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Information Systems for Integrated Watershed Management

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Abstract: Watershed management is a broad concept incorporating plans, policies and activities used to control water and related resources and processes in a given watershed. Watershed management is a decision process that is informed by a combination of biophysical sciences, socio-economic information, and local knowledge. Information systems are the infrastructure and mechanisms that deliver and process watershed information to serve diverse information needs of watershed manager and stakeholders for achieving watershed management goals. Great technological progresses took place in computer and information technologies during the last two decades that can significantly change the ways of delivering and processing the watershed information. This paper reviews the impacts of technological progresses on watershed information delivery and process, various information systems for integrated watershed management, and their current application and future challenges. Five types of information systems for integrated watershed management are reviewed: (i) watershed information clearing house (WIC), (ii) biophysical modeling, (iii) integration of GIS with biophysical models, (iv) spatial decision support system (SDSS), and (v) web-based spatial decision support system (WSDSS). The five information systems represent the wide spectrum of available practices that deliver and process the watershed information. WIC represents the simplest, well-developed information system while WSDSS represents the most complicated, less-developed information system that serves diverse needs in the integrated watershed management process.

Key words: Watershed management, information system, watershed information clearinghouse, biophysical modeling, geographic information system, spatial decision support system, and web-based spatial decision support system.

A watershed is a geographic area in which water, sediment and dissolved materials drain to a common outlet - a point on a larger stream, a lake, an underlying aquifer, an estuary, or an ocean (USEPA, 1993). Individual watersheds are the most logical geographical units for identifying holistic cause-and-effect water quality relationships, linking upstream uses to down-stream effects, developing reasonable water clean up plans, targeting limited resources, and educating and involving the public (Water Environmental Federation, 1992).

World Meteorological Organization (1974) defined watershed management as planned use of drainage basins in accordance with predetermined objectives. Watershed management is a broad concept incorporating the plans, policies, and activities used to control water and related resources and processes in a given watershed (USNRC, 1999). It takes an integrated and holistic problem-solving strategy to restore and maintain the physical, chemical and biological integrity of aquatic ecosystems, protect human health, and provide sustainable economic growth within watersheds (USEPA, 1993). The integrated watershed management approach has become a social movement for solving water and related resource problems in the United States and worldwide. For example, there were 1500 locally-led watershed initiatives in the United States, almost all of which were established in the 1990s (Lant, 1999). Similar observations can be made in many other countries such as Canada, Australia, and Brazil.

An integrated watershed management approach is generally recognized as the most practical and efficient way to improve water quality and other environmental indicators while maintaining regional economic viability. Successful integrated watershed management shares the following characteristics. First, for every natural watershed there is a "shadow" watershed defined by human and natural features that extend the decision-maker's interest beyond the physical boundaries of a watershed. Integrated watershed management reconciles the political, economic and social conditions with the ecological and biophysical aspects of an area and draws influential and voluntary participation of multiple local and non-governmental interests (USNRC, 1999). Second, watershed management is a decision process that is informed by a combination of biophysical sciences, socio-economic information, and local knowledge. Integrated watershed management actively seeks inputs from both biophysical and social scientists on development, implementation and evaluation of policies and practices for achieving integrated watershed management (USNRC, 1999). Third, integrated watershed management takes a collaborative problem-solving planning and management orientation (Born and Genskow, 2001).

Watershed managers and stakeholders need substantial information about watershed and watershed processes to manage a watershed. First, there is a general need for information about watershed. People generally want to know watershed conditions and what is going on in their watershed. Second, there is decision need for watershed information. Different interest groups usually have perspectives on watershed problems and their solutions. There is a need to convert the diverse interests, perspectives and solutions into comparable economic and environmental impacts in the watershed and to use available watershed information in a group setting to make informed watershed management decisions. Information systems for integrated watershed management are the infrastructure and mechanisms that deliver and process watershed information to serve diverse information needs of watershed managers and stakeholders for achieving watershed management goals.

