Basin Commission, Michigan City Port Authority), staff from several state agencies (Indiana Department of Environmental Management, Indiana Department of Natural Resources), county environmental planners, consultants, and US EPA Region 5 personnel.

The workshop started with an overview of the Web-GIS SDSS, including its work flow, modeling capability, and underlying theories for quantifying impacts of land management decisions and BMPs on sedimentation within the study area of the Burns Ditch and Trail Creek watersheds. Then, a hands-on training session was conducted for three hours. Case exercises were provided to the workshop participants who used their own laptop computers to access the Web-GIS SDSS via a wireless Internet connection. At the conclusion of the workshop, various aspects of the system were discussed and feedback forms were distributed among the participants.

User feedback is summarized in Table 3.1. Overall, feedback from participants was very positive. The workshop was rated excellent or good for its content and presentation by six out of seven and five out of seven completed user surveys, respectively.

Evaluation of the ACOE Sediment Runoff Predictive Tool and Training Session				
Training Material		Total number of response received: 7		
		Excellent	Good	Fair
- content		4 out of 7	2 out of 7	1 out of 7
- presentation		4 out of 7	1 out of 7	2 out of 7
Web Site Design and Content			Scale: 1= poor, 5= exceptional	
4.0	Navigability is good. Links are clearly labeled. Can move from page to page easily.			
4.0	This site offers interactivity. The visitor is engaged using the site.			
4.0	This site uses appropriate page format. Pages are not inordinately long.			
4.0	Can easily find information			
4.1	This site is aesthetically appealing. Good use of graphics and color.			
4.0	Additional resource links are included.			
4.0	Information is useful			
4.2	Rich content and will likely be revisited.			
4.1	How this website compares in content to similar websites			
4.1	Please indicate the usefulness of the Watershed Tools and Summary?			
Modeling tools in the SDSS		Scale: 1= poor, 5= exceptional		
	Score	User-envisioned usage		
View watershed/Apply BMPs	4.3	1 Target specific problems 1 This can provide a "first peek" into land use changes		
Estimate sediment	4.0	1 Look at and compare drainage calculations for new projects 1 to protect coldwater fishery		
Estimate Imperviousness	4.2	1 Look at and compare drainage calculations for new projects 1 to protect coldwater fishery		
Estimate Peak Runoff	4.0	1 Look at and compare drainage calculations for new projects 1 calculate rough number for peak discharge 1 Impacts on flooding and water quality impacts		
Run L-THIA Model	4.0	1 Changing land use—for watershed planning		
Run SEDSPEC Model	3.8	1 To identify areas of concern		

Table 3.1 User Feedback Summary

Participants also viewed design of the website and content displayed throughout the site favorably. Design elements such as layout, navigability, interactivity, formatting, aesthetics, and similarity to other websites covering similar topics received consistent scores between 4.0 and 4.1 on a scale of 1 to 5 (1 being poor and 5 being excellent). Combined with participants' responses to usefulness of the information (4.0) and likelihood of revisiting the site (4.2), this part of the survey results suggest that the site's design and content is user-friendly, meaningful and allows users to focus on making decisions, which is the purpose of an SDSS.

The last section of the survey queried participants about specific models and tools that constitute the SDSS. The first three tools – view watershed/apply BMPs, estimate sediment, and estimate imperviousness – received very favorable scores. Participants rated the "view watershed/apply BMPs" tool the highest (4.3). The importance of this score cannot be understated since this specific tool assumes users understand their water quality problem, use the GIS map service to learn about existing land cover and other resource conditions, know about or can quickly learn about agricultural BMPs from the website, construct scenarios for improving water quality and input required data. A score of 4.3 out of a possible 5 suggests we are meeting our goals of developing a user-friendly, meaningful decision support system.

Direct feedback from participants during and after the workshop also indicate acceptance of the SDSS. Participants stated that they would continue to use the Web-GIS SDSS for watershed management planning and implementation in target areas and for quantifying changes in water quality and evaluating nutrient reductions from various BMPs (using the NPS results from L-THIA) and consider the integration of this information into future enhancements. One participant, for example, stated the following regarding the expansion of the L-THIA model: "*Would like the ability to change assumption to consider agricultural land with land application of manure*". Another participant encouraged expansion of the SDSS to include more agricultural BMPs as well as urban BMPs by stating the following: "*Conversion of agricultural land to urban development is one of our biggest threats. For future updates, it would be nice to* *incorporate various development types (traditional, low impact development (LID), conservation design, etc) to provide planners with additional discussion. ... Also expand BMP options if possible*". Finally, tool developers have continued to answer questions in the months following the workshop about the SDSS from the participants as they apply the tools.

In summary, the survey results and user feedback echo findings from other DSS researchers such as Jarupathirun and Zahedi (2007). In their effort to study the influence of users' perceptual factors in the success of web-based SDSS, they found that well-designed, user friendly, and focused SDSS can help improve its perceived "task-technology fit" (TTF) and "perceived goal commitment", which in turn improves users' "self-efficacy" and their satisfaction in decision quality from using the SDSS. This would lead to greater adoption of the SDSS in real life decision making processes. Other researchers also attributed the greater community acceptance and participation of a Web-based SDSS to developing customized, focused, and user friendly tools for community users who do not have extensive technical skills (Rattray, 2006). From the outset, Web-based GIS improves the availability of geospatial data and the adoption of spatially explicit analysis, and, at the same time, incurs no cost to the end-user through the use of web clients (Peng and Tsou, 2003). Indeed, after the conclusion of the modeling system development and the workshop, users continued communicating with the development team to provide feedback on their experiences using the tool and provide suggestions for tool enhancements.

There are some weaknesses in this watershed management SDSS. First, as pointed out by a number of users after the workshop, the system only considers a limited list of erosion BMPs. Second, the land use classification considered by the current SDSS is overly broad, lacking the representation of variations within some of the land use types, e.g., residential area of different densities. These deficiencies are largely due to the lack of site specific information and data for models to develop such capabilities.

This system proves that integrating multiple SDSS within a VO according to specific user needs and requirements is an excellent way to facilitate the watershed management tasks. To assess whether the VO-based SDSS approach provides better tools for watershed management, user evaluations collected by Wisconsin DNR during two workshops in 2003 and 2004 and two papers (Lucero et al., 2004; Watermolen, 2008) published by its staff members are used in the following sub-section to illustrate the point.

3.3.7. Validation of VO-based SDSS Approach for Watershed Management

Wisconsin DNR, as a member of Midwest Spatial Decision Support System Partnership, assembled over two hundred representatives from diverse agencies and organizations that make or influence land use decisions for two "Changing Landscapes" workshops in 2003 and 2004. Table 3.2 shows a breakdown of workshop participants by affiliation. Workshop attendees examined and evaluated several tools including Digital Watershed and L-THIA. They were asked to provide feedback regarding the tools' utility and accessibility and evaluate them against a number of measures to help Wisconsin DNR identify the factors that make tools particularly useful. Table 3.3 contains a list of criteria derived from the workshops that characterize tools regarded as being most useful to local decision makers. The original raw user survey results can be found in Lucero 2004.

Affiliation	Percent
Federal Government	4%
State Agency	25%
Tribal Government	1%
Local Government	21%
Regional Planning Commission	6%
University/Extension	18%
Private Firm	18%
Nonprofit	7%
Other	1%

Table 3.2 Affiliation of "Changing Landscapes" Workshop Participants (Percentages are rounded to the nearest whole number and may not sum to 100) (Lucero et al., 2004).

Characteristic	Comments
Web-based	Accessible via the Internet; only required software or hardware is an Internet browser.
Cost-free	Housed within the public domain; no purchase cost. Our research indicates that tools that perform basic functions like data access, interactive mapping, and routine modeling increasingly will be made available in the public domain.
Data included	Data required for the tool to function is implicit to the tool. For example, all mapping tools contain spatial data sets that can be customized and displayed to illustrate local conditions. For modeling tools, only the most basic inputs are required. Thus, there is no cost to create unique scenarios when using the tools.
Scalable	Data are accessible at various spatial scales. Tool allows user to assess local conditions within a regional context.
Customizable	Users can address specific needs through features inherent in the tool or through "plug-in" components.
Relatively intuitive	With a user friendly interface. As users and tool developers increasingly rely on Internet-based services for their daily activities (e.g., travel arrangements, news sources, search engines, etc.), consistent, intuitive navigation features are becoming increasingly common.

Table 3.3 What makes a tool useful? Characteristics derived from Wisconsin DNR's evaluative workshops (Watermolen, 2008).

Watermolen (2008) also noted that participants in Wisconsin DNR's technical assistance program often indicate that the "tools do not 'talk' to each other." These users also repeatedly ask for the capability of two or more tools to interoperate with each other so they don't have to worry about the compatibility issues among the tools. Watermolen (2008) further stated that such interoperability can help narrow the choice of tools and create integrated decision support systems allowing users to answer questions in a more holistic manner.

Based on these criteria identified by Wisconsin DNR, it is very clear that VO-based SDSS approach such as the Burns Ditch Trail Creek example system described above offers better tools for watershed management for four general reasons. First, technical components within a VO-based SDSS are already made interoperable so users can utilize them in a more integrated manner. Second, such a VO-based SDSS is also web-based, cost free and doesn't require users to provide data to use them. Third, as the Burns Ditch Trail Creek example system demonstrated, a VO-based SDSS can be made relatively intuitive, scalable and customizable to meet watershed management needs. Finally, a VO-based SDSS can support capacity building on a broader scale because of the involvement of multiple organizations in a VO-based SDSS for watershed management.

In the Burns Ditch Trail Creek example system described above, the author and his collaborators were able to implement and support highly interactive modeling because of relatively low resolution of data and simplicity of the model. But modern data collection technologies now enable researchers to collect large quantities of geographically referenced data at low cost. Increased levels of investment in the public and private sectors also have led to expansions in the areal coverage of spatial databases as well as to increases in their levels of details (spatial resolution) (Dowman, 2005). Spatial models linked to these databases, such as those used for environmental simulation modeling, spatial statistics, interpolation, and network optimization also continue to increase in computational intensity (Armstrong, 1994; Wang et al., 2005). As a consequence of these increases in database size and model complexity, interactive problem-solving and modeling can be difficult to support. Grid-based high performance computing can be used to overcome the computational intractability of large, complex spatial analysis problems. The following section demonstrates the parallelization of a water quality model in a Grid environment. The parallelized model can be integrated into the VO-based watershed management SDSS to utilize distributed computing resources for real time modeling and scenario analysis purposes.

3.4. Parallelization of a Water Quality Model

To support complex real time modeling and scenario analysis in a VO-based SDSS, Grid-based parallel computing technology can be used to improve the computational efficiency of environmental models in general. But such parallelization work for different models is more likely to be done individually because a single generalizable parallelization solution doesn't exist for different computing algorithms used in these models (Magillo and Puppo, 1998; Shi et al., 2002). This is also why a VO-based SDSS using Grid technology can play a very important role in socially oriented watershed management. Once a complex model is parallelized, it can be integrated into the system and become a part of the watershed computing infrastructure. As more models are being parallelized and integrated over time, the VO-based watershed computing infrastructure also grows. This collective effort will benefit generations to come in the watershed or more broadly environmental computing area.

Many spatial modeling applications utilizing geoprocessing are extremely resource-intensive due to large volumes of data and intensive algorithms (Armstrong, 1994). For such applications, parallel processing enables the division of the work onto multiple machines, with potentially large reductions in time to complete the task. This goal has attracted the attention of researchers involved in diverse, high-load geoprocessing activities. Hunsaker et al. (1996) developed a parallel implementation for spatial data error simulation. The task required the production of many equiprobable realizations of a land cover data set using a complex spatial statistical model. Terrain modeling involves operations to generate terrain meshes from scattered points, detecting local surface properties, and calculating viewsheds. Executing these operations on multiple processors is especially useful when grids are large or dense. Magillo and Puppo (1998) summarized progress towards implementing parallel terrain modeling. Spatial environmental modeling of snow conditions across the United States involves intensive use of resources. Research by El Haddi et al. (1996) sought to improve model performance by parallelizing the application. Spatial data mining that involves knowledge extraction from vast stores of spatial data could also benefit from parallelization. Sorokine et al. (2005) presented parallel visualization techniques for large spatial dataset. In all the cases described here, parallelization involves some combination of algorithm development and data model architecture design.

An interesting and relevant technical issue for intensive scientific computation concerns the different rates of technological change for computing power, storage, and network speed, typically measured in doubling time. These rates are roughly 18 months, 12 months, and 9 months, respectively (Foster, 2002). Foster notes that petabyte-magnitude data archives are in the planning stages based on the assumption that this trend will continue. However, processing capacity is not keeping pace. The implication is that local computer power will not be up to the task of processing this volume of data. Network speed, on the other hand, is increasing even more rapidly than storage, as is exemplified by the 40 Gbs/second rate for the Terragrid network (Benner, 2001). As a result, communication-intensive tasks will become relatively more efficient than processor-intensive tasks, encouraging network-distributed solutions for major, processor-intensive tasks.

In general, two separate problems exist for distributing spatial modeling. The first is the problem of parallelizing the relevant algorithms so that they may be employed on multiple machines. The second is concerned with identifying an optimal spatial partition of the database so that the load for each processor is roughly equivalent. Researchers developed parallel algorithms and spatial declustering techniques (Hoel & Samet, 1994; Shekhar et al., 1996). Spatial operations that may be amenable to parallelization possess several qualities. The algorithms may have regularities for parallel processing so they can efficiently use idle cycles on different computers within a VO. Second, the problem may be one that can be spatially partitioned into smaller geographic units and distributed to different processors. Third, although spatial analysis may be intensive due to large data volume rather than complex processing, the results of the analysis may be much smaller than the data volume used for it. For intensive spatial analysis with parallel regularities in the algorithms, the data domain can be divided spatially. Then subsets of data are transmitted along with the (sub) algorithm to different machines. Once these smaller, more tractable subtasks are done, the outcomes are collected, reassembled spatially, and presented or stored.

A substantial challenge for the parallelization of distributed spatial modeling applications has been implementing the low-level processing necessary for enabling multiple processors to work in concert. The Grid facilitates parallel processing by handling much of this. Toolkits have been developed that supply protocols for data handling and communications, fault detection, and cross-platform portability (Foster, 2005). This frees the programmer to concentrate on higher-level issues, such as specific parallelization implementations, improved algorithm design, or speedier heuristics.

To illustrate how Grid-based parallel computing techniques can be used to meet the real time modeling needs of watershed modeling, a parallelized spatially explicit soil loss model was developed using the Message Passing Interface (MPI) standard library that underlies the Grid. The model was run on both a CrayT3E supercomputer located in University of Texas and local PC clusters built by the author at Michigan State University using Grid packages. The architecture of the system is illustrated in Figure 3.8.

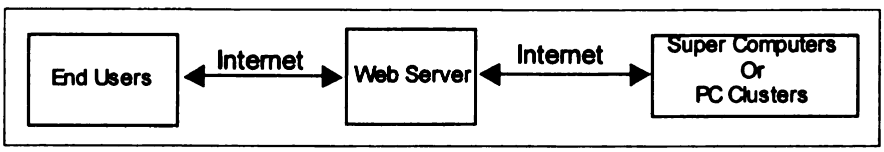

Figure 3.8 Prototype system architecture for parallel processing application.

The soil loss model is the RUSLE (Revised Universal Soil Loss Equation) introduced earlier in this Chapter. The RUSLE model was typically applied in a watershed context using an integrated GIS approach in a raster environment so as to obtain maps for each RUSLE factor. In other words, every factor was obtained or derived from source data as a raster layer. The final result of the model is also a raster layer from map algebra calculation (Fernandez et al., 2003).

In this experiment, RUSLE factors for a 1000x1000 cell raster grid were developed for the calculation of erosion result. This model was run on a single processor on the Cray T3E; processing required 6.5 seconds. The parallel model was then executed on 10 processors, which required 0.83 seconds. Performance gain is significant, although this improvement must be weighed against network transfer time.

This spatial application employs purely local map algebra operations upon one or more input raster layers; that is, the resulting value in cell [i,j] in the output raster is solely a function of values at [i,j] in the input raster(s). In general, for applications involving local operations, processing time may be calculated for a single processor:

$$T_S = nRows \times nCols \times T_C \qquad (1)$$

where T_S is the time to complete the task on a single processor, *nRows* and *nCols* are the dimensions of the raster, and T_C is the time to perform the local function on a single cell. If the operation is parallelized, processing speed is:

$$T_P = 2 \times nLayers \times \frac{(nRows \times nCols) \times bytes_C}{NetworkSpeed(bytes/s)} + \frac{nRows}{nProcs} \times nCols \times T_C \qquad (2)$$

where *nLayers* is the number of input raster layers, $bytes_c$ is the number of bytes per cell value that need to be transmitted, and *nProcs* is the number of distributed processors handling spatial subsets of the operation. Processor speed is held constant for both single and parallel implementations, which is highly conservative (typically one would take advantage of very powerful distributed processors). Setting Eqs. (1) and (2) equal to one another and simplifying results in the following expression:

$$T_C = \frac{2 \times nLayers \times bytes_C}{NetworkSpeed(bytes / s)} + \frac{T_C}{nProcs}. \qquad (3)$$

The right-hand side of Eq. (3) consists of two elements: the added cost of parallelization, which is the time required to transfer the data, and the benefit, which is the reduction in processing time. As *nProcs* increases, the processing time drops. For a given application then, one can identify the number of processors required to offset the network speed bottleneck.

This example shows the great potential of Grid based high performance computing for environmental applications. The complexity and urgency of the world's environmental issues demands us to improve our collective problem solving capabilities. The author believes that building a distributed environmental software system capable of utilizing distributed computing resources is the most effective way to achieve this goal. Such a system can record patterns at different scales and understand different processes that shape these patterns. This system should also be able to grow over time with the ideal of once developed; new knowledge of our planet in the form of databases and models can be integrated into the system. Based on state of the art Grid computing and advanced GIS technology, this system can become part of a national environmental computing infrastructure and will also be able to answer questions about the environment based on information entered.

3.5. Conclusions

Modern watershed management practices require participatory decision making processes involving multiple shareholders due to increasing complexity, interdependency and fragmentation of interests and identities within a watershed. The research in this chapter demonstrates that a multi-organizational VO-based watershed management SDSS based on advanced information and communication technology and geospatial technology offers an effective way to facilitate this process.

Based on the requirement analysis conducted in chapter two, a general Grid based integration framework for the VO-based watershed management SDSS was conceptualized to provide guidance on how to set up the institutional and technical framework for such a system. Then a specific VO-based watershed management SDSS application was described in detail. This application engages government agencies, universities and local planning and watershed groups for the common purpose of reducing sediment runoff into the streams in two relatively small watersheds in northern Indiana. It differs from most stand-alone or single organizational watershed management SDSS seen today because it integrates two separate web-based watershed management spatial decision support systems from two universities to serve the needs of local stakeholders and managers. It also demonstrates how distributed modeling and modularity of environmental model components can be implemented within a VO environment for watershed management. This has rarely been done in the watershed management community. Most of the requirements specified in chapter two were fulfilled in this system of systems. The positive feedbacks from end users of the system demonstrated the effectiveness of VO-based watershed management SDSS approach.

User evaluation results collected by Wisconsin DNR are used to validate that a VO-based SDSS approach offers better tools for watershed management.

As geospatial data resolution continues to increase and spatial modeling becomes more complex and computationally intensive, a more efficient computing infrastructure is needed to improve the performance of complex environmental models so end users can utilize distributed computing resources to conduct what-if scenario analysis in a more timely fashion. The author argues that VO-based Grid Computing technology is an excellent fit for this requirement. A water quality model was parallelized using basic Grid techniques in this chapter to demonstrate this point. The parallelized model can take advantage of distributed computing resources in a Grid environment. A VO-based watershed management SDSS built on top of the Grid technology capable of growing over time offers the best opportunity for participatory decision making process in the watershed management context.

In the next chapter, a new fundamental DEM-based flow analysis algorithm will be designed, implemented and applied to different physiographic regions in the US. This statistically shown better algorithm could be integrated into an evolving VO-based watershed management SDSS to provide better information for decision makers.

Chapter 4. A New DEM-based Flow Analysis Algorithm

4.1. Introduction

It is well known that a number of the algorithms associated with DEM-based flow analysis in most commercially available software are not ideal and they may contain inherent systematic errors. A specific example is the so-called D8 flow routing algorithm. Zhou and Liu (2002) evaluated the errors for various flow routing algorithms based on synthetic, mathematically generated surfaces and found that the D8 algorithm is the worst performer of all. Turcotte et al. (2001) identified three major problem areas for the D8 approach: (1) representation of flow by only eight possible directions with no flow divergence consideration; (2) presence of flat areas and pits, and (3) the absence of information about lakes. But despite all these issues with the D8 method, it is still the most widely used flow routing algorithm in most GIS-based distributed hydrological models today because of its easy availability in commercial software packages. Even though researchers around the world have developed better algorithms for flow routing, they are not easily accessible to most end users. This is where a VO-based Watershed Management SDSS can come into play. In a VO-based Watershed Management SDSS, better models incorporating better algorithms can be integrated into the system and applied to real-world applications in a more timely fashion because of the ubiquitous accessibility of the system. For example, if a new erosion model using a better flow-routing algorithm is developed and integrated into the online system, end users of the VO-based Watershed Management SDSS will have instant access to the new model. This chapter presents a new DEM-based flow routing analysis algorithm based on principles in fluid mechanics. Various existing DEM-based flow modeling methods and their limitations are reviewed in section 4.2. Section 4.3 introduces the new flow routing algorithm called FlowNet. The applications of FlowNet, along with two other popular algorithms, in different physiographic regions are described in section 4.4. Section 4.5 examines the spatial variation in flow accumulation derived from different algorithms. Section 4.6 contrasts algorithm performance on hydrologic applications. Section 4.7 concludes the chapter.

4.2. Hydrologic Modeling Using Digital Elevation Data

GIS-based hydrological modeling has come a long way since the early 1990s. Even though the ten-step modeling procedure presented by David Maidment (1996) still holds true (see Table 4.1), much progress has been made towards the tighter and smoother integration of hydrological models and core GIS functionality and more accurate and realistic representation of physical and man-made features within a watershed.

1. Study design: Objectives and scope of study; spatial and time domain; process models needed, variables to be computed.
2. Terrain analysis: Deriving a watershed and stream network layout from digital elevation data and mapped streams.
3. Land surface: Describing soils, land cover, land use, cities, and roads.
4. Subsurface: Hydrogeologic description of aquifers
5. Hydrologic data: Locating point gages, attaching time series and their average values, interpolating point climatic data onto grids.
6. Soil water balance: Partitioning precipitation into evaporation, groundwater recharge and surface runoff; partitioning of chemicals applied to the land surface.
7. Water flow: Movement of water through the landscape in streams and aquifers. Computing streamflow and groundwater flow rates.
8. Constituent transport: Transport of sediment and contaminants in water as it flows. Computing concentrations and loadings.
9. Impact of water utilization: Locating reservoirs, water withdrawals and discharges in rivers, and aquifer pumping. Their effects on water flow and constituent transport.
10. Presentation of results: Developing visual and tabular presentation of the study results. Use of Internet and CD-ROM to transmit results.

Table 4.1 Ten-step procedure for a GIS hydrology study (David Maidment 1996).

Terrain analysis based on digital elevation data is a fundamental step in GIS-based hydrological modeling. A digital elevation model (DEM), also widely known as a digital terrain model (DTM), is a digital representation of ground surface topography or terrain. A DEM can be represented as a raster (a grid of squares) or as a triangular irregular network (TIN). DEMs are commonly built using remote sensing techniques; however, they may also be built from land surveying and secondary sources such as maps and contours etc. (Wilson and Gallant 2000). DEMs are being increasingly used in GIS for hydrologic analysis. For example, in the popular watershed modeling package SWAT, DEMs are used as a fundamental data layer for watershed modeling (Diluzio et al. 2001, Arnold et al. 1998). This is due to the general availability of digital elevation data, nationally from the USGS (2003) and worldwide including the space-based data available from the NASA Shuttle Radar Topography Mission (SRTM). The increasing computing power in personal computers has also made DEM processing functions more readily accessible and easy to use. DEM-based flow routing analysis has been a traditional research topic for decades in the Geographic Information Sciences (Wilson et al. 2000).

The function of a flow algorithm in a GIS is to transfer flow (water, sediment, nutrients) to lower, adjacent points or areas in a landscape (Desmet and Govers 1996a). Hence, a raster-based, flow-routing algorithm determines the way in which the outflow from a given cell will be distributed to one or more downslope cells. The choice of flow routing algorithm is important and affects the calculation of the upslope contributing area, specific catchment area, stream power index, and several other topographic attributes. Zhou and Liu (2002) used mathematical surfaces to calculate true values of specific catchment area and compared the results with ones generated using different grid-based flow routing algorithms. They found all these algorithms have some level of error associated with them. They indicated that the major cause of these processing errors is the nature of the grid data structure and over-simplified assumptions about the behavior of water flow controlled by the surface morphology. Clarke and Lee (2007) investigated the impact of spatial resolution and algorithm choice on the computation of downslope flow from DEMs. Their analysis revealed only minor differences among the algorithms used. They also found that these algorithms are fraught with critical assumptions and scale effects.

Many different raster-based flow routing algorithms have been implemented to simulate water flow in specific environments. The guiding principles and decision rules employed in five of the most commonly adopted algorithms – the D8 (O'Callaghan and Mark 1984), Rho8 (Fairfield and Leymarie 1991), FD8 (Quinn et al. 1991), DEMON (Lea 1992; Costa-Cabral and Burges 1994), and D∞ (Tarboton 1997) algorithms are reviewed in this section, along with several studies that have compared their performance in different environments.

The deterministic eight-node (D8) single-flow-direction algorithm, the earliest and simplest method for specifying flow directions, assigns flow from each pixel to one of its eight neighbors, either adjacent or diagonally, in the direction with steepest downward slope. This method was introduced by O'Callaghan and Mark (1984). The D8 algorithm works well to mimic the flow of rivers and streams, and flow convergence in valleys (Chorowicz et al. 1992; Quinn et al. 1991; Fairfield and Leymarie 1991; Costa-Cabral and Burges 1994; Tarboton 1997). However, the D8 approach oversimplifies the possible flow direction from a grid center by limiting flow to one grid cell, and as a result, is unable to simulate divergent flows (Holmgren 1994). These limitations are most often expressed by the presence of multiple parallel flow paths in either the cardinal or diagonal directions (*i.e.*, multiples of 45°) that are produced with this algorithm (Fairfield and Leymarie, 1991; Quinn et al., 1991; Costa-Cabral and Burges, 1994). Other sources of error for D8 include the presence of flat areas and pits, and the lack of information on the locations of lakes (Turcotte et al. 2001). An advantage of the method is that it is relatively easy to calculate upslope contributing area and specific catchment area since all flow in one pixel drains into the steepest downslope pixel. Upslope contributing area, therefore, is the number of pixels whose flow reaches the pixel of interest multiplied by the pixel area (Costa-Cabral and Burges 1994).

Fairfield and Leymarie (1991) developed the random eight-node (Rho8) algorithm to break up the parallel flow paths that D8 produces by randomly assigning a flow direction to one of the downslope neighbors, with the probability proportional to slope. This algorithm starts by identifying all the downslope neighboring cells, then calculating the slope gradients in each of these directions, and finally choosing a number from a table of random numbers to direct the flow to one of these candidate cells. The numbers are allocated on a slope-weighted basis such that the potential flow paths with the steepest gradients have the greatest probability of being selected and the overall pattern more or less matches that which would have been produced with the D8 algorithm. However, this algorithm may still calculate unrealistic flow directions in upslope areas and there is now the added problem that a different flow network will be produced each time the algorithm is used because of the reliance on a table of random numbers to allocate flow among multiple downslope cells (Wilson and Gallant 2000). The upslope contributing areas for each cell are calculated using the flow accumulation approaches adopted for D8; however, the degree of randomness implemented in Rho8 means that this attribute will be overestimated or underestimated for numerous cells (Costa-Cabral and Burges 1994).

FD8 multiple flow direction algorithms (Quinn et al., 1991; Freeman, 1991) have also been developed to address the limitations of D8. These methods direct water to every adjacent downslope cell on a slope-weighted basis. Each cell will receive only a fraction of the discharge from each upslope cell, and therefore, the upslope contributing area of the receiving cell is composed of fractional contributions from different cells (Costa-Cabral and Burges 1994).

Lea (1992) developed an algorithm that uses the aspect associated with each pixel to specify flow directions. Flow is routed as though it were a ball rolling on a plane released from the center of each grid cell. A plane is fit to the elevations of pixel corners, these corner elevations being estimated by averaging the elevations of adjoining pixel center elevations. This procedure has the advantage of specifying flow direction continuously (as an angle between 0 and 2π). Costa-Cabral and Burges (1994) presented an elaborate set of procedures named DEMON (Digital Elevation Model Network) that extend the ideas of Lea (1992). Grid elevation values are used as pixel corners, rather than block centered, and a plane surface is fitted for each pixel. The upslope contributing area for each cell in DEMON is computed by successive addition of the influence matrix of every pixel in the DEM (Costa-Cabral and Burges 1994).

Tarboton (1997) proposed the D∞ method that incorporates several ideas from DEMON to assign multiple flow directions to selected cells. This single flow direction (represented as a continuous quantity between 0 and 2π radians) is determined in the direction of the steepest downward slope on the eight triangular facets formed in a 3 x 3 pixel window centered on the pixel of interest (Figure 4.1). Each downslope vector is drawn outward from the center and may be at an angle that lies within or outside the 45° vector (or a multiple of $\pi/4$ radians). If the slope vector angle falls within the facet, it represents the steepest flow direction of that facet. If the slope vector angle lies outside the facet, the steepest flow occurs along the steepest edge. The slope for each vector is calculated and used to determine the ordering of the facet numbers from 1 to 8 (Figure 4.1). If vectors do not flow downslope, a flow direction angle of -1 is assigned to signify flat areas or pits. The flow direction is forced to flow toward a neighbor of equal elevation that has a flow direction resolved in these instances. This ensures that flat pixels drain to a neighbor that ultimately drains to a lower elevation, and eliminates loops in the flow direction angles, so that the user does not need to worry about spurious pits in the DEM. The upslope area of each pixel is taken as its own area plus the fractional areas of upslope neighbors that drain into the pixel of interest, similar to FD8 and DEMON (Tarboton 1997). If the angle falls on a cardinal or diagonal direction, then the flow from each cell drains to one neighbor. If the flow direction falls between the direct angles to two adjacent neighbors, the flow is proportioned between the two neighbor pixels according to how close the flow direction angle is to the direct angle for those pixels (Tarboton 1997).

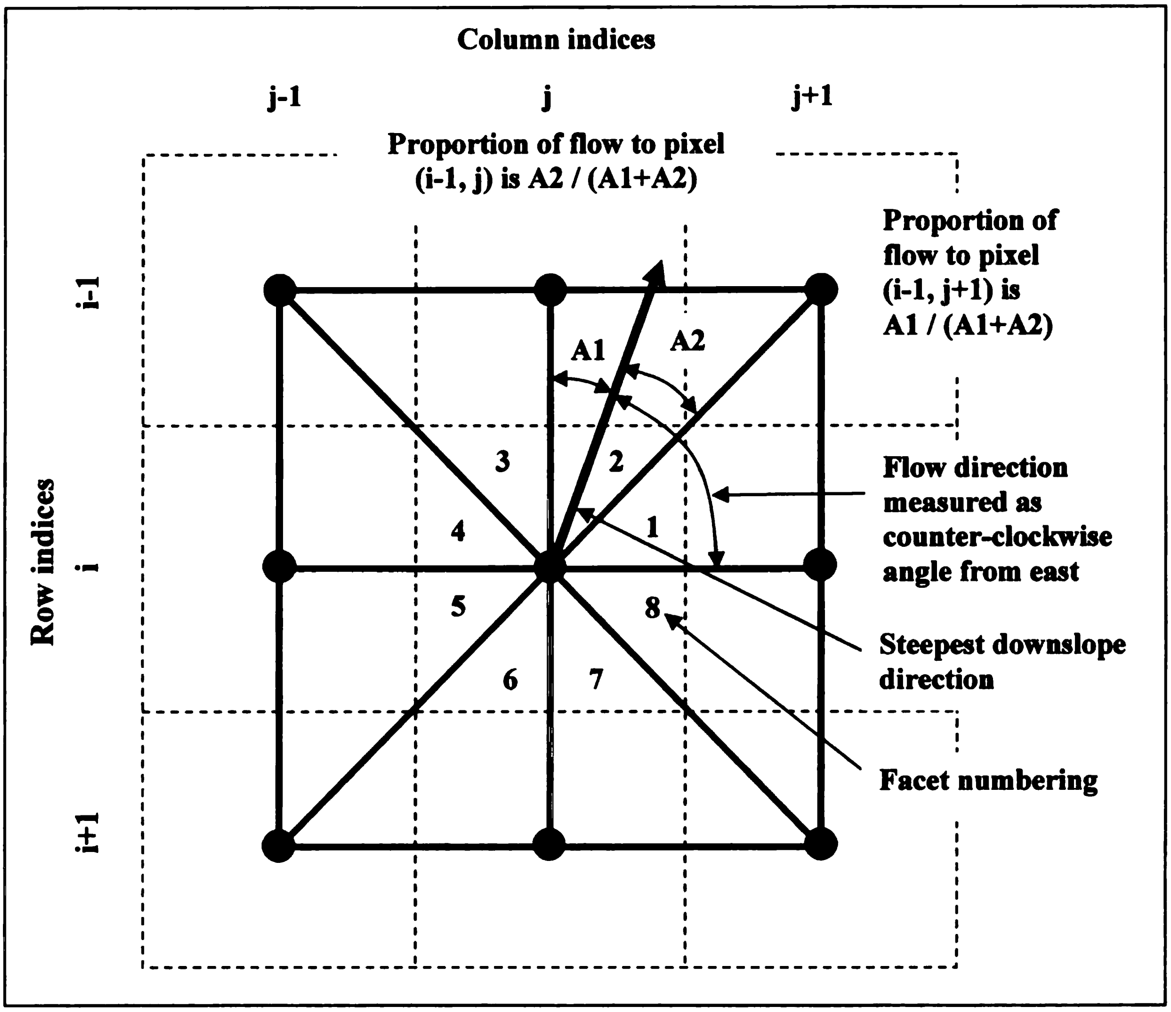

Figure 4.1 Flow direction on planar triangular facets in a block-centered grid (from Tarboton 1997).

The five algorithms described in this section provide a series of rules for directing flow across the land surface represented as a square-grid DEM. These rules vary in two key ways: (1) the method or granularity used for aspect calculations, and (2) the number of downslope cells that can receive flow from each upslope cell.

Despite all the advances in the DEM-based flow routing analysis, all the above-mentioned algorithms do not consider or utilize the physical laws that govern water movement as a fluid through the landscape. These algorithms oversimplify water movement and often treat water as a solid instead of a fluid moving through the landscape.

4.3. New Flow Routing Algorithm

Here the author proposes a new method for the representation and calculation of flow direction and accumulation based on mathematical principles and physical laws that govern water movement through the landscape. In the study of fluid dynamics, we often consider that fluids form a continuum wherein the motion of individual particles is not traced. The focus is on a control volume, a fixed frame in space through which the fluid passes. This is also called the Eulerian view of motion. In the proposed method, this view is adopted and every DEM cell is treated as a control volume. The assumption is that water flows through the saturated DEM surface, so Darcy's law can be applied for the water flow. One implication of this new method is that only four direct neighboring cells (directly above, below and directly left and right) instead of eight for every DEM cell are considered when the water flow is modeled. The four diagonal cells are not considered because mathematically the common area between every DEM cell and its diagonal neighboring cell is 0, so that there is no possible flow between them. This forms the foundation of the new algorithm. The actual flow volume to one or more of the remaining direct neighboring cells is determined by Darcy's law. Darcy's Law is a generalized relationship for flow in a porous medium (Chow et al. 1988). It states that volumetric flow rate is a function of the flow area, elevation, fluid pressure and a proportionality constant. Darcy's Law can be summarized as:

$$Q = AK\frac{\Delta h}{L} \qquad (1)$$

Where,

Q = volumetric flow rate (m^3/s),

A = flow area perpendicular to L (m^2),

K = hydraulic conductivity (m/s),

L = flow path length (m),

Δh = change in hydraulic head (m)

Let's assume that the total incoming flow equals Qt for any center cell that has one or more direct lower neighboring cells. The flow proportion for cell m that is lower than the center cell can be calculated as:

$$Qm = Qt \frac{Slp_m}{Slp_1 + \ldots + Slp_m + \ldots + Slp_n} \quad (2)$$

Where,

Qm = flow proportion for the cell m that is lower than the center cell,

Qt = total incoming flow for the center cell,

Slp_1 = slope between the center cell and the first lower direct neighboring cell,

Slp_m = slope between the center cell and the mth lower direct neighboring cell,

Slp_n = slope between the center cell and the nth lower direct neighboring cell,

m = any integer number between 1 and n,

n = total number of cells that are lower than the center cell, note $n <= 4$.

The proposed algorithm routes the actual flow according to formula (2) from the highest cell to the lowest cell. Its output is a flow accumulation grid A, in which each cell value A_{ij} is the sum of all upstream flows that pass through cell (*i,j*). The algorithm works as follows: First a list *L* is produced by sorting the elevation values in the DEM in decreasing order, and every cell in *A* is initialized to one unit of flow. Then the points are visited in decreasing order of elevation by scanning through *L,* while flow is distributed to lower neighboring cells by updating entries in *A*. When point (*i,j*) is processed, A_{ij} contains the correct final flow accumulation value for (*i,j*), since all higher points (if any) pushing flow into (*i,j*) have already been processed. Conceptually the algorithm corresponds to sweeping the terrain top-down with a horizontal plane, "pushing" flow down the terrain in front of the plane (See figure 4.2 for an illustration of this concept). The actual flow routing calculation of formula (2) is implemented in the following C++ function:

```
void FlowCalculator::moveFlow(int col, int row)
{

	int i, cOffs, rOffs;
	int offsresult; /*, lowCount;*/

	stSortGC *tmp;
	vector <stSortGC *>lowList; // we only need to know the contents
	double ptVal = source->get(col, row);
	double slopeTotal;


	// determine which values are lower
	for (i = 0; i < 4; i++) {
		cOffs = col;
		rOffs = row;
		offsresult = source->calcOffs(i, cOffs, rOffs);

		if (offsresult) {
			if (source->get(cOffs, rOffs) < ptVal) {
				//lowCount++;
				//isLow[i] = TRUE;
				tmp = new stSortGC;

				tmp->dZ = source->get(cOffs, rOffs);
				tmp->iCol = cOffs;
				tmp->iRow = rOffs;
				lowList.push_back(tmp);
			}
```

```
        }
    }

    //calculate slopeTotal
    slopeTotal = 0;
    for (i = 0; i < lowList.size(); i++) {
        slopeTotal += (ptVal - lowList[i]->dZ) / source->cellSize();
    }

    double proportion, curSlope;
    for (i = 0; i < lowList.size(); i++) {
        curSlope = (ptVal - lowList[i]->dZ) / source->cellSize();
        proportion = curSlope/slopeTotal;
        result->get(lowList[i]->iCol, lowList[i]->iRow) += result->get(col, row) * proportion;
    }


    // Done, cleanup
    for (i = 0; i < lowList.size(); i++) {
        if (lowList[i] != NULL) {
            delete lowList[i];
            lowList[i] = NULL;
        }
    }
    lowList.clear();
}
```

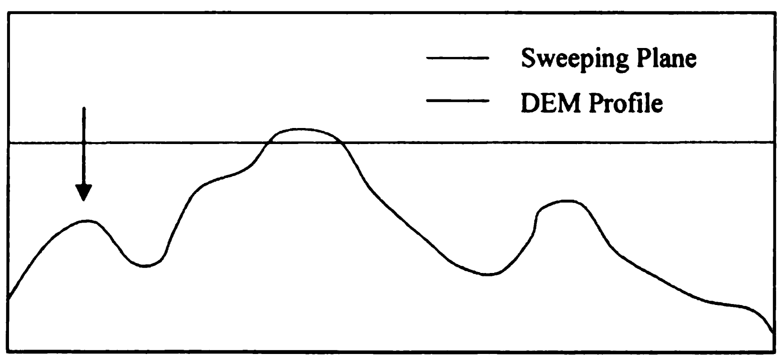

Figure 4.2 Illustration of the Sweeping Plane Concept

This algorithm requires that the DEM data set be preprocessed to make sure every cell except for boundary cells has at least one lower direct neighboring cell. A method based on mathematical morphology called lower complete transformation (Soille 1994) is used to achieve this goal. The lower complete transformation removes all pits and flat areas in a DEM and mathematically guarantees every cell except for those on the boundary has at least one lower direct neighboring cell. This new algorithm shall be referred to as the "FlowNet" method in this chapter and beyond.

4.4. Application to Different Physiographic Regions

To evaluate the performance and effectiveness of the FlowNet algorithm on a variety of real-world topographic surfaces, a sampling process based on physiographic provinces, state boundaries and available 12-digit watershed HUC (Hydrologic Unit Code) boundaries is used to select sample watersheds for testing purposes. The purpose is to test the algorithm on a number of watersheds in different types of landscapes. The core sampling unit is the elevation of the 12-digit watershed. All DEM data were downloaded from USGS National Map Seamless Server (USGS 2003). The horizontal resolution of these DEMs is 1/3 arc second, which were then projected into UTM projections with a horizontal spacing of 10 meters. The physiographic provinces were used to ensure that different types of landscapes are sampled. Figure 4.3 is a map of United States physiographic provinces based on data from the USGS (USGS 2002). Different provinces are expected to have terrain with varying surface properties; therefore they were used to stratify the study sites. Since the 12-digit watershed boundary data are made available by state for a limited number of states, both 12-digit watershed boundary and state boundary data are used to select the sample dataset. The United States is divided and sub-divided into successively smaller watersheds which are classified into different levels. Each watershed is identified by a unique hydrologic unit code (HUC) consisting of numbers based on the different levels of classification in the hierarchical coding system. A typical

12 digit HUC level watershed is a relatively small (10,000 – 40,000 acres) local watershed. As of November 2008, the 12 digit HUC level watershed boundary data are not available across the US. Figure 4.4 is a map showing availability of 12-digit watershed boundary data at the time when data for this research were collected. The gray shaded states have certified data available for download.

This experimental application started with sample data selection in three different physiographic provinces (Central Lowland of Interior Plains, Valley and Ridge of Appalachian Highlands, and Basin and Range of Intermontane Plateaus), and then three flow routing algorithms (FlowNet, D∞ and D8) were applied to all data in the sample. Finally the results were collected and analyzed. The following is the detailed process.