Since the physical, biological, social and economic processes in a watershed are complicated, it is not an easy task to develop and maintain information systems. During the last two decades, there have been great technological progresses in computer and information technologies. Powerful computers have become affordable. Complicated technologies such as remote sensing, geographic information system (GIS) and global positioning system (GPS) are accessible. Internet has been emerging as a primary computing and communication power. Such technological progresses significantly change information systems for integrated watershed management. This paper will review the impacts of technological progresses on watershed information delivery and process, various information systems for integrated watershed management, and their current application and future challenges.

In summary, we review five types of information systems for integrated watershed management: (i) watershed information clearing house (WIC), (ii) biophysical modeling, (iii) integration of GIS with biophysical models, (iv) spatial decision support system (SDSS), and (v) web-based spatial decision support system (WSDSS). The five information systems represent the wide spectrum of available practices that deliver and process watershed information. WIC represents the simplest, well-developed information system while WSDSS represents the most complicated, less-developed information system that serves diverse needs in the integrated watershed management process.

Watershed Information Clearing House

The simplest and most popular information system for integrated watershed management is WIC. WIC is a central place to inventory, document and share the critical watershed information among the watershed managers, government agencies, researchers and the general public for integrated watershed management. The shared information includes not only spatial data such as topography, soils, hydrology, land use/cover and aerial photo, but also non-spatial information such as institutional structure, watershed meetings and activities, meeting minutes and assessment reports. WIC brings together all available biophysical, social and economic data about the watershed to promote communication and collaboration among watershed managers, stakeholders and researchers. WIC allows data providers to advertise existing data, the conditions of these data and instructions for accessing these data. WIC also reduces duplication efforts of developing expensive spatial data among different agencies and groups.

GIS is the backbone for maintaining, sharing and querying spatial data in WIC. A GIS is a system of hardware, software and procedures designed to support the capture, management, manipulation, analysis, modeling and display of spatially- referenced data for solving complex planning and management problems. GIS provides the capacity to register the spatial data from different sources to a common geographic coordinate system such as latitude/longitude, Universal Transverse Mercator and State Plane. With the same geographic coordinate system, the data from different sources at different scales (such as the US Census data based on the block group, economic survey based on the administrative boundary) can be interpolated based on the watershed boundary. GIS allows the users to combine and evaluate different spatial data sets and to produce and display new composite information that is of interest to the different groups in watershed management.

The Internet provides additional conveniences and power to WIC. With watershed information hosted in a web server, people can access WIC any time anywhere through web browsers such as the Internet Explorer and Netscape. Internet also allows mixing spatial and non-spatial information in well-designed web pages to provide comprehensive information about the watershed. In recent years, many GIS vendors have developed powerful

Web-based GIS packages. For example, the Environmental System Research Institute (ESRI) developed ArcView Internet Mapping Server (IMS) and Arc IMS. Since many standard GIS functions can be performed through the Internet, WIC powered by the Web-based GIS provides expanded capacity to download, display and query spatial information in watershed through Internet.

There are many WICs hosted through the Internet. One example of WIC is the Pennsylvania Spatial Data Access (PASDA) system developed as part of the National Spatial Data Infrastructure (NSDI) effort. PASDA answers questions like "where are data about watersheds in Pennsylvania?" PASDA consists of two resources: a metadata collection of over 2200 records configured to support distributed NSDI searches using US Federal Geographic Data Committee's standard wide area information server protocol and a web site (www.pasda.psu.edu) that supports search and retrieval of GIS data and preview images, in addition to the metadata collection (USNRC, 1999).

The Map Room hosted by the Center for Agricultural Resource and Environmental Systems (CARES) at the University of Missouri, Columbia, Missouri, USA, provides another example of a comprehensive WIC (www.cares.missouri.edu). This site compiles the best available spatial layers about the biophysical, social and economic conditions in Missouri. The site is powered by Arc IMS of ESRI. Well-customized web pages allow the users to easily delineate, display, query and download the spatial information based on predetermined or user-supplied watershed boundary. The Map Room offers enormous values to watershed management in Missouri. The comprehensive data serve diverse needs of different people such as farmers, watershed managers, government agencies and researchers in watershed and resource management practices.