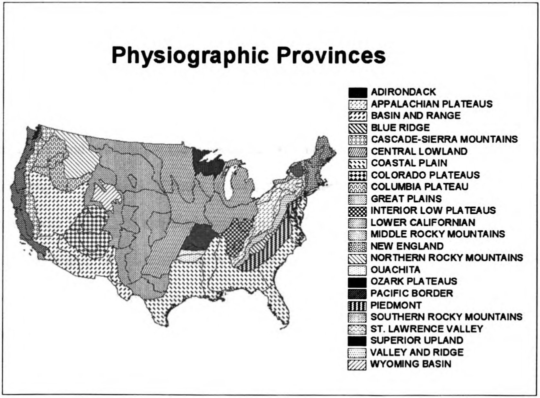

Figure 4.3 Physiographic Provinces

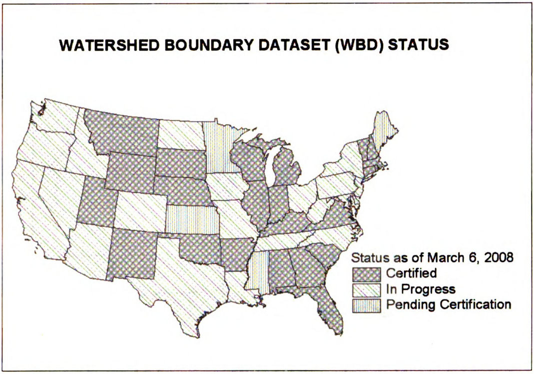

Figure 4.4 Watershed Boundary Dataset Status (NRCS)

According to the map overlay of available 12-digit watershed boundaries, state boundaries and physiographic provinces, a total of 21 digit watersheds in three physiographic provinces (Central Lowland of Interior Plains, Valley and Ridge of Appalachian Highlands, and Basin and Range of Intermontane Plateaus) located in three states (Michigan, New Mexico and Virginia) were selected. Each state or physiographic province has exactly seven representative 12-digit watersheds selected. The selection process was not random. Visual judgment was used to select representative watersheds in the three physiographic provinces. Figure 4.5 – 4.7 show locations of selected watersheds.

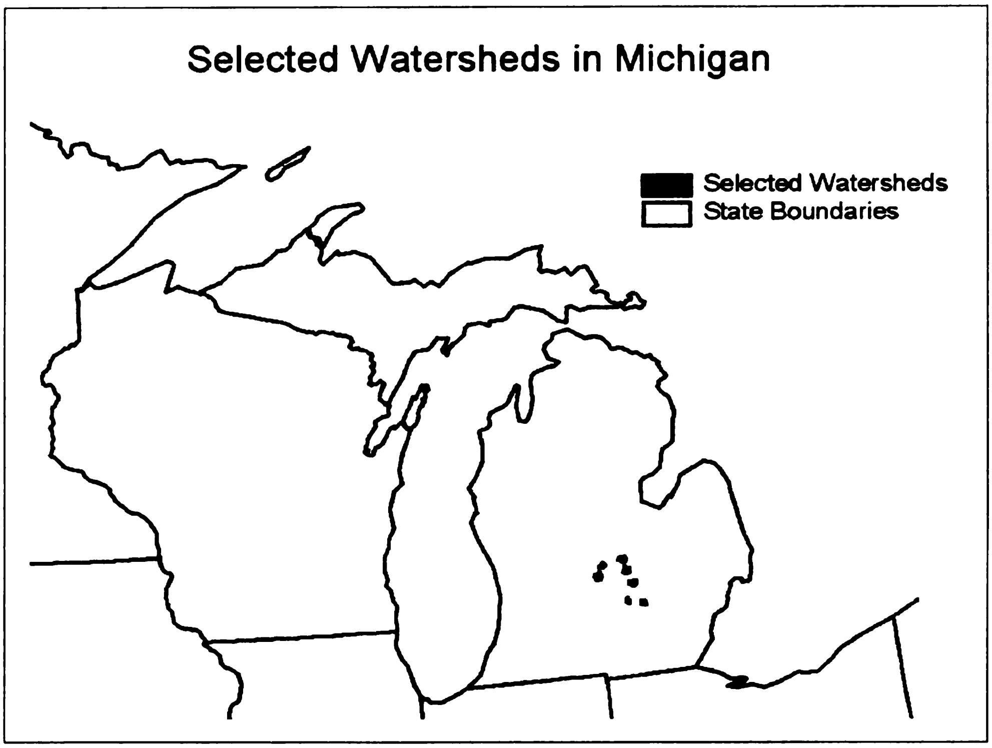

Figure 4.5 Locations of Selected Watersheds in Michigan

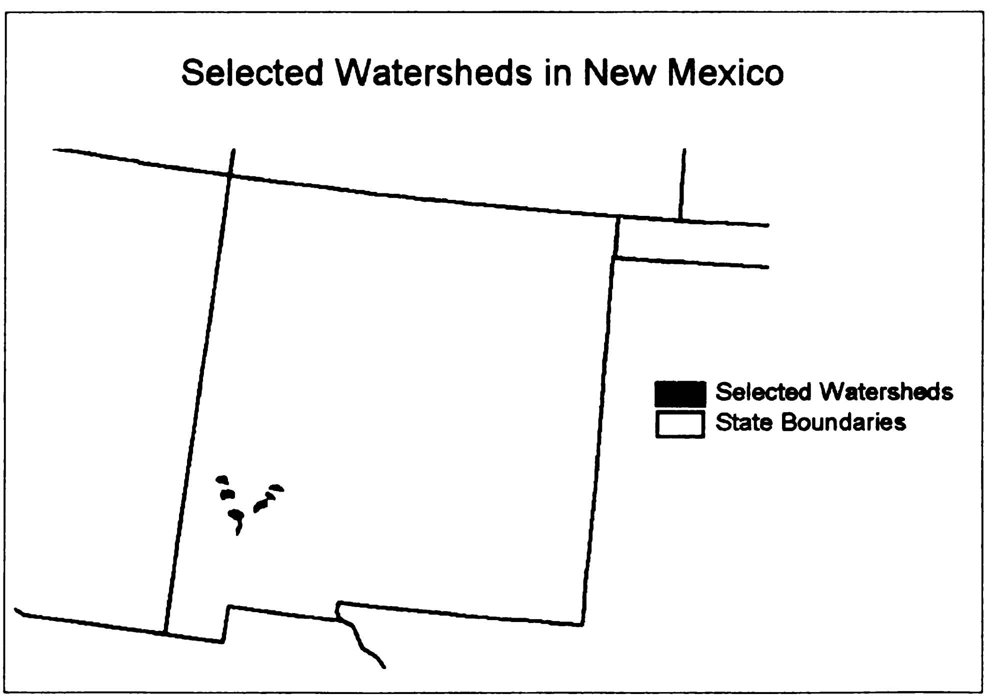

Figure 4.6 Locations of Selected Watersheds in New Mexico

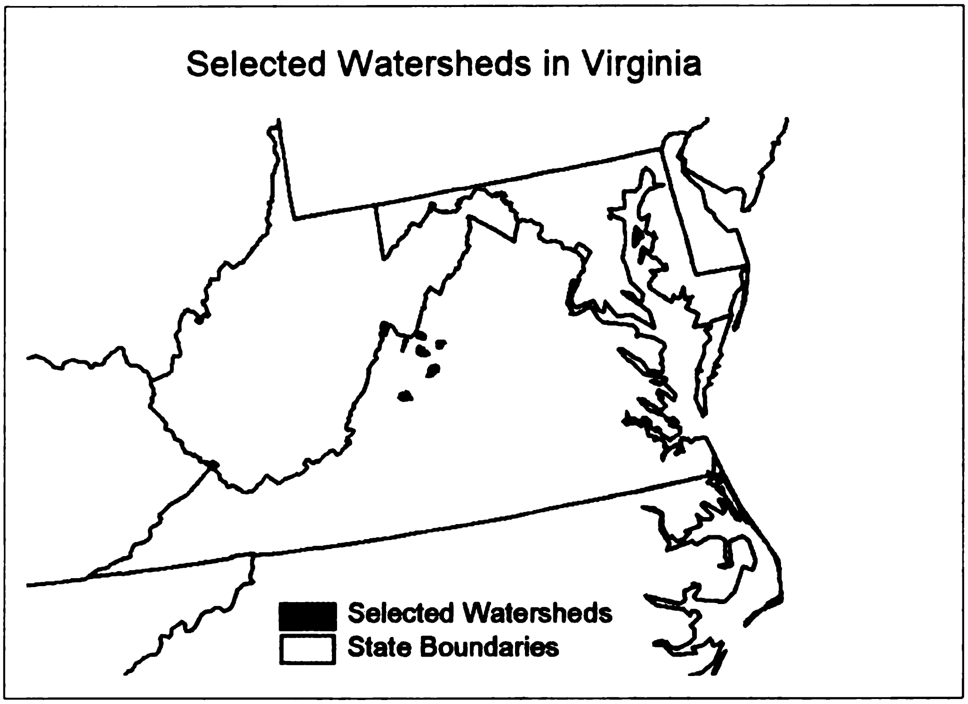

Figure 4.7 Locations of Selected Watersheds in Virginia

Table 4.2 lists common descriptive metrics for all 21 selected watersheds. These metrics include area, average slope, minimum elevation, maximum elevation, mean elevation and standard deviation of elevation. A comparison of these metrics indicates that all watersheds have relatively similar sizes. Selected watersheds in Michigan are very flat with small elevation ranges, while the New Mexico and Virginia watersheds have rugged terrain with relatively large elevation ranges.

Watershed	Area (Acres)	Average Slope (degree)	Minimum Elevation	Maximum Elevation	Mean Elevation	Standard Deviation Of Elevation
MI WS 1	23,843	1.0	215	256	236.2	6.5
MI WS 2	17,509	0.8	210	245	225.0	5.1
MI WS 3	18,958	1.1	222	263	244.9	6.9
MI WS 4	20,735	0.9	260	301	271.7	5.3
MI WS 5	10,424	1.2	274	316	285.1	5.4
MI WS 6	13,201	1.2	274	305	285.8	4.5
MI WS 7	14,597	0.8	208	247	223.9	4.9
NM WS 1	23,171	18.9	2,083	3,210	2,566.2	189.2
NM WS 2	32,955	28.3	1,455	2,671	2,110.6	220.8
NM WS 3	20,211	21.2	1,783	2,821	2,147.1	192.5
NM WS 4	11,472	26.2	1,863	2,969	2,323.1	227.2
NM WS 5	34,729	21.3	1,965	3,100	2,448.4	248.3
NM WS 6	16,512	6.7	1,653	2,319	1,868.7	122.4
NM WS 7	38,336	17.5	1,651	2,751	2,115.7	205.5
VA WS 1	9,495	18.0	574	1,012	745.4	89.5
VA WS 2	16,235	21.1	474	1,337	824.5	172.3
VA WS 3	22,785	14.2	416	1,148	616.4	149.4
VA WS 4	14,685	6.8	330	523	405.9	33.3
VA WS 5	29,115	7.5	395	678	514.2	63.4
VA WS 6	22,797	15.4	278	1,111	517.8	146.1
VA WS 7	24,021	17.0	775	1,362	1,084.1	101.1

Table 4.2 Summary Table for 21 Selected Watersheds

Three flow routing algorithms, FlowNet, D8 and D∞, were applied to all 21 watersheds, and flow accumulations for each cell were calculated. The FlowNet algorithm was implemented in C++ as a command line tool for this experiment. The D∞ algorithm was implemented in C++ as a command line tool by David Tarboton. It was downloaded from Tarboton's website (Tarboton 2008). Both FlowNet and D∞ command line tools were used to batch process the elevation data and generate results. The D8 algorithm is available in ArcGIS, so ArcGIS was used to calculate D8 results. Results were compared using qualitative and quantitative techniques. Qualitative approaches included looking at output maps and contrasting method performance. The following section presents detailed results on a subset of three watersheds, one from each physiographic region. Quantitative approaches included:

- conducting difference of means testing on average flow accumulation values and erosion potential erosion values for each method
- evaluating the linear relationship between D8 and FlowNet methods via linear regression
- assessing whether significant differences in model performance occurred between physiographic provinces

Quantitative results are reported and discussed in section 4.5.

4.5. Spatial Variation in Flow Accumulation

The first watershed, called South Fork Hayworth Creek, is located in Clinton County, Michigan, in the "Central Lowland of Interior Plains" province. The area of this watershed is 14,597 acres. It's very flat with an average slope of 0.8 degrees, and drains to the north, with relatively higher elevations in the southeast. The minimum and maximum elevation values are 208 and 247 meters respectively. The following is a map of the watershed.

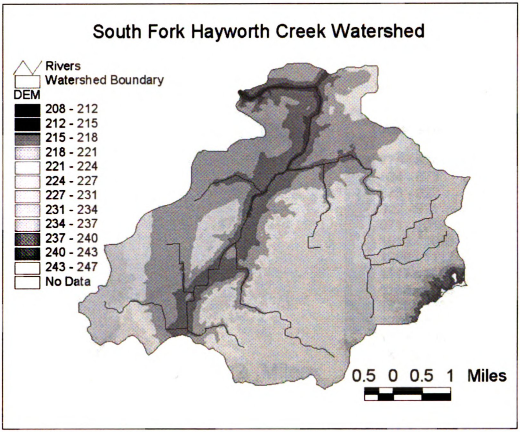

Figure 4.8 South Fork Hayworth Creek Watershed in Clinton, MI

The second watershed, called North Fork South Branch Potomac, is located in Highland County, Virginia. This watershed falls in the physiographic province of "Valley and Ridge of Appalachian Highlands." The area of this watershed is 24,021 acres. The average slope is 17.0 degrees. The minimum and maximum elevation values are 775 and 1362 meters respectively. It drains to the north with higher elevations in the southwest. The following is a map of the watershed. Note that this 12-digit watershed actually contains two subwatersheds. This situation may occur for other 12-digit watersheds as well.

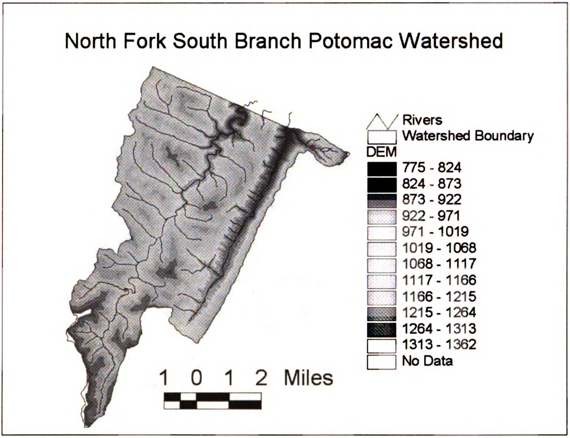

Figure 4.9 North Fork South Branch Potomac Watershed in Highland, VA

The third watershed, called Upper Bear Creek, is located in Grant County, New Mexico. This watershed falls in the physiographic province of "Basin and Range of Intermontane Plateaus." The area of this watershed is 38,336 acres. The average slope for this watershed is 17.5 degrees. The minimum and maximum elevation values are 1651 and 2751 meters respectively. It drains to the west with higher elevations in the northeast. The following is a map of the watershed.

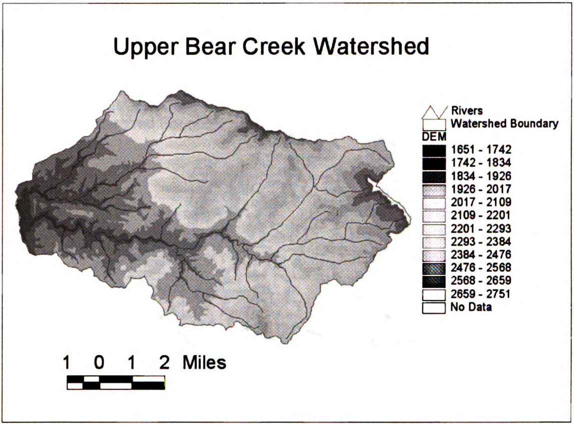

Figure 4.10 Upper Bear Creek Watershed in Grant, NM

Now let's take a look at the detailed results for three flow routing algorithms. The first set of six figures (4.11 – 4.16) is for South Fork Hayworth Creek watershed in Michigan. All stream cells are derived from the flow accumulation grid with a threshold value of 100 cells for comparison purposes; they do not necessarily reflect permanent stream locations.

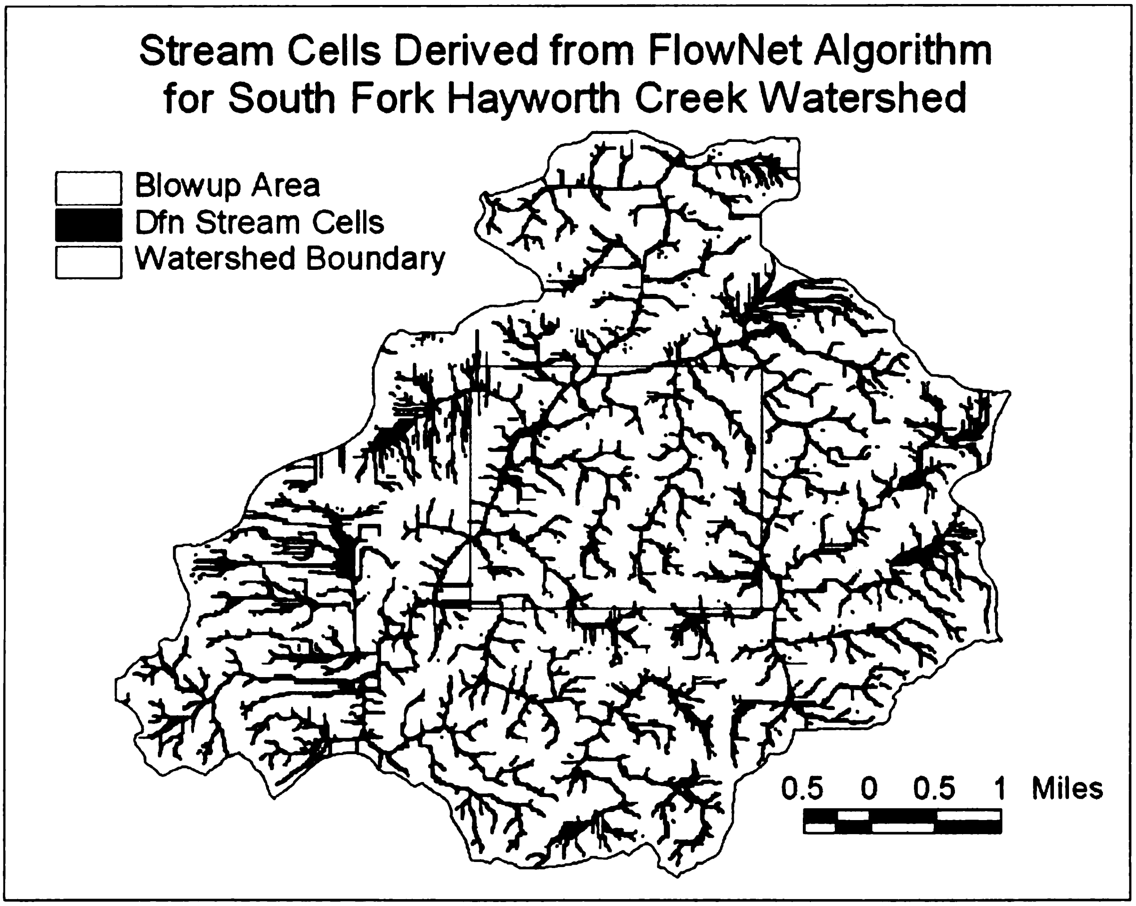

Figure 4.11 Stream Cells Derived from Flow Accumulation Grid Calculated Using the FlowNet Algorithm

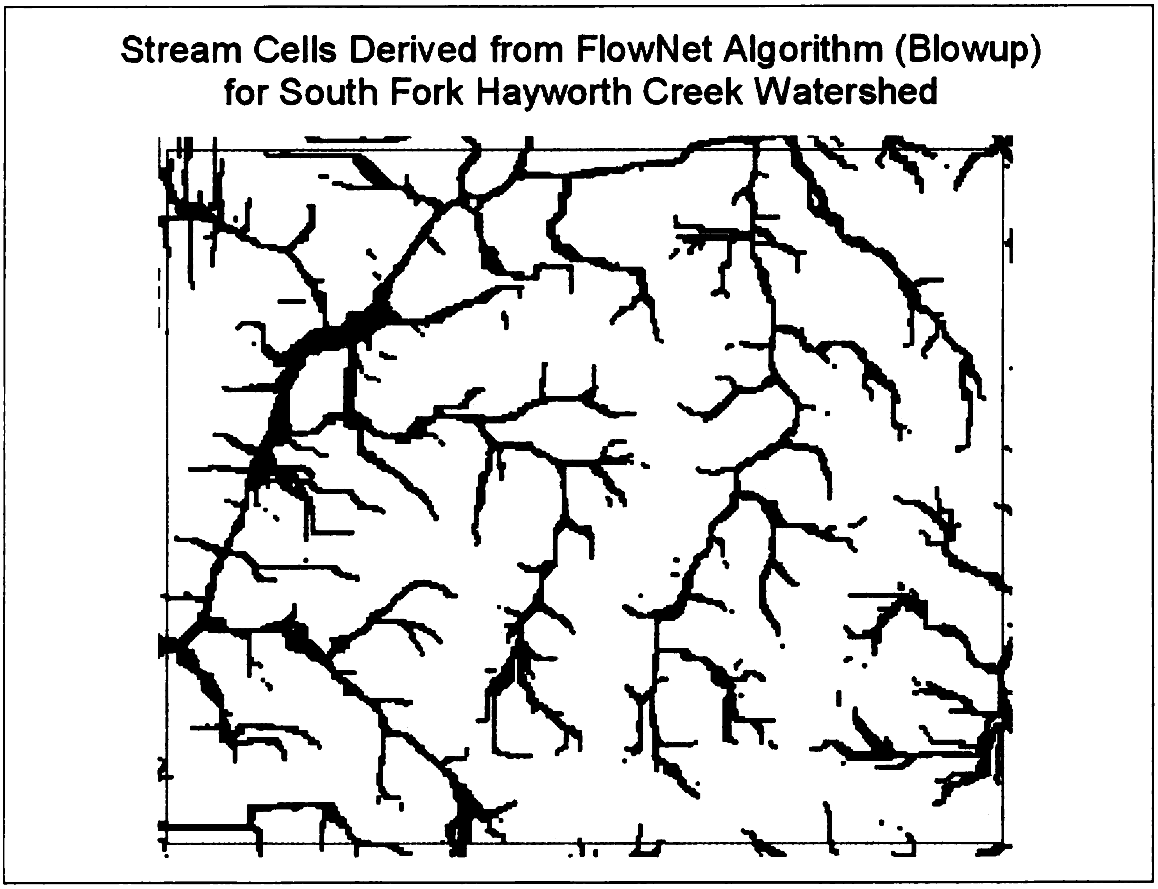

Figure 4.12 Local Blowup of Figure 4.11

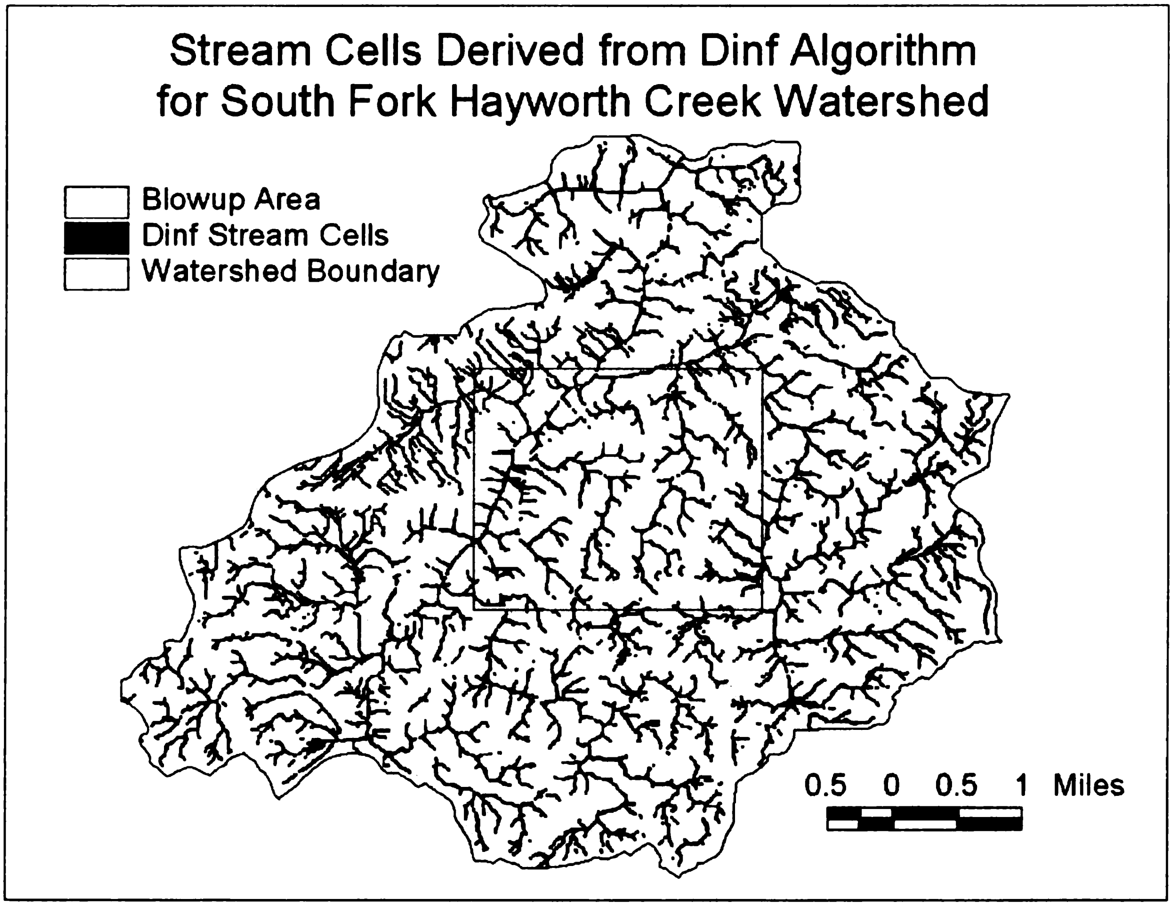

Figure 4.13 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D∞ Algorithm

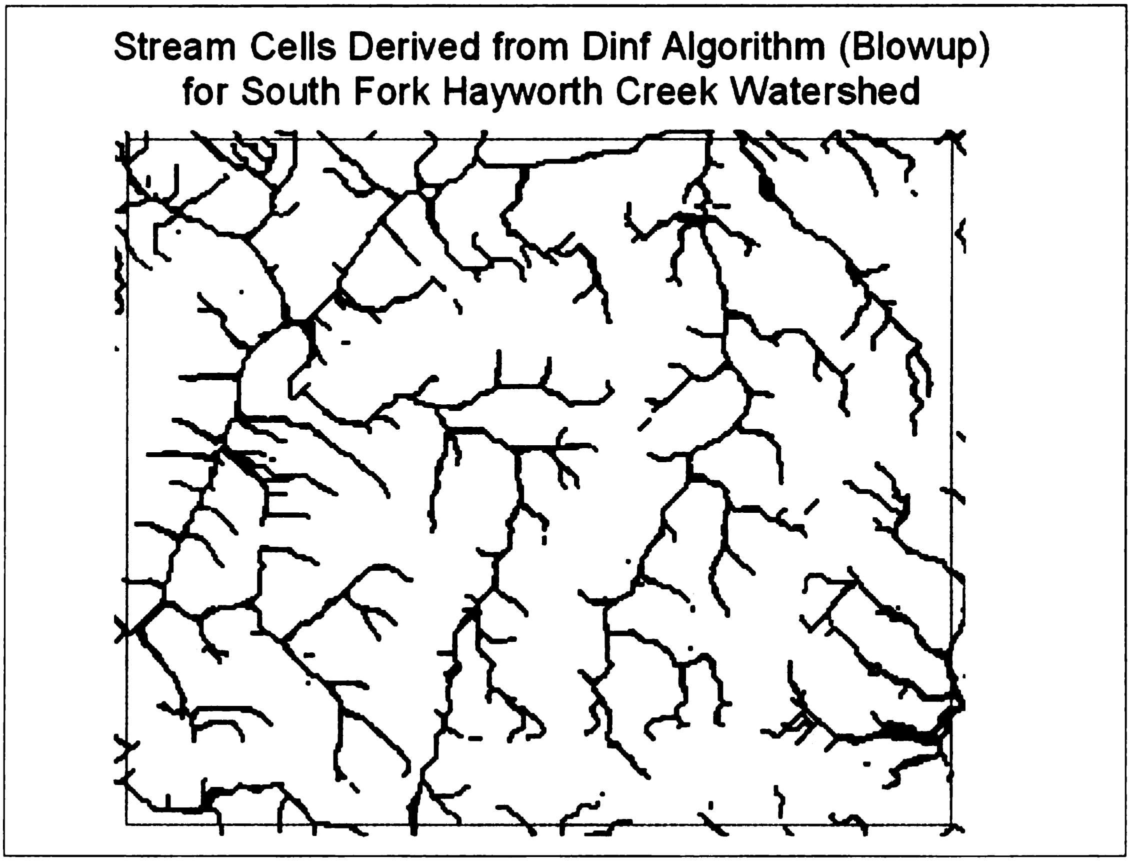

Figure 4.14 Local Blowup of Figure 4.13

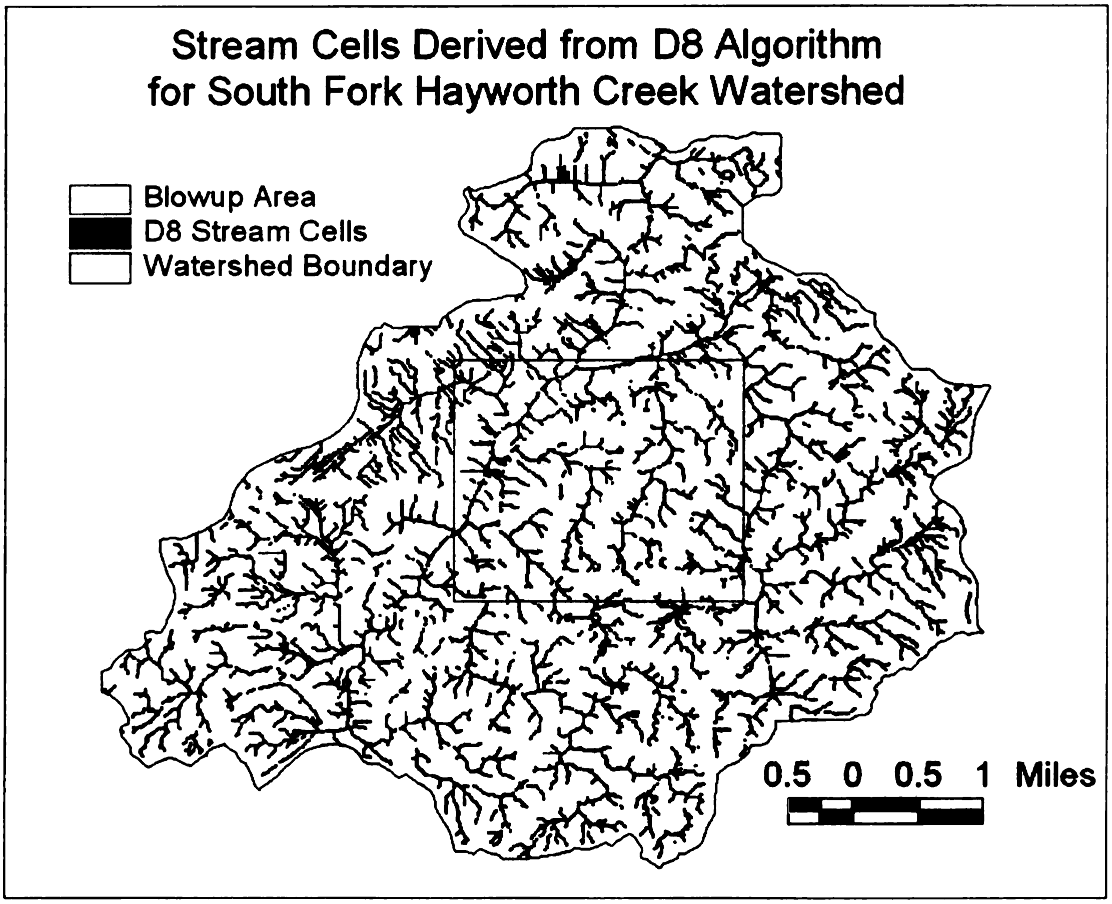

Figure 4.15 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D8 Algorithm

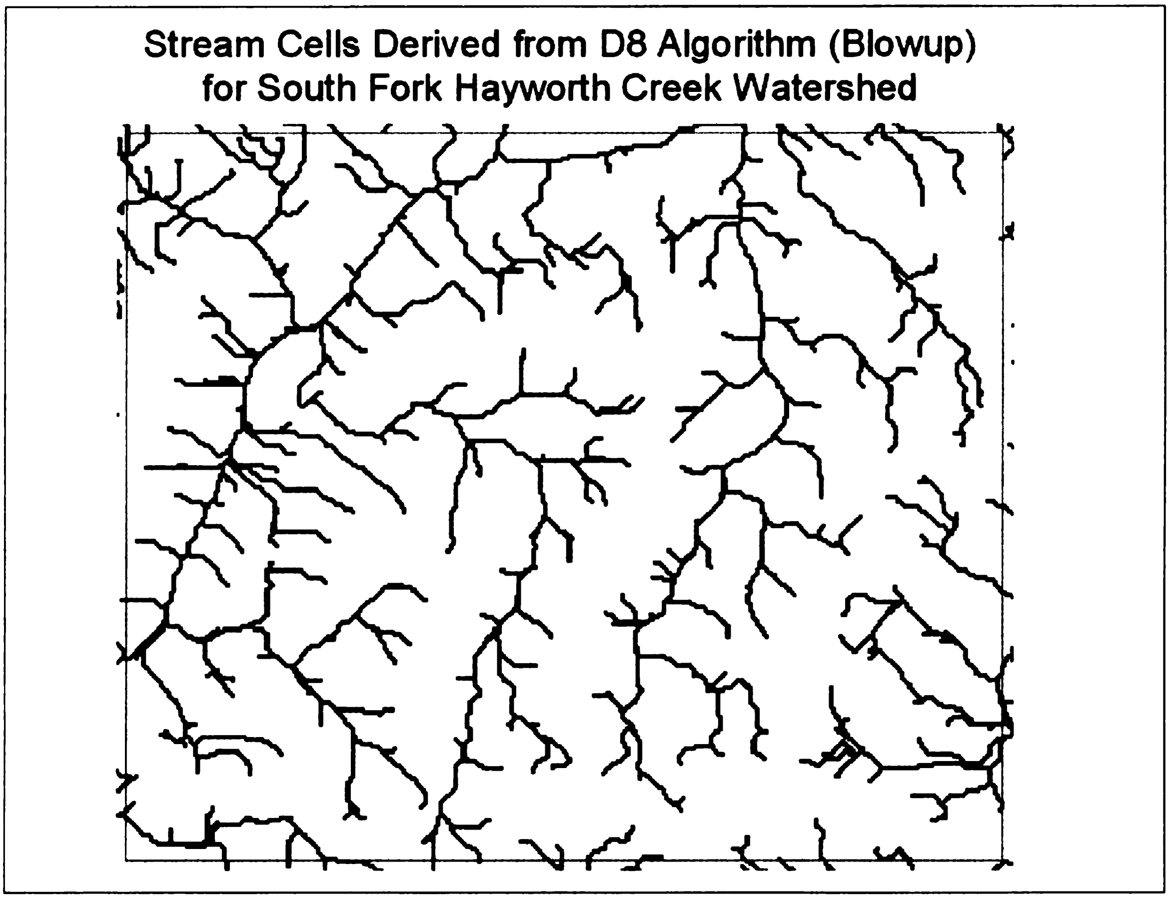

Figure 4.16 Local Blowup of Figure 4.15

The flow accumulation figures for the Michigan watershed illustrate that the stream cell patterns derived from D8 and D∞ are very similar. Two factors may explain this. The first is that D∞ also uses single flow direction, even though the flow direction is not limited to 8 possible directions like in D8. The second is that D∞ uses the same method as D8 when dealing with relatively flat areas like the majority of this watershed. Flow directions in flat areas are determined iteratively by making them flow towards a neighbor of equal elevation that has a flow direction resolved. A very obvious difference is that the FlowNet algorithm produces 'thick' streams. D∞ also produces 'thick' streams, but not as many as the FlowNet algorithm does. D8 does not produce 'thick' streams at all. This is due to how flow is routed in different algorithms. In the FlowNet algorithm, which is based on physical laws that govern water movement through the landscape, flow can be routed to up to four neighboring cells. In D∞, which is based on the geometric configuration of neighboring grid cells, flow can be routed to a maximum of two neighboring cells. In D8, flow can only be routed to one of eight neighboring cells based on slopes.

Similar observations can be made for the other 6 watersheds in Michigan after examining their respective results derived from using the three algorithms.

Now results for the other two watersheds are considered.

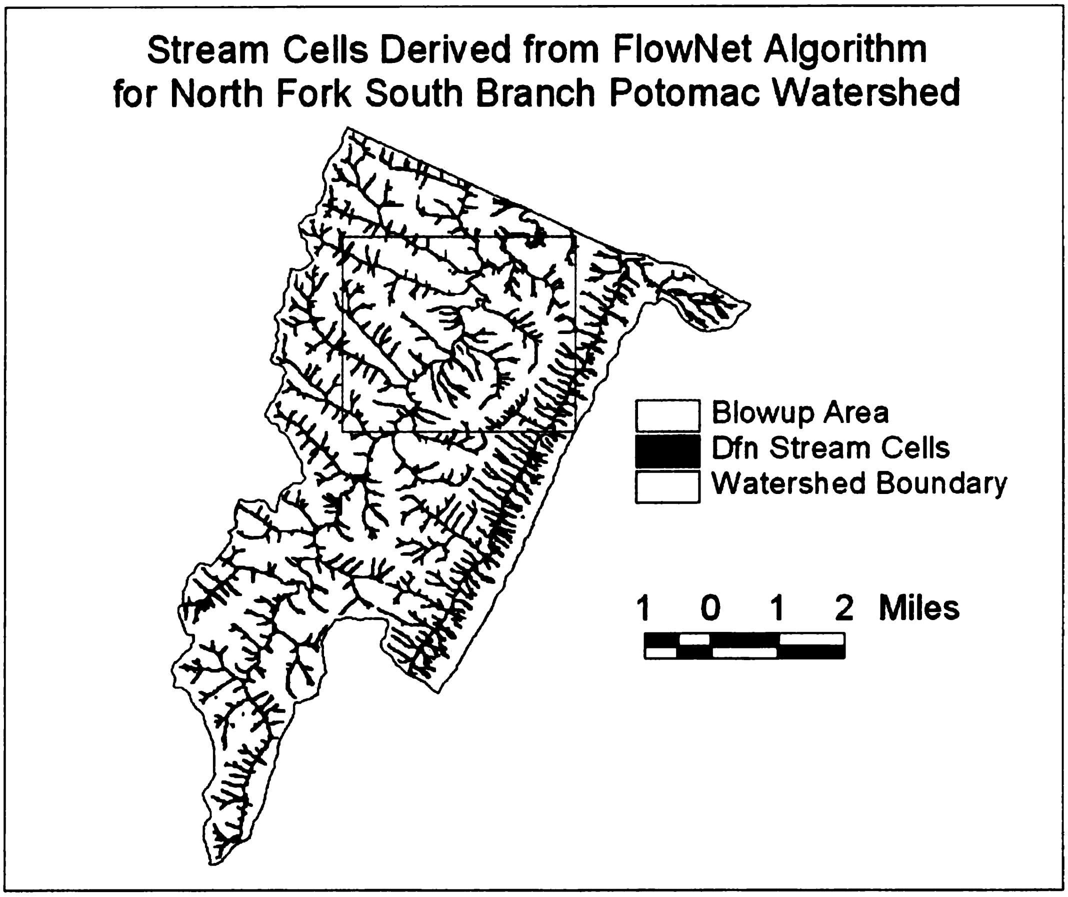

Figure 4.17 Stream Cells Derived from Flow Accumulation Grid Calculated Using the FlowNet Algorithm