Biophysical Modeling

A biophysical simulation model is a computer program that compiles biological and physical data to simulate biophysical processes and the environmental consequences of human activities in a watershed. Since biophysical processes of a watershed are complicated and direct monitoring of the biological and physical conditions of a watershed is expensive and time-consuming, biophysical modeling becomes an important means to help watershed managers, stakeholders and scientists to understand the physical watershed and possible environmental impacts of watershed management plans. Biophysical modeling transforms the biophysical data about a watershed such as weather, topography, soils, land use/cover and hydrology into human understanding of biophysical processes of a watershed for watershed management decisions. The most popular biophysical simulation models in integrated watershed management are Hydrological Simulation Program – Fortran (HSPF), Soil and Water Assessment Tool (SWAT) and Agricultural Nonpoint Source Model (AGNPS). Each model and its application will be briefly discussed below.

HSPF

HSPF has its root in the Stanford Watershed Model (Crawford and Linsley, 1966), which was frequently cited in the literature as being one of the first comprehensive watershed biophysical models. The original Stanford watershed model was further expanded to create HSP, the Hydrocomp Simulation Program, which included sediment transport and water quality simulation (Hydrocomp, Inc., 1976). During the early 1970's Hydrocomp developed the ARM (Agricultural Runoff Management Model) and the NPS (Nonpoint Source Pollutant Loading Model) for the US Environmental Protection Agency. HSPF was developed in the late 1970's to handle all the functions performed by HSP, ARM and NPS with easily maintained data structure. The most updated version of HSPF is WinHSPF that embeds HSPF version 12.0 with Windows user interfaces. It can be directly downloaded from the USEPA's web site (www.epa.gov/ost/basins).

HSPF is a comprehensive, conceptual, continuous watershed simulation model designed to simulate all the water quantity and water quality processes that occur in a watershed, including sediment transport and movement of contaminants (Bicknell *et al*., 1996). Although it is usually classified as a lumped model, it can reproduce spatial variability by dividing the basin into hydrologically homogeneous land segments and simulating runoff for each land segment independently, using different meteorological input data and watershed parameters. The model includes fitted parameters as well as parameters that can be measured in the watershed. It has been widely applied for flood mapping, urban drainage studies, river basin planning, studies of sedimentation and water erosion problems and in-stream water quality planning.

SWAT

Unlike HSPF, which requires tremendous work to calibrate fitted parameters using the observed water quality and quantity data, SWAT is a process-based model and most of its parameters can be directly measured from different sources such as topography, soils, land use/cover and hydrology. Its development can be traced back to the US Clean Water Act of 1972 (Arnold *et al*., 1994). In the early to mid-1970's, in response to the Clean Water Act, USDA Agricultural Research Service (ARS) assembled a team of interdisciplinary scientists from across the US and developed a process-based, nonpoint source simulation model called the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980). CREAMS is a field-scale model that simulates the impact of land management on water, sediment, nutrients and pesticides, leaving the edge of a field. By the early and mid-1980's, Williams *et al*. (1983) extended the original CREAMS model and developed EPIC (Erosion and Productivity Index Calculator), which became one of the most popular field-scale biophysical models worldwide. As watershed management became a popular practice to tackle agricultural nonpoint source pollution, Williams *et al*. (1985) developed a watershed biophysical model called SWRRB (Simulator for Water Resources in Rural Basins) to deal with a wide variety of watershed management problems. SWRRB is a continuous daily time step, basin-scale model that allows a basin to be subdivided into a maximum of ten subbasins (Arnold *et al*., 1990). Algorithms used in EPIC were simplified to simulate the biophysical processes within subbasins and the outputs from the sub-basin outlets were routed directly to the basin-outlet using a routing model called ROTO (Routing Outputs to Outlet). SWRRB model has certain limitations such as limited number of sub-basins and cumbersome routing