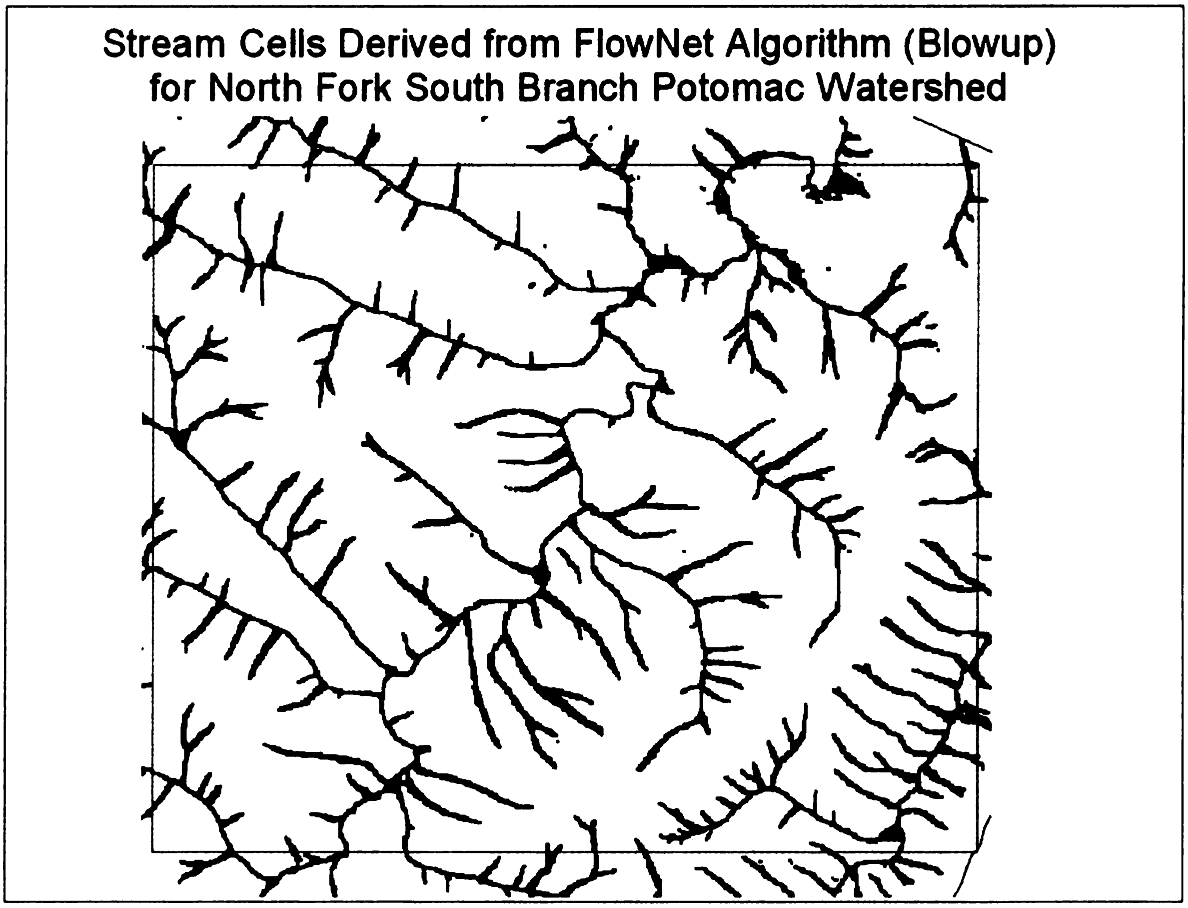

Figure 4.18 Local Blowup of Figure 4.17

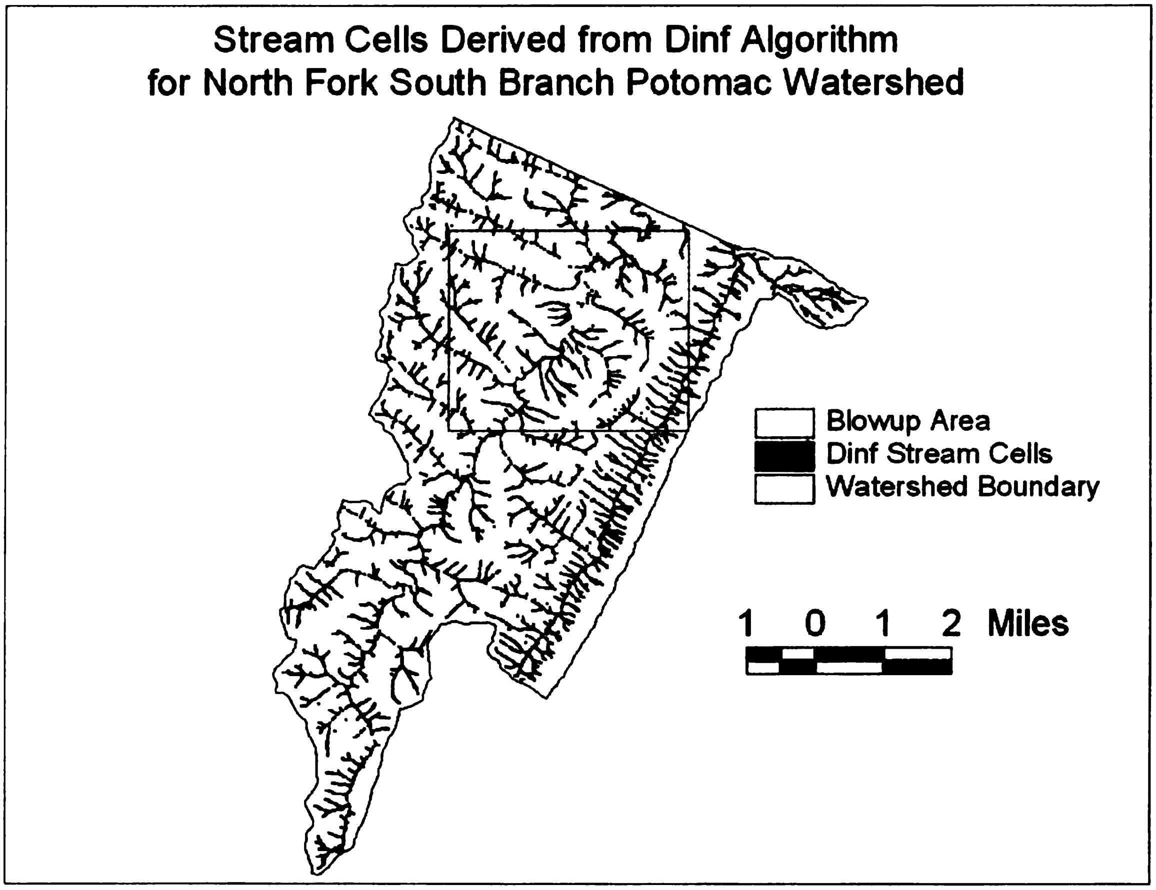

Figure 4.19 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D∞ Algorithm

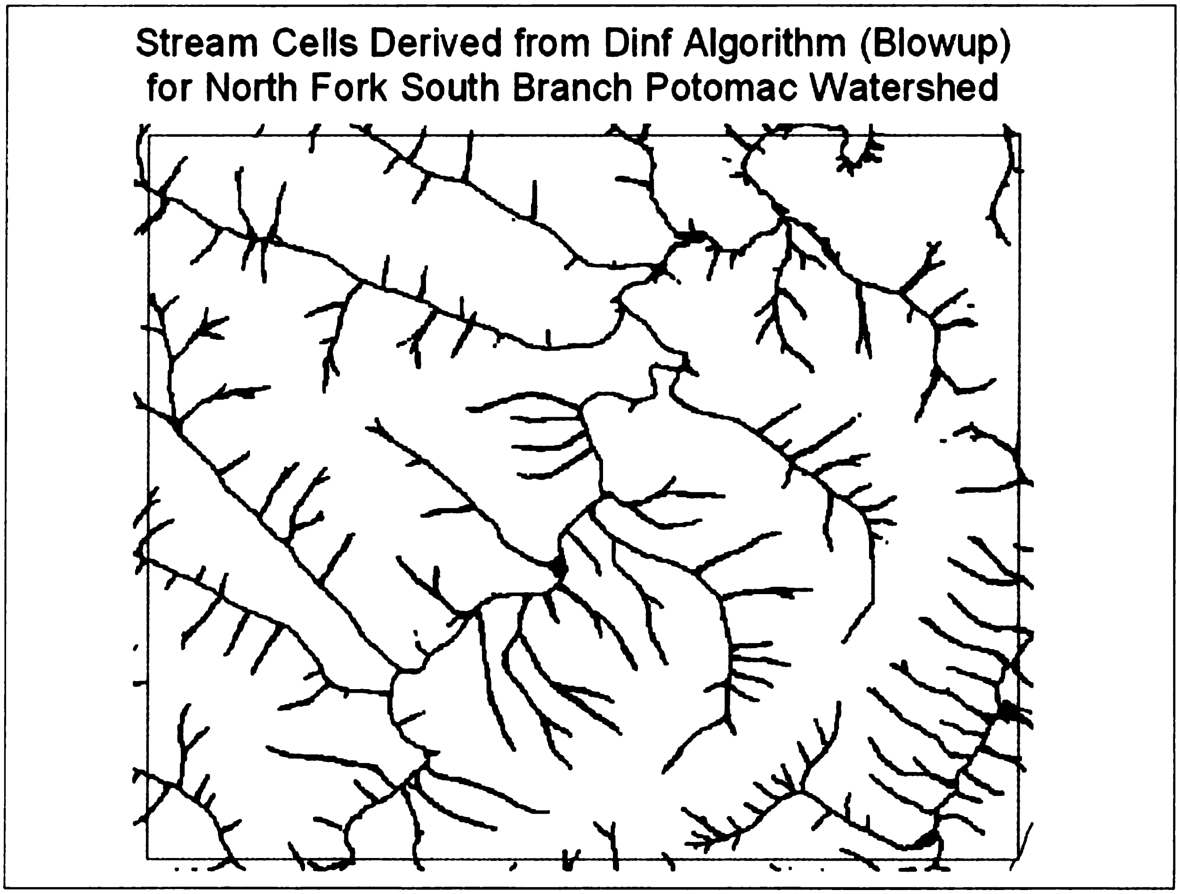

Figure 4.20 Local Blowup of Figure 4.19

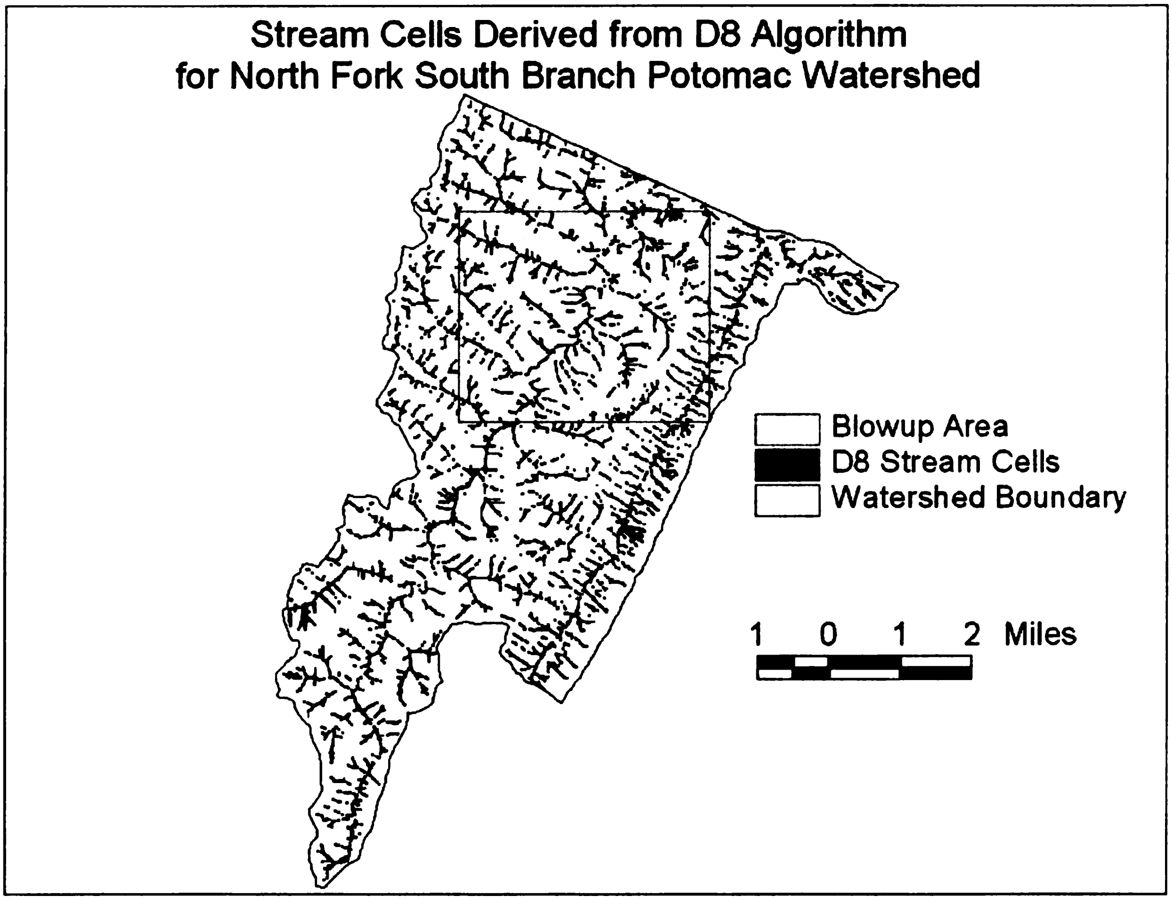

Figure 4.21 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D8 Algorithm

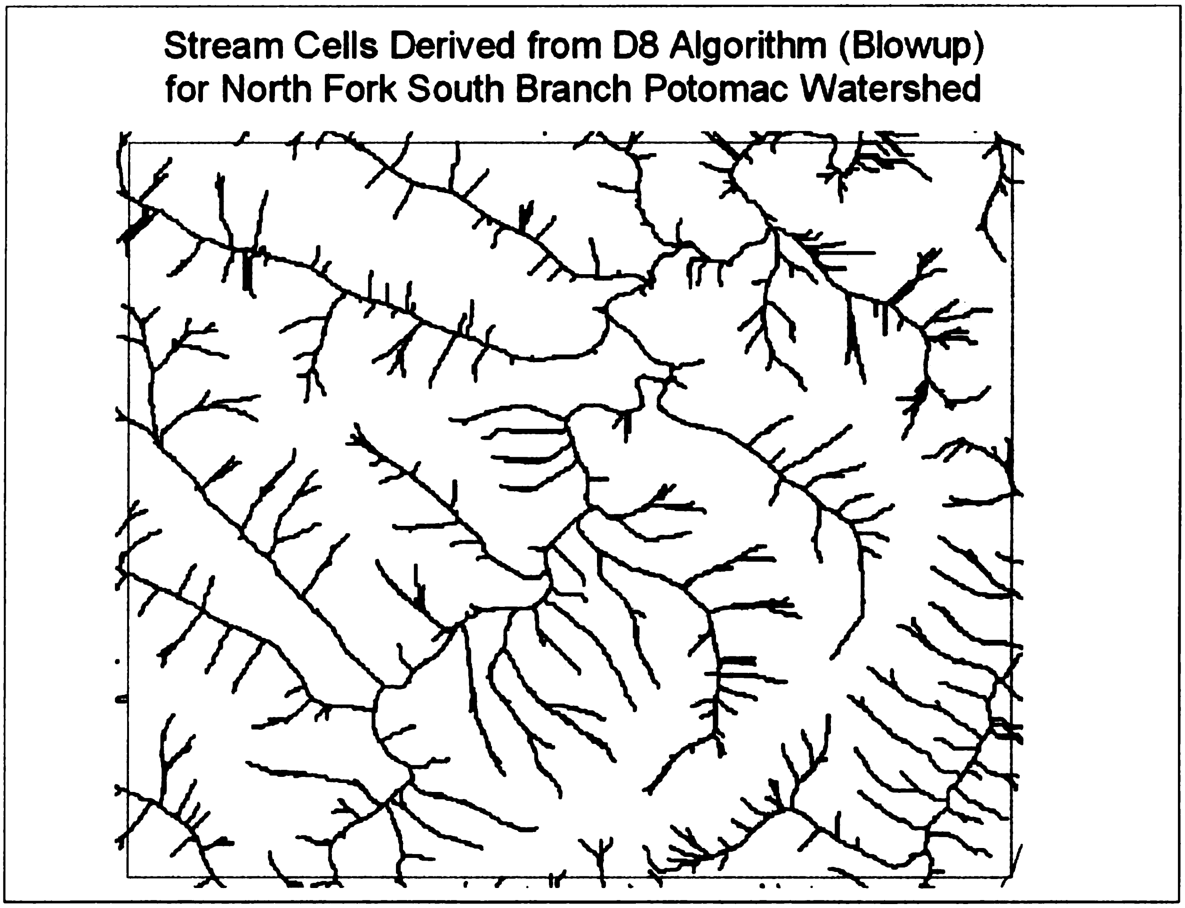

Figure 4.22 Local Blowup of Figure 4.21

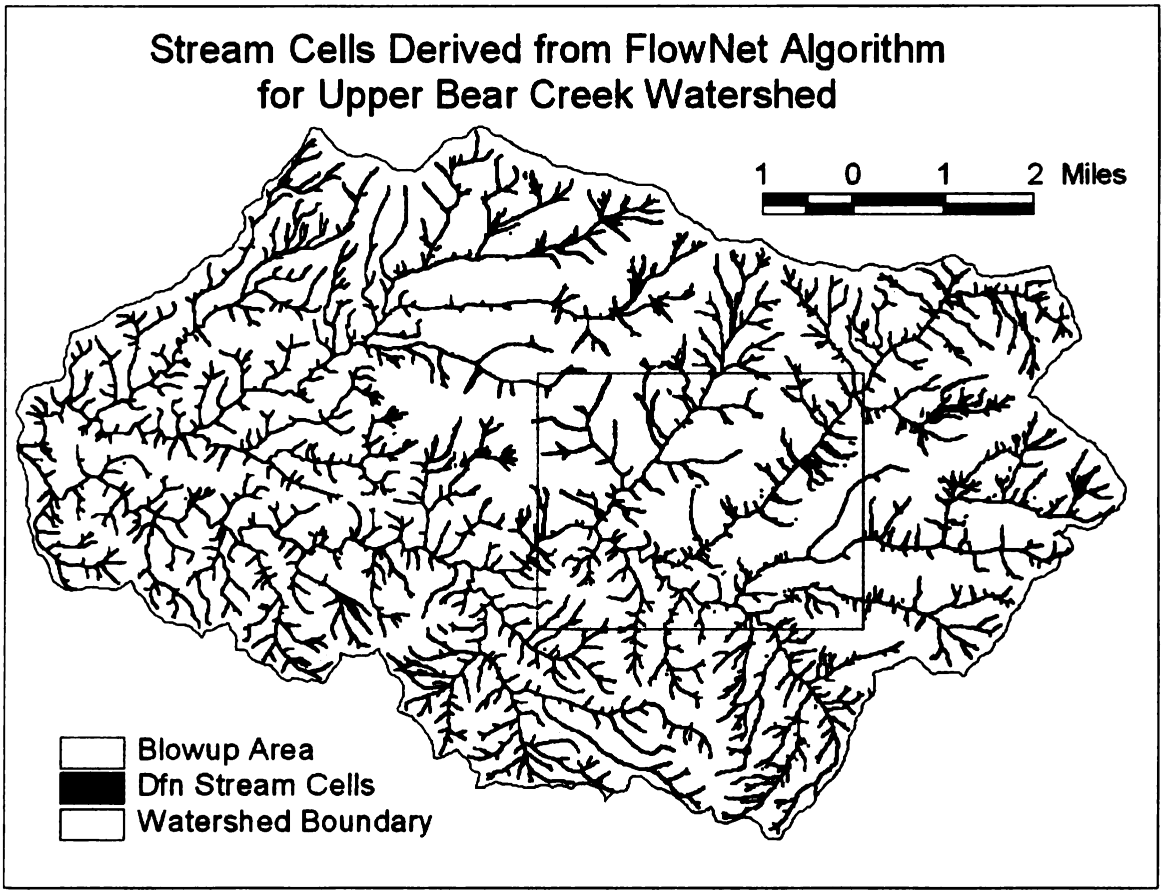

Figure 4.23 Stream Cells Derived from Flow Accumulation Grid Calculated Using the FlowNet Algorithm

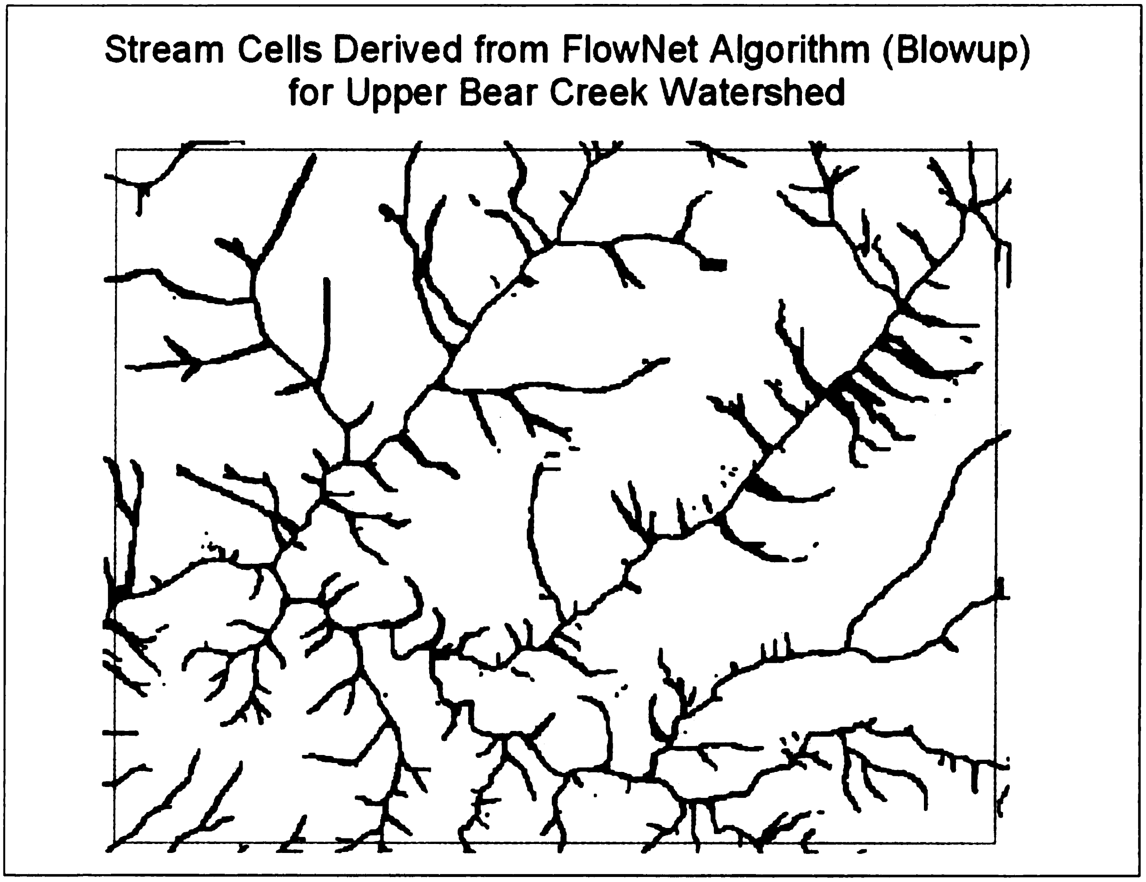

Figure 4.24 Local Blowup of Figure 4.23

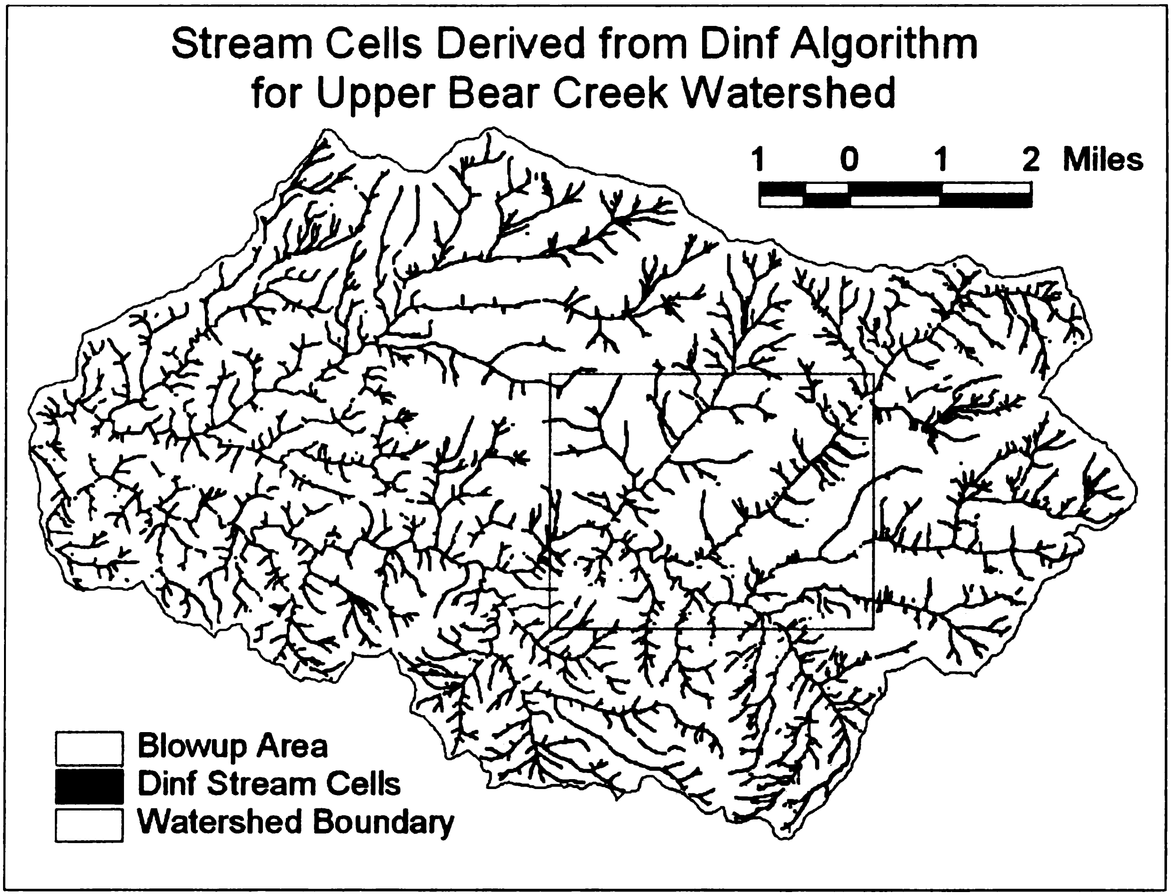

Figure 4.25 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D∞ Algorithm

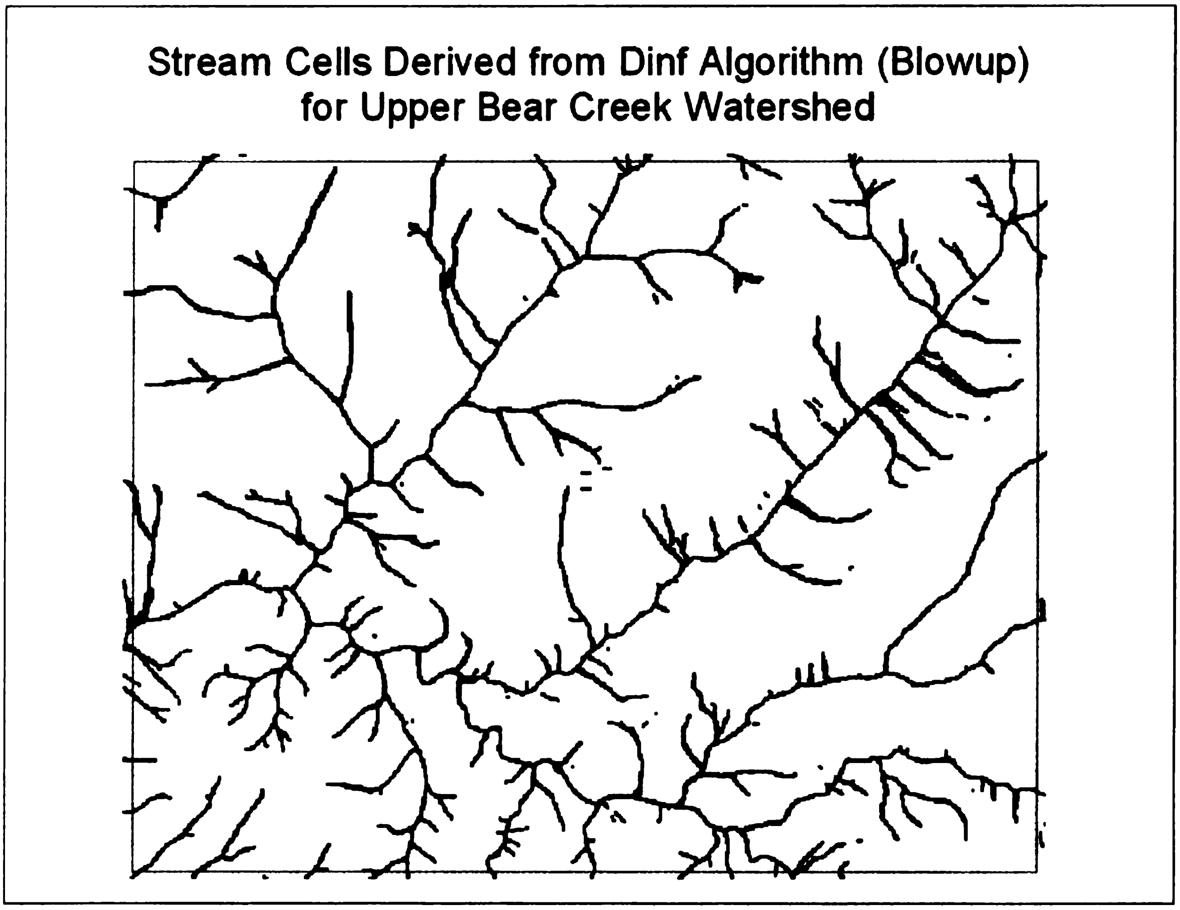

Figure 4.26 Local Blowup of Figure 4.25

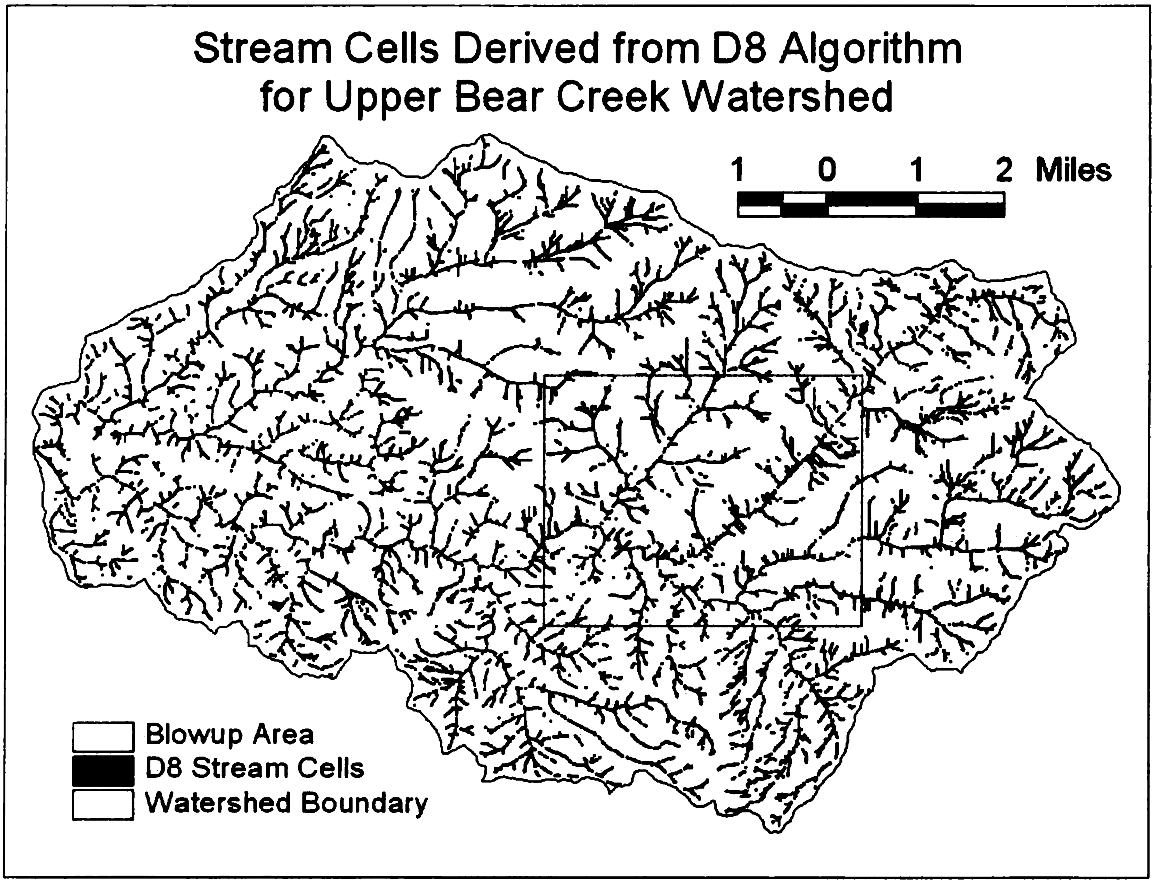

Figure 4.27 Stream Cells Derived from Flow Accumulation Grid Calculated Using the D8 Algorithm

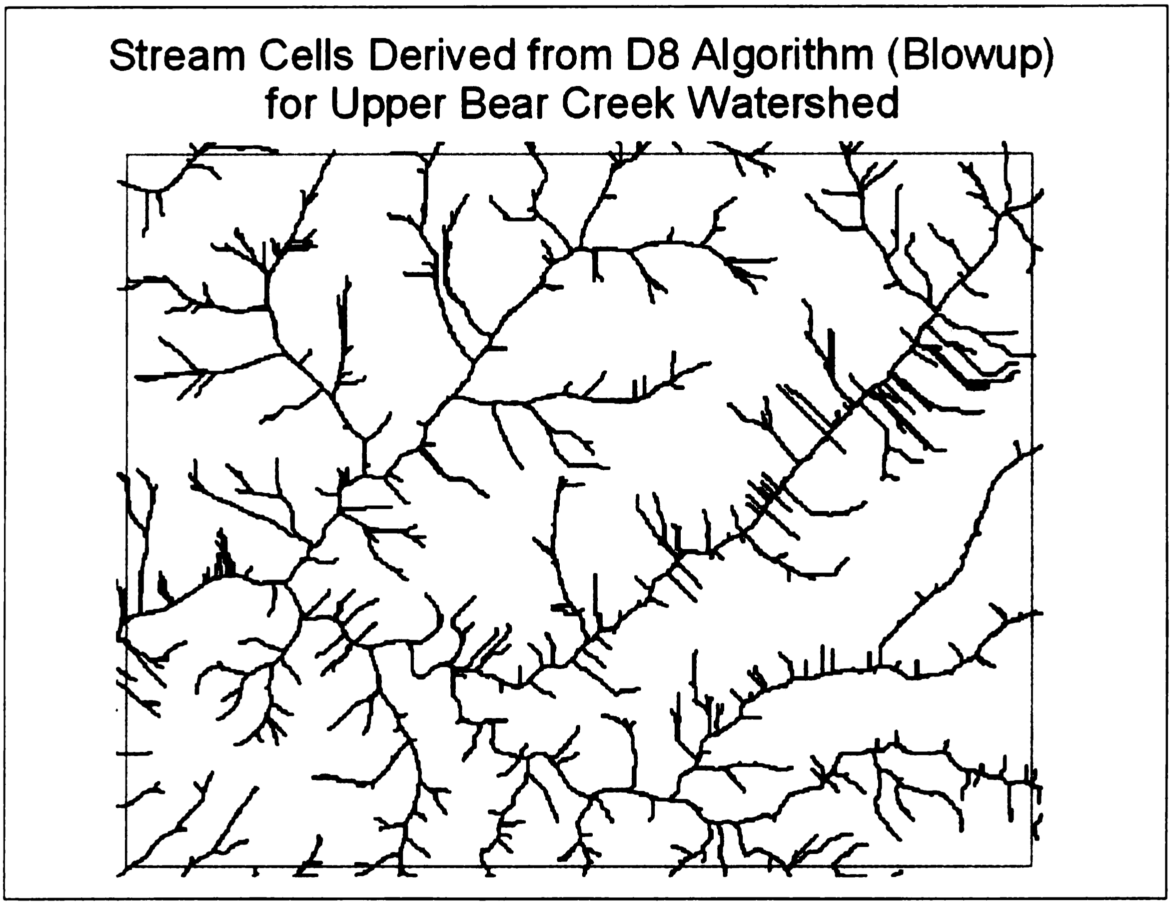

Figure 4.28 Local Blowup of Figure 4.27

Similar observations can be made for these two watersheds in Virginia and New Mexico as ones for the previous watershed in Michigan from this set of figures. But the streams derived from the FlowNet algorithm in these mountainous areas are not as 'thick' as those derived from the FlowNet algorithm in flat areas. The reason for this difference is that in mountainous areas water flow tends to disperse less because of steep slopes. In other words, flows tend to be more concentrated because of the rugged terrain. The better channelization effects in mountainous areas also contribute to this fact.

Similar observations can be made for the other 12 watersheds in Virginia and New Mexico after examining their respective results derived from using the three algorithms.

4.6. Contrasting Algorithm Performance on Hydrologic Applications

The previous section provided a visual comparison of a few representative watersheds. To get more information on how different algorithms perform, we also need to find a way to directly compare flow accumulation grids generated from different algorithms. Mean values of all 21 flow accumulation grids were collected for this purpose (table 4.3).

Watershed	D8 Flow Accumulation Mean	D∞ Flow Accumulation Mean	FlowNet Flow Accumulation Mean
MI WS 1	1,023.9	1,024.7	1,378.9
MI WS 2	794.7	793.1	1,028.2
MI WS 3	1,072.0	1,071.2	1,372.1
MI WS 4	945.0	945.4	1,190.5
MI WS 5	605.0	602.7	778.1
MI WS 6	585.6	585.3	753.2
MI WS 7	886.2	885.5	1,203.6
NM WS 1	945.8	949.3	1,378.6
NM WS 2	1,298.9	1,298.3	1,752.4
NM WS 3	1,050.8	786.0	1,485.4
NM WS 4	906.8	907.8	1,280.2
NM WS 5	1,315.6	1,316.4	1,866.5
NM WS 6	1,262.5	1,262.8	1,755.3
NM WS 7	1,231.8	1,236.4	1,769.8
VA WS 1	761.4	761.1	1,111.4
VA WS 2	799.7	793.1	1,109.2
VA WS 3	1,048.5	1,044.7	1,462.7
VA WS 4	740.4	740.9	1,073.4
VA WS 5	1,054.2	1,050.8	1,498.1
VA WS 6	1,110.8	1,103.9	1,606.0
VA WS 7	963.7	962.0	1,352.9

Table 4.3 Mean Values of Flow Accumulation Grids

From Table 4.3 we can see that flow accumulation grid mean values for D8 and D∞ appear to be very similar, but the FlowNet algorithm seems to produce systematically larger mean values. To test whether these differences are significant, paired T-Tests were conducted using the open-source statistical package R (R Development Core Team 2005); output is provided in Appendix A. The results are listed as follows:

1. Paired T-Test between D∞ and D8 flow accumulation mean values:

H0: Actual difference in means between D∞ and D8 flow accumulation grids is equal to 0.

HA: Actual difference in means between D∞ and D8 flow accumulation grids is not equal to 0.

t = -1.0665, df = 20, p-value = 0.2989, mean of the differences = -13.42090

The calculated p-value exceeds 0.05, so we fail to reject the null hypothesis and conclude that the D∞ flow accumulation grid mean value is the same as the D8 flow accumulation grid mean value.

2. Paired T-Test between FlowNet algorithm and D8 flow accumulation mean values:

H0: Actual difference in means between FlowNet algorithm and D8 flow accumulation grids is equal to 0.

HA: Actual difference in means between FlowNet algorithm and D8 flow accumulation grids is greater than 0.

t = 15.4888, df = 20, p-value = 6.652e-13, mean of the differences = 371.5763

In this case, the calculated p-value is much smaller than 0.05, so we reject the null hypothesis and conclude that the FlowNet algorithm flow accumulation grid mean value is greater than the D8 flow accumulation grid mean value.

Flow accumulation has been widely used in a variety of GIS-based environmental models. In order to find out how the FlowNet algorithm will affect environmental models that use flow accumulation, the RUSLE model described in Chapter 3 is chosen and run for all 21 watersheds using the three algorithms. The RUSLE is a set of mathematical equations that estimate average annual soil loss and sediment yield resulting from interrill and rill erosion by multiplying five factors such as slope length (LS) and soil erodibility (K) (Renard et al. 1994). The erosion potential mean results are listed in the table 4.4.

Watershed	D8 Erosion Potential Mean	D∞ Erosion Potential Mean	FlowNet Erosion Potential Mean
MI WS 1	0.96	1.01	1.98
MI WS 2	0.65	0.69	1.25
MI WS 3	0.87	0.94	1.58
MI WS 4	0.75	0.80	1.58
MI WS 5	0.75	0.82	1.17
MI WS 6	0.80	0.85	1.36
MI WS 7	0.74	0.78	1.51
NM WS 1	33.73	36.01	49.80
NM WS 2	46.10	48.99	68.52
NM WS 3	29.30	30.77	42.55
NM WS 4	40.92	43.23	60.16
NM WS 5	32.32	34.38	48.04
NM WS 6	8.08	8.74	11.70
NM WS 7	28.61	30.72	42.01
VA WS 1	23.59	24.96	34.20
VA WS 2	34.26	36.26	52.82
VA WS 3	19.04	20.03	27.35
VA WS 4	6.81	7.22	10.68
VA WS 5	9.26	9.78	16.47
VA WS 6	20.81	22.15	30.70
VA WS 7	26.53	28.40	38.74

Table 4.4 Mean Values of Erosion Potential Grids from RUSLE

By examining the results in the table it seems that similar observations can be made about erosion potential grid mean as for flow accumulation grid mean previously. Therefore two paired T-Tests are run for the erosion potential means.

1. Paired T-Test between D∞ and D8 erosion potential mean values:

H0: Actual difference in means between D∞ and D8 erosion potential grids is equal to 0.

HA: Actual difference in means between D∞ and D8 erosion potential grids is not equal to 0.

$t = 5.1517$, $df = 20$, p-value = 4.854e-05, mean of the differences = 1.079048

The calculated p-value is much smaller than 0.05, so we reject the null hypothesis and conclude that the D∞ erosion potential grid mean value is not the same as D8 erosion potential grid mean value. This is not what we expected even though the difference does not appear to be large.

2. Paired T-Test between FlowNet algorithm and D8 erosion potential mean values:

H0: Actual difference in means between FlowNet algorithm and D8 erosion potential grids is equal to 0.

HA: Actual difference in means between FlowNet algorithm and D8 erosion potential grids is greater than 0.

$t = 5.3756$, $df = 20$, p-value = 1.458e-05, mean of the differences = 8.537714

The calculated p-value is much smaller than 0.05, so we reject the null hypothesis and conclude that that FlowNet erosion potential grid mean value is larger than the D8 erosion potential grid mean value. This difference favors the proposed algorithm because the current RUSLE method based on D8 tends to underestimate the overall erosion potential of a watershed (USEPA Region 7 and IOWA Dept. of Natural Resources 2006). The preceding results demonstrate significant differences in erosion potential for the commonly employed D8 algorithm and FlowNet algorithm. Is this difference predictable? To evaluate this, a linear regression model was developed in R to predict FlowNet erosion potential grid mean value from the D8 erosion potential grid mean value. The model is listed as follows and detailed R output can be found in appendix A:

$$Epna = A + B * Epd8$$

Where $A = 0.38890$, $t = 1.33$, $Pr(>|t|) = 0.199$

$B = 1.46902$, $t = 115.45$, $Pr(>|t|) < 2e-16$

Adjusted $R^2 = 0.9985$

From the adjusted R-squared value, as well as a scatterplot of the two variables (figure 4.28), it is clear that a strong linear relationship exists between the two variables. The intercept coefficient is 0.38890; meaning even if there is no erosion predicted by D8 algorithm, the FlowNet algorithm will have an estimated erosion value of 0.38890. The slope coefficient is 1.46902, indicating a strongly positive relationship between the variables. An increase of 1 in Epd8 corresponds to a rise of 1.46902 in Epna. This coefficient differs significantly from zero (t=115.45, P << 0.0001). Standard regression diagnostics revealed no problems with this model.

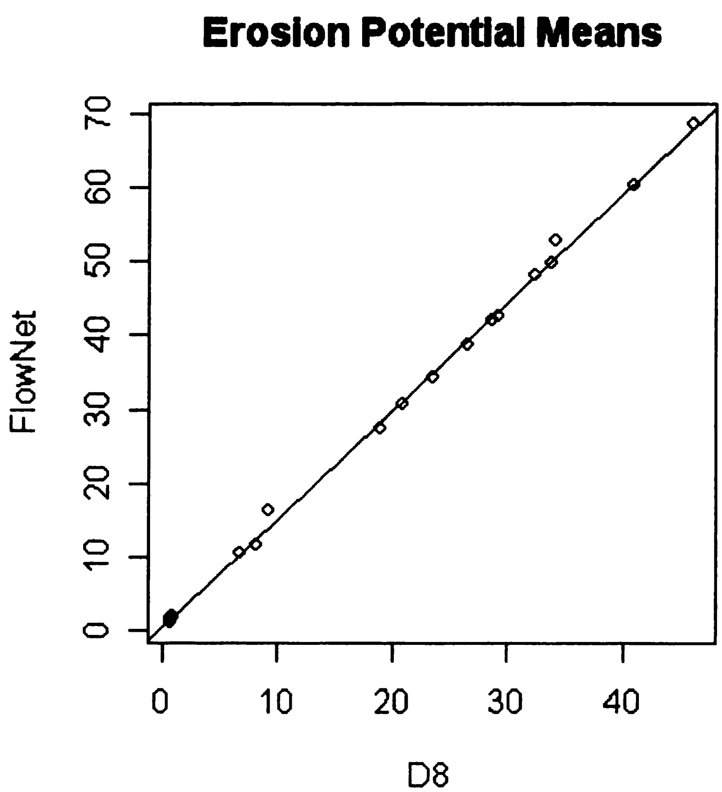

Figure 4.29 Relationship between FlowNet algorithm and D8 erosion potential means

To evaluate the variability of this relationship between different physiographic regions, residuals of the linear model for each watershed were collected (table 4.5) and T-Tests were conducted to determine whether model differences varied significantly among regions. More detailed results are listed in Appendix A.

No.	MI Residual	NM Residual	VA Residual
1	0.173957	-0.12971	-0.84904
2	-0.10218	0.412	2.105704
3	-0.08442	-0.87894	-1.0027
4	0.089859	-0.34046	0.285516
5	-0.3118	0.175202	2.47694
6	-0.19425	-0.56114	-0.26569
7	0.030549	-0.40919	-0.62022

Table 4.5 Linear Model Residuals for Watersheds in Different Physiographic Regions

1. Residual T-Test between MI and NM

t = 1.0715, df = 7.714, p-value = 0.3163, mean of x = -0.0569, mean of y = -0.2475

2. Residual T-Test between MI and VA

t = -0.6661, df = 6.167, p-value = 0.5294, mean of x = -0.0569, mean of y = 0.3044

3. Residual T-Test between NM and VA

t = -0.979, df = 7.132, p-value = 0.3596, mean of x = -0.2475, mean of y = 0.3044

These T-Test results tell us that the linear relationship between the FlowNet algorithm erosion potential mean values and the D8 erosion potential mean values does not vary significantly among different physiographic regions. But Table 4.5 also shows us that the absolute differences for the VA residuals are much bigger than the MI residuals. This indicates that high terrain variability leads to high variability in residuals. What this means for the linear model derived above is that it performs well in the flat areas such as Michigan with less variability in the results.

Even though we may be able to derive FlowNet algorithm erosion potential mean values from D8 erosion potential mean values using this linear relationship, how do these differences appear spatially within the watersheds? Are differences essentially constant across each watershed, or are there important patterns of differences between them? To answer these questions, map algebra based calculations were done for all watersheds to derive mapped differences. First a predicted FlowNet algorithm erosion potential grid from D8 erosion potential grid was calculated using the above linear model. Then a difference grid was calculated using the actual FlowNet algorithm erosion potential grid and the predicted FlowNet algorithm erosion potential grid. The detailed results for three selected watersheds are shown below.

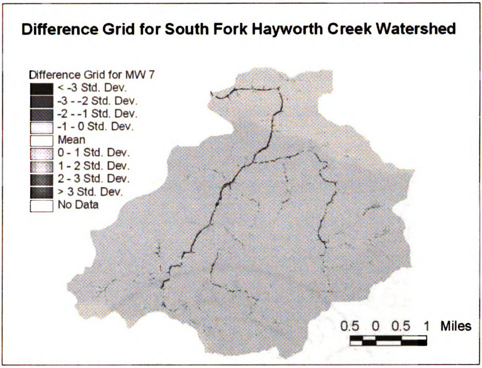

Figure 4.30 Difference Grid for South Fork Hayworth Creek Watershed in MI

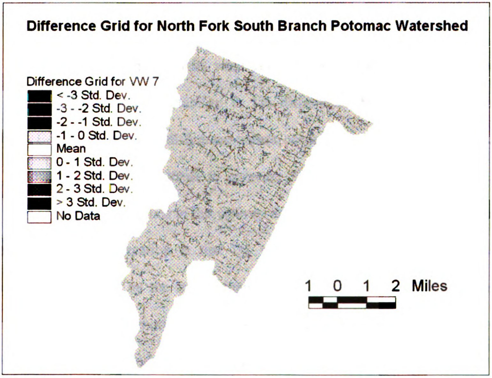

Figure 4.31 Difference Grid for North Fork South Branch Potomac Watershed in VA

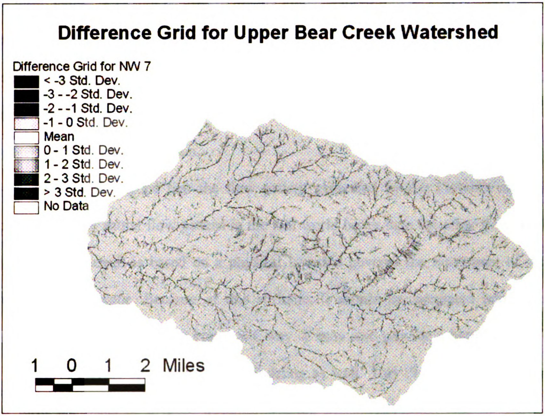

Figure 4.32 Difference Grid for Upper Bear Creek Watershed in NM

Similar difference grid results were derived from all other watersheds as well. There is tremendous spatial variability in the differences between the accumulation algorithms. Both high and low difference values occur close to streams. The reason for this is the FlowNet algorithm tends to generate 'thick' streams with more cells with higher flow accumulation values in the vicinity of the real stream than the D8 algorithm. Another interesting observation is that D8 generates stream cells with higher flow accumulation value right on the stream than the FlowNet algorithm. This is due to the fact that flow is distributed more to cells near the stream in the FlowNet algorithm. From these results we can conclude that even though the linear relationship can be used to predict FlowNet algorithm erosion potential grid mean values from D8 erosion potential grid mean values, it cannot be used to predict FlowNet algorithm erosion potential spatial distributions from D8 erosion potential spatial distributions. This is particularly important because in real world applications involving erosion potential, spatial distributions give people specific information about where those might occur, and shape management responses to the threat of erosion.

It could be argued that the flow pattern generated by the FlowNet algorithm should reflect the actual flow pattern in the real world better than the other flow-routing algorithms because it is based on a physical law that governs the movement of water through the landscape. Because of this attribute, it should be integrated into various hydrological models in a more systematic way. It may also provide a better foundation for combined surface and groundwater modeling as well. This FlowNet algorithm may also form the basis of a more accurate wetness index. To assess whether FlowNet produces more realistic flow accumulation results than D8 method, wetland data collected by Michigan state government were used to validate results generated by both FlowNet and D8 algorithms. The details of this validation work are described in the next section.

4.7. Validation of FlowNet Algorithm

To test whether the FlowNet algorithm matches reality better than the traditional D8 approach, the independent wetland location data (e.g. Figure 4.33) available from Michigan Center for Geographic Information (MI CGI Website, 2008) are used to collect sampling data from flow accumulation grids generated by both FlowNet and D8 methods for seven Michigan watersheds for comparison purposes. The rationale is that if FlowNet is a better algorithm, then wetland locations not in the stream channel should have higher values than D8 for those same cells. At the same time, non-wetland locations should have similar values between algorithms. The following sampling procedure and statistical tests are designed based on this principle.

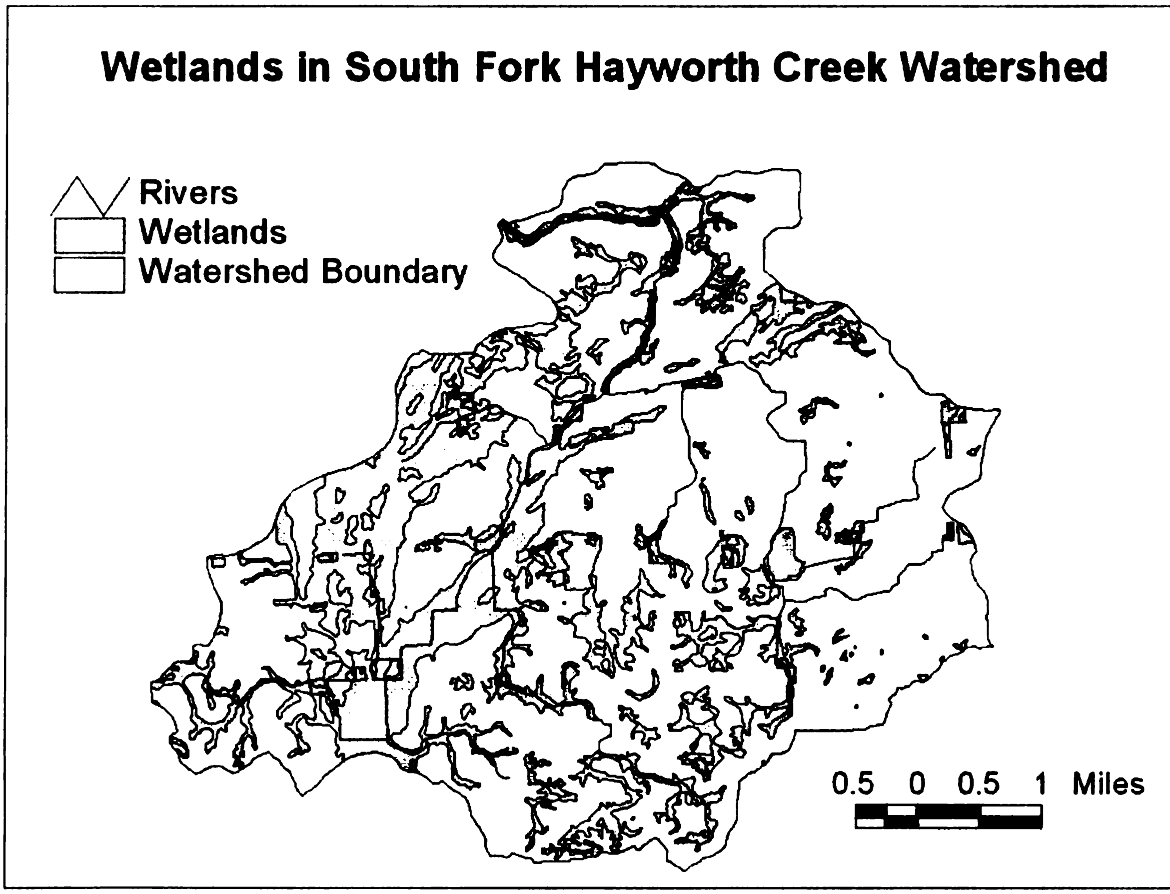

Figure 4.33 Wetlands in South Fork Hayworth Creek Watershed, MI

Specific steps for data sampling and statistical tests are described as follows:

1. Flow accumulation grids derived from both FlowNet and D8 for all seven watersheds are pre-processed in ArcGIS Grid environment to exclude stream cells derived from D8 algorithm using a threshold value of 500 cells. The threshold value is chosen by visually comparing the resulting

stream cells with national hydrography vector data. This exclusion is necessary because these stream cells are not considered as part of the land mass.

2. The wetland polygons are overlaid on top of the flow accumulation grids and then used to clip these grids to produce both wetland flow accumulation grids and non-wetland flow accumulation grids respectively using ArcGIS Grid functions. This process is repeated for each of the seven watersheds in Michigan. In the end, for every watershed two wetland flow accumulation grids and two non-wetland flow accumulation grids are generated for FlowNet and D8 respectively (e.g. Figure 4.34 - 4.37).
3. Hawth Analysis Tools for ArcGIS (Hawth Analysis Tools website, 2008) is used to generate two random sampling point themes for each watershed, one for wetland flow accumulation grids and one for non-wetland flow accumulation grids (e.g. Figure 4.38 – 4.39).
4. One thousand random sampling point locations are used to sample accumulation values from both FlowNet and D8 grids in wetland areas for each watershed. A total of 7 tables are generated and ready for use in statistical tests.
5. One thousand random sampling point locations are used to sample accumulation values from both FlowNet and D8 grids in non-wetland areas for each watershed. A total of 7 tables are generated and ready for use in statistical tests.

6. Paired differences of means t-tests are conducted between FlowNet and D8 wetland flow accumulation samples for every watershed. The null hypothesis (H0) for this test is: actual difference in means between wetland flow accumulation samples from FlowNet method and wetland flow accumulation samples from D8 method is equal to 0. The alternative hypothesis (HA) is: actual difference in means between wetland flow accumulation samples from FlowNet method and wetland accumulation samples from D8 method is greater than 0. Here one-sided tests are used because our purpose is to show flow accumulation values generated by FlowNet are bigger than those generated by D8 in wetland areas. The results of these tests are included in table 4.6. The raw outputs of these tests from R are included in appendix A.
7. Statistical paired t-test is conducted between FlowNet and D8 non-wetland flow accumulation samples for every watershed. The null hypothesis (H0) for this test is: actual difference in means between non-wetland flow accumulation samples from FlowNet method and non-wetland flow accumulation samples from D8 method is equal to 0. The alternative hypothesis (HA) is: actual difference in means between non-wetland flow accumulation samples from FlowNet method and non-wetland accumulation samples from D8 method is not equal to 0. Here two-sided tests are used because our goal is to demonstrate flow accumulation values generated by FlowNet are similar than those generated by D8 in non-wetland areas. And if they are not similar, we expect FlowNet samples

could either be bigger or smaller than D8 samples. The results of these tests are also included in table 4.6. The raw outputs of these tests from R are included in appendix A.

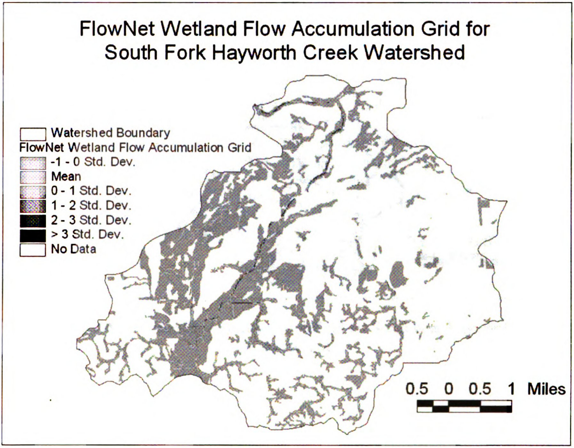

Figure 4.34 FlowNet Wetland Flow Accumulation Grid for South Fork Hayworth Creek Watershed, MI

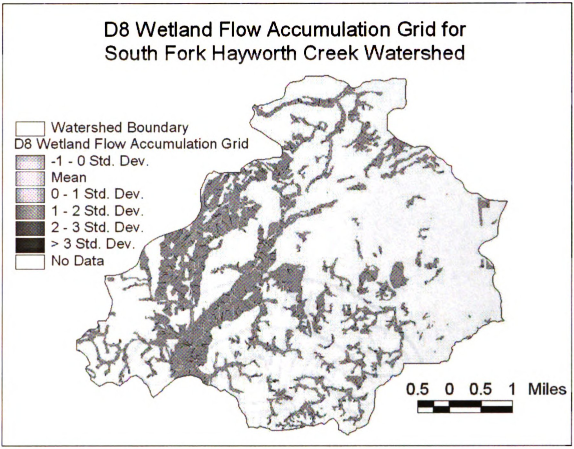

Figure 4.35 D8 Wetland Flow Accumulation Grid for South Fork Hayworth Creek Watershed, MI

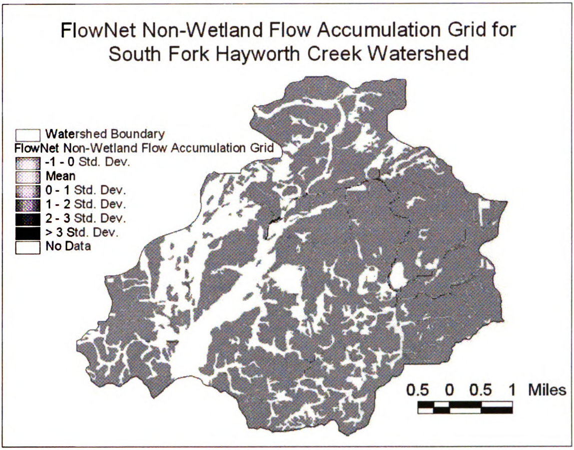

Figure 4.36 FlowNet Non-Wetland Flow Accumulation Grid for South Fork Hayworth Creek Watershed, MI

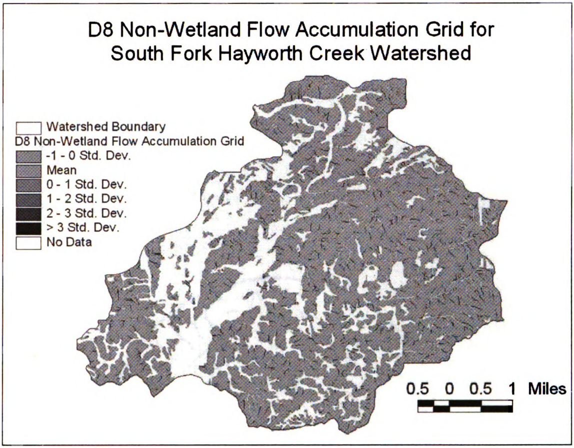

Figure 4.37 D8 Non-Wetland Flow Accumulation Grid for South Fork Hayworth Creek Watershed, MI

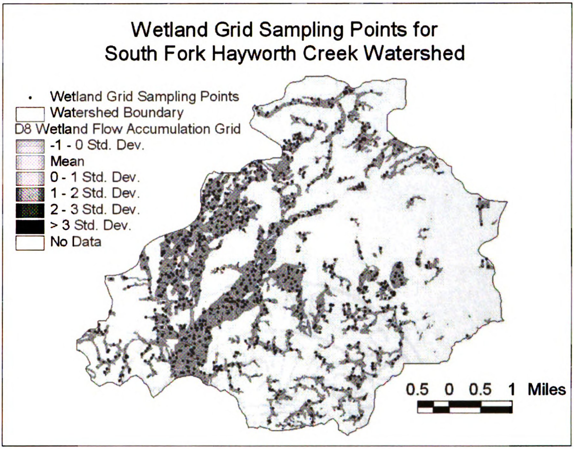

Figure 4.38 Wetland Grid Sampling Points for South Fork Hayworth Creek Watershed, MI

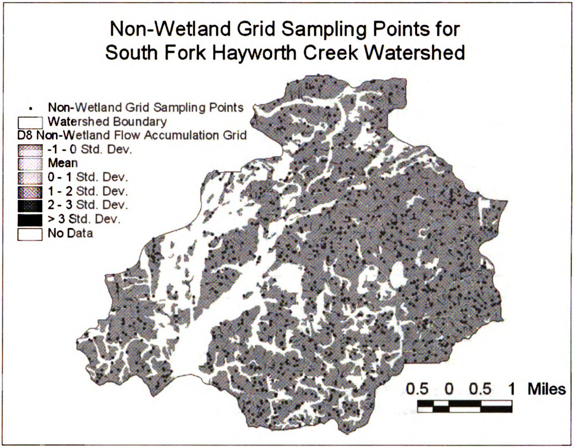

Figure 4.39 Non-Wetland Grid Sampling Points for South Fork Hayworth Creek Watershed, MI

Watershed	Test	T	Df	P-value	Mean of the differences
MI WS 1	Wetland	2.59	999	0.005	1820
MI WS 1	Non-Wetland	1.47	999	0.141	299
MI WS 2	Wetland	3.89	999	<0.001	2174
MI WS 2	Non-Wetland	1.18	999	0.240	169
MI WS 3	Wetland	4.02	999	<0.001	3462
MI WS 3	Non-Wetland	2.21	999	0.027	276
MI WS 4	Wetland	2.73	999	0.003	3273
MI WS 4	Non-Wetland	1.45	999	0.148	261
MI WS 5	Wetland	3.73	999	<0.001	1805
MI WS 5	Non-Wetland	1.82	999	0.068	71
MI WS 6	Wetland	4.07	999	<0.001	1828
MI WS 6	Non-Wetland	2.22	999	0.027	88
MI WS 7	Wetland	2.93	999	0.002	776
MI WS 7	Non-Wetland	1.80	999	0.072	178

Table 4.6 Paired T-Test Results between FlowNet and D8 Flow Accumulation Samples for both Wetland and Non-Wetland Areas

Considering the t-test results between FlowNet and D8 wetland flow accumulation samples listed in table 4.6 for all seven watersheds, it is clear that all calculated p-values are much smaller than 0.05. Therefore, we can reject the null hypothesis and conclude that the mean of FlowNet wetland flow accumulation samples is larger than the mean of D8 wetland flow accumulation samples. While seeing t-test results between FlowNet and D8 non-wetland flow accumulation samples, five out of seven watersheds have calculated p-values bigger than 0.05. In those cases we fail to reject the null hypothesis and conclude that mean of FlowNet non-wetland flow accumulations samples is the same as the mean of D8 non-wetland flow accumulation samples. For the remaining two watersheds 3 and 6, even though judging from the calculated p-value we cannot accept the null hypothesis for non-wetland flow accumulation samples, there are big differences between p-values for wetland and non-wetland tests. These results show that FlowNet flow accumulation totals are higher in wetland, non-channel locations than D8 flow accumulation totals, and they are generally not significantly different in non-wetland locations. This means FlowNet flow accumulation results capture the wetland locations better than D8 ones because FlowNet algorithm produces 'wetter' cells in wetland areas while still generates 'dry' cells in non-wetland areas in comparison with D8 method. Therefore, it can still be concluded that FlowNet algorithm is better than D8 method in terms of matching wetland locations.

4.8. Conclusions

Various flow routing algorithms and their advantage and shortcomings were reviewed in this chapter. The review found that the existing flow routing algorithms tend to oversimplify the water movement across the landscape without consideration of physical laws that govern the fluid movement. Based on this fact, a new flow routing algorithm called FlowNet was developed and applied to the total of 21 watersheds in three different physiographic regions in the US. Two other algorithms, the popular D8 and D∞, were also applied to these watersheds for comparison purposes. RUSLE soil erosion estimates based on the three flow routing algorithms were also done for all these watersheds. The final results were collected and compared to show the advantages of the FlowNet algorithm. Statistical analyses were conducted to find out whether certain relationships exist between the results using three algorithms. Wetland data collected from Michigan Center for Geographic Information were also used to validate that FlowNet algorithm performs better than D8 method in terms of matching wetland locations.

Compared with D8 and D∞, the FlowNet algorithm tends to generate 'thicker' stream cells because of the flow patterns governed by physical laws. FlowNet shares important similarities with the FD8 algorithm because they both distribute flow to lower neighboring cells on a slope-weighted basis, but the key difference is that FlowNet only distributes flow to four possible orthogonal neighbors according to the physical law that governs the flow. Of course, if the FD8 algorithm routing scheme is limited to four orthogonal neighbors as well, it should work the same way as the FlowNet algorithm. However, FlowNet has the capability to incorporate other parameters for fluid movement besides topography and it can be further developed into a complete surface water flow model.

The flow pattern generated by the FlowNet algorithm should reflect the actual flow pattern in the real world situations and hence make it a better basic flow routing algorithm for various hydrological models. The RUSLE soil erosion modeling results seem to confirm this because the RUSLE model based on D8 often underestimates erosion while the results in this study show that RUSLE model based on FlowNet systematically generate significantly larger results than the model based on D8. The statistical linear relationship found between RUSLE erosion based on FlowNet and RUSLE erosion based on D8 is Eflownet = 0.38890 + 1.46902 * Ed8. The residuals results from different physiographic regions for this linear model indicate it performs well in the flat areas such as Michigan with less variability in the results.

If the FlowNet algorithm is integrated into our VO-based Watershed Management SDSS discussed in the previous chapters, it can be hosted on universities' server nodes along with all DEM datasets. Other server nodes in the system or end users could directly access this new function over the network immediately for their own use and benefit from the new algorithm. Also in a modular environmental modeling environment within a VO-based Watershed Management SDSS, this new algorithm can replace the problematic method currently in place and improve the modeling capability of the overall system. But to make this happen, FlowNet algorithm would have to be improved by parallelization using Grid technology. This also illustrates how a living VO-based Watershed Management SDSS capable of integrating new algorithms or models over time can help hydrologists, information scientists, and policymakers extend their collective abilities for watershed management.

Another recent advance in DEM-based flow routing techniques that could complement the FlowNet algorithm is the realistic representation of physical and man-made features such as roads and bridges in a watershed and use this secondary information to generate even more realistic flow patterns. Turcotte et al. (2001) described a new approach to couple the DRLN (digital river and lake network) to the modeled drainage structure. Vogt et al. (2003) proposed a methodology to combine digital elevation data and environmental characteristics to derive drainage networks and catchment boundaries. Duke et al. (2003, 2006) reported a new approach to improve overland flow routing by incorporating ancillary road data into DEMs. Further research is needed to find out how to integrate this new advance with the FlowNet algorithm.

Chapter 5. Summary and Conclusions

5.1. Introduction

Watershed management is essentially a consensus-building process relying on the active involvement of multiple stakeholders. A good watershed management plan must reflect social consensus regarding water as a resource and the society's vision of an ideal watershed and water quality and quantity (Nickum and Easter, 1990; Davenport, 2002; Gregersen et al., 2008). The nature of watershed management demands a holistic integrative approach to consider the impacts of various human activities in a watershed on water resources and other related natural resources (Reimold, 1998). Watershed management often entails close collaboration among specialists from different disciplines such as hydrology, ecology, biology, engineering, economics, management science, law and policy, as well as government agencies, private industries, non profit organizations, and the public (Heathcote, 1998; Reimold, 1998; Gregersen et al., 2008). An effective way to integrate scientific information from multiple disciplines into the real world decision making process is mandatory for successful watershed management practices.

Even though the advances in information technology, geospatial technology and environmental modeling techniques have dramatically changed watershed management practices in the past few decades, the reality of current watershed management is still highly fragmented in terms of the data collection, modeling activities and management practices (Savory et al., 1999; Acreman, 2005; Cash et al., 2003). Due to the spatial nature of watershed environmental data, information is collected and analyzed by organizations and people who typically care about a specific location such as a state, a county or a watershed. Various computer models that use these data to describe watershed systems have been created by research organizations or private environmental consulting companies. All these data, information, analytical methods and simulation models are often scattered across different organizations with limited or no communication between organizations because of fragmented management practices (Acreman, 2005; Cash et al., 2003; NRC, 1999). Since many watershed environmental problems require ongoing investigation, the next team or individual investigators who want to study the same place usually spend significant time and effort collecting existing information from multiple sources. This is not an efficient way to build up our collective watershed management capabilities.

In this research, the author argues that a collaborative online Virtual Organization based Watershed Management Spatial Decision Support System capable of integrating distributed databases and computational models offers superior opportunities for holistic watershed management. This system can provide an effective way to embed science in the decision making process by improving the communication between the scientific and the policy sector and between decision-makers and involved stakeholders and translating often complicated modeling results into an easy to understand format for environmental decision makers. Based on the user evaluation results collected by Wisconsin DNR, it can be concluded that this VO-based approach for spatial decision support offers better tools for watershed management.

5.2. Major Contributions

The research conducted led to the conceptualization of an Internet based integration framework for the VO-based watershed management SDSS based on requirements analysis for the VO-based watershed management SDSS and implementation of an example VO-based watershed management SDSS. This example system engages government agencies, universities and local planning and watershed groups for the common purpose of reducing sediment runoff into the streams of two relatively small watersheds in northern Indiana. It integrates two separate web-based watershed management spatial decision support systems from two universities to serve the needs of local communities. The system allows end users to simulate different best management practices (BMP) scenarios online in real time with an easy to use graphical user interface. This system also demonstrates how distributed modeling and modularity of environmental model components can be implemented in a VO environment.

With continuing growth of availability of higher resolution geospatial data and computational intensity of spatial and watershed models, more efficient computing infrastructure is needed for the improvement of complex modeling performance so end users can carry out management scenario analyses in a real time fashion. The author believes that VO-based Grid Computing technology can play a significant role in fulfilling this requirement. To demonstrate this point, a water quality model was parallelized using basic Grid techniques to show how performance can be improved by utilizing distributed computing resources. A VO-based watershed management SDSS built on top of the Grid technology with the ability of evolving over time is a strong architecture for participatory decision making process in the watershed management context.

To illustrate the importance of technical aspects of watershed management process, a new basic DEM-based flow analysis algorithm called FlowNet based on the physical law that governs water movement was designed, implemented and applied to different physiographic regions in the US. The statistical results show this is a better algorithm in terms of overcoming the erosion potential underestimation problem associated with traditional D8 method (USEPA Region 7 and IOWA Dept. of Natural Resources 2006). This algorithm was also validated using independent wetland data available in Michigan to illustrate that it performs better than D8 method in terms of matching wetland locations. If FlowNet is integrated into an evolving modular VO-based watershed management SDSS, it can help decision makers get better flow information.

The major contributions of this research to the literature on spatial decision support system, watershed management and geographic information science are:

- Analysis and documentation of requirements for VO-based Watershed Management Spatial Decision Support Systems. This is reported in Chapter two.
- Conceptualization and documentation of an Internet–based integration framework for the VO-based watershed management SDSS. This is reported in Chapter three.
- Implementation of the example VO-based Watershed Management Spatial Decision Support System for sediment runoff reduction in two watersheds in northern Indiana and validation of VO-based SDSS Approach for Watershed Management. These are documented in Chapter three.
- Demonstration of the utility of Grid Computing technology in VO-based Watershed Management Spatial Decision Support System via parallelization of a selected water quality model and subsequent performance analysis. This is documented in Chapter three.

- Design, implementation, application and validation of a fundamentally new DEM-based flow analysis algorithm and statistical analysis of application results. This is described in Chapter four.

5.3. Major Conclusions

Results from this study produced several conclusions related to the fields of spatial decision support systems, watershed management and geographic information science:

- The social technical nature of watershed management process requires a multi-organizational and multi-disciplinary integration framework for the participatory consensus building decision making process.
- A VO-based Watershed Management Spatial Decision Support System utilizing Grid Computing and advanced geospatial technology offers an effective way to involve multiple shareholders and integrate scientific information from multiple disciplines into participatory decision making process in watershed management.
- Parallelization based on Grid technology provides an efficient way to improve the performance of watershed models so they can be integrated into the VO-based Watershed Management Spatial Decision Support system in real time fashion.
- A better basic DEM-based flow analysis algorithm can be designed and implemented by considering the physical laws that govern water flow in the real world landscape.

5.4. Recommendations for Future Research Directions

The research in this study suggests the following future research directions:

1). How to define the institutional agreement framework so organizations can be encouraged to participate in the watershed management VO and be willing to integrate and share their resources. More organizational research needs to be done to identify policies and incentives that will bring more related institutions into the watershed management VO. Policies that encourage and reward VO participation and incentives such as extra funding mechanism will likely help in this aspect.

2). How to integrate Grid Computing technology into the technical infrastructure of major players such as government agencies and universities in a VO. Even though Grid technology is increasingly gaining popularity, it still largely remains in the academic and research communities. Further research needs to be done to develop easy-to-implement methods for transforming existing facilities into or constructing new Grid-enabled technical infrastructure in non-academic institutions such as government agencies.

3). How to integrate data intensive and complex watershed simulation models into Grid-based computing infrastructure so end users can conduct real or near real time scenario analysis online. Data intensive and complex watershed simulation models are often too time consuming for real or near real time scenario analysis. New specific parallelization techniques need to be developed for various simulation models by modeling communities.

4). How to calibrate and validate complex watershed models in a VO and carry out uncertainty analysis in a relatively short time period utilizing Grid infrastructure.

The calibration of complex watershed models is still a major challenge in using watershed models for environmental decision making. Even though some auto calibration modules have been developed to calibrate watershed models, most of these tools currently run on a single computer requiring significant CPU hours to complete the model calibration. More research is needed to develop the model calibration process utilizing Grid Computing so that the model calibration can be performed in a relatively shorter time frame.

5). How to present and visualize environmental information in a more easy to understand way so any stakeholder can quickly understand the complexities and make an informed decision. Even though some animations on rainfall, temperature, and graphs/maps on streamflow conditions exist, there are no other easy means of creating visualizations for use as educational tools to both decision makers and stakeholders. More research needs to be done to develop various educational tools that will use public domain and data as well as user provided data and 2D/3D visualization techniques to explain hydrologic/water quality processes to various stakeholders in the Grid environment.

6). How to better organize watershed environmental information, engage more people in the watershed decision making process and help them build social consensus regarding solutions to environmental problems in a VO environment. Watershed environmental information within a VO often comes in different format from different sources. Organizing and presenting this information in a consistent, transparent and holistic way is a major challenge that will demand more research efforts in ontologies and semantics for environmental information. Getting more people involved in the watershed decision making process is a very import goal of any watershed management VO. New technology such as social networking is likely to help with this objective. Further research is needed to investigate new ways for integrating social networking technology into watershed management VO to bring together a diverse group of people (scientists, policymakers, NGOs, stakeholders, students, educators, and the public) who are concerned with watershed environmental issues and provides a platform that encourages them to voice their opinions, share information, and make connections with other people.

Appendix A. Statistical Test Results from R:

1. Paired T-Test between Dinf and D8 flow accumulation mean values:

H0: Actual difference in means between Dinf and D8 flow accumulation grids is equal to 0.

HA: Actual difference in means between Dinf and D8 flow accumulation grids is not equal to 0.

```
> t.test(mydata$fadi,mydata$fad8,paired=T)

        Paired t-test

data:  mydata$fadi and mydata$fad8
t = -1.0665, df = 20, p-value = 0.2989
alternative hypothesis: true difference in means is not equal to
0
95 percent confidence interval:
 -39.67098  12.82917
sample estimates:
mean of the differences
              -13.42090
```

2. Paired T-Test between FlowNet algorithm and D8 flow accumulation mean values:

H0: Actual difference in means between FlowNet algorithm and D8 flow accumulation grids is equal to 0.

HA: Actual difference in means between FlowNet algorithm and D8 flow accumulation grids is greater than 0.

```
>
t.test(mydata$fana,mydata$fad8,alternative=c("greater"),paired=T)

        Paired t-test

data:  mydata$fana and mydata$fad8
t = 15.4888, df = 20, p-value = 6.652e-13
alternative hypothesis: true difference in means is greater than
0
95 percent confidence interval:
 330.2002      Inf
sample estimates:
```

```
mean of the differences
               371.5763
```

3. Paired T-Test between Dinf and D8 erosion potential mean values:

H0: Actual difference in means between Dinf and D8 erosion potential grids is equal to 0.

HA: Actual difference in means between Dinf and D8 erosion potential grids is not equal to 0.

```
> t.test(mydata$epdi,mydata$epd8,paired=T)

        Paired t-test

data:  mydata$epdi and mydata$epd8
t = 5.1517, df = 20, p-value = 4.854e-05
alternative hypothesis: true difference in means is not equal to
0
95 percent confidence interval:
 0.6421343 1.5159609
sample estimates:
mean of the differences
               1.079048
```

4. Paired T-Test between FlowNet algorithm and D8 erosion potential mean values:

H0: Actual difference in means between FlowNet algorithm and D8 erosion potential grids is equal to 0.

HA: Actual difference in means between FlowNet algorithm and D8 erosion potential grids is greater than 0.

```
>
t.test(mydata$epna,mydata$epd8,alternative=c("greater"),paired=T)

        Paired t-test

data:  mydata$epna and mydata$epd8
t = 5.3756, df = 20, p-value = 1.458e-05
alternative hypothesis: true difference in means is greater than
0
95 percent confidence interval:
 5.798465      Inf
sample estimates:
```

```
mean of the differences
               8.537714
```

5. Linear regression model between FlowNet erosion potential grid mean value and D8 erosion potential grid mean value:

```
> regnad8<-lm(mydata$epna~mydata$epd8)
> summary(regnad8)

Call:
lm(formula = mydata$epna ~ mydata$epd8)

Residuals:
     Min       1Q  Median      3Q     Max
-1.0027 -0.4092 -0.1297  0.1740  2.4769

Coefficients:
                       Estimate Std. Error  t value    Pr(>|t|)
(Intercept)       0.38890    0.29240     1.33       0.199
mydata$epd8  1.46902    0.01272  115.45   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.877 on 19 degrees of freedom
Multiple R-Squared: 0.9986,     Adjusted R-squared: 0.9985
F-statistic: 1.333e+04 on 1 and 19 DF,  p-value: < 2.2e-16
```

6. Linear model residuals T-Test for different physiographic regions:

```
> t.test(epresidatast$residmi,epresidatast$residnm)

        Welch Two Sample t-test

data:  epresidatast$residmi and epresidatast$residnm
t = 1.0715, df = 7.714, p-value = 0.3163
alternative hypothesis: true difference in means is not equal to
0
95 percent confidence interval:
 -0.2222181  0.6033515
sample estimates:
  mean of x   mean of y
-0.05689679 -0.24746349

> t.test(epresidatast$residmi,epresidatast$residva)

        Welch Two Sample t-test
```

```
data:  epresidatast$residmi and epresidatast$residva
t = -0.6661, df = 6.167, p-value = 0.5294
alternative hypothesis: true difference in means is not equal to
0
95 percent confidence interval:
 -1.6796426  0.9571285
sample estimates:
  mean of x   mean of y
-0.05689679  0.30436027

> t.test(epresidatast$residnm,epresidatast$residva)

        Welch Two Sample t-test

data:  epresidatast$residnm and epresidatast$residva
t = -0.979, df = 7.132, p-value = 0.3596
alternative hypothesis: true difference in means is not equal to
0
95 percent confidence interval:
 -1.879661  0.776013
sample estimates:
 mean of x  mean of y
-0.2474635  0.3043603
```

7. Paired T-Test between FlowNet and D8 wetland flow accumulation samples for seven watersheds in Michigan:

H0: actual difference in means between wetland flow accumulation samples from FlowNet method and wetland flow accumulation samples from D8 method is equal to 0.

HA: actual difference in means between wetland flow accumulation samples from FlowNet method and wetland accumulation samples from D8 method is greater than 0.

```
>
t.test(mw1wgst$MW1FNWGNS,mw1wgst$MW1D8WGNS,alternative=c("greater"),pair
ed=T)

      Paired t-test

data:  mw1wgst$MW1FNWGNS and mw1wgst$MW1D8WGNS
t = 2.5866, df = 999, p-value = 0.004917
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
```

```
 661.6799      Inf
sample estimates:
mean of the differences
             1820.378

>
t.test(mw2wgst$MW2FNWGNS,mw2wgst$MW2D8WGNS,alternative=c("greater"),pair
ed=T)

        Paired t-test

data:  mw2wgst$MW2FNWGNS and mw2wgst$MW2D8WGNS
t = 3.8868, df = 999, p-value = 5.413e-05
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 1253.360      Inf
sample estimates:
mean of the differences
             2174.381

>
t.test(mw3wgst$MW3FNWGNS,mw3wgst$MW3D8WGNS,alternative=c("greater"),pair
ed=T)

        Paired t-test

data:  mw3wgst$MW3FNWGNS and mw3wgst$MW3D8WGNS
t = 4.0211, df = 999, p-value = 3.114e-05
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 2044.606      Inf
sample estimates:
mean of the differences
             3462.111

>
t.test(mw4wgst$MW4FNWGNS,mw4wgst$MW4D8WGNS,alternative=c("greater"),pair
ed=T)

        Paired t-test

data:  mw4wgst$MW4FNWGNS and mw4wgst$MW4D8WGNS
t = 2.7332, df = 999, p-value = 0.003192
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 1301.61      Inf
```

```
sample estimates:
mean of the differences
          3273.375

>
t.test(mw5wgst$MW5FNWGNS,mw5wgst$MW5D8WGNS,alternative=c("greater"),pair
ed=T)

      Paired t-test

data:  mw5wgst$MW5FNWGNS and mw5wgst$MW5D8WGNS
t = 3.7341, df = 999, p-value = 9.951e-05
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 1009.417      Inf
sample estimates:
mean of the differences
          1805.439

>
t.test(mw6wgst$MW6FNWGNS,mw6wgst$MW6D8WGNS,alternative=c("greater"),pair
ed=T)

      Paired t-test

data:  mw6wgst$MW6FNWGNS and mw6wgst$MW6D8WGNS
t = 4.0705, df = 999, p-value = 2.531e-05
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 1088.810      Inf
sample estimates:
mean of the differences
          1828.284

>
t.test(mw7wgst$MW7FNWGNS,mw7wgst$MW7D8WGNS,alternative=c("greater"),pair
ed=T)

      Paired t-test

data:  mw7wgst$MW7FNWGNS and mw7wgst$MW7D8WGNS
t = 2.9332, df = 999, p-value = 0.001716
alternative hypothesis: true difference in means is greater than 0
95 percent confidence interval:
 340.5154      Inf
sample estimates:
```

```
mean of the differences
         776.181
```

8. Paired T-Test between FlowNet and D8 non-wetland flow accumulation samples for seven watersheds in Michigan:

H0: actual difference in means between non-wetland flow accumulation samples from FlowNet method and non-wetland flow accumulation samples from D8 method is equal to 0.

HA: actual difference in means between non-wetland flow accumulation samples from FlowNet method and non-wetland accumulation samples from D8 method is not equal to 0.

```
> t.test(mw1nwgst$MW1FNNWGNS,mw1nwgst$MW1D8NWGNS,paired=T)

     Paired t-test

data:  mw1nwgst$MW1FNNWGNS and mw1nwgst$MW1D8NWGNS
t = 1.4731, df = 999, p-value = 0.1411
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -99.18173 696.37664
sample estimates:
mean of the differences
         298.5975

> t.test(mw2nwgst$MW2FNNWGNS,mw2nwgst$MW2D8NWGNS,paired=T)

     Paired t-test

data:  mw2nwgst$MW2FNNWGNS and mw2nwgst$MW2D8NWGNS
t = 1.1765, df = 999, p-value = 0.2397
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -112.9532  451.1824
sample estimates:
mean of the differences
```

```
          169.1146

> t.test(mw3nwgst$MW3FNNWGNS,mw3nwgst$MW3D8NWGNS,paired=T)

        Paired t-test

data:  mw3nwgst$MW3FNNWGNS and mw3nwgst$MW3D8NWGNS
t = 2.2146, df = 999, p-value = 0.02701
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
  31.40946 520.03519
sample estimates:
mean of the differences
          275.7223

> t.test(mw4nwgst$MW4FNNWGNS,mw4nwgst$MW4D8NWGNS,paired=T)

        Paired t-test

data:  mw4nwgst$MW4FNNWGNS and mw4nwgst$MW4D8NWGNS
t = 1.4478, df = 999, p-value = 0.148
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -92.74754 614.68799
sample estimates:
mean of the differences
          260.9702

> t.test(mw5nwgst$MW5FNNWGNS,mw5nwgst$MW5D8NWGNS,paired=T)

        Paired t-test

data:  mw5nwgst$MW5FNNWGNS and mw5nwgst$MW5D8NWGNS
t = 1.8247, df = 999, p-value = 0.06834
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
  -5.386305 148.204066
sample estimates:
mean of the differences
          71.40888

> t.test(mw6nwgst$MW6FNNWGNS,mw6nwgst$MW6D8NWGNS,paired=T)

        Paired t-test

data:  mw6nwgst$MW6FNNWGNS and mw6nwgst$MW6D8NWGNS
```

t = 2.2213, df = 999, p-value = 0.02656
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 10.28564 166.17910
sample estimates:
mean of the differences
         88.23237

```
> t.test(mw7nwgst$MW7FNNWGNS,mw7nwgst$MW7D8NWGNS,paired=T)
```

    Paired t-test

data: mw7nwgst$MW7FNNWGNS and mw7nwgst$MW7D8NWGNS
t = 1.8013, df = 999, p-value = 0.07196
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -15.94429 372.58035
sample estimates:
mean of the differences
         178.3180

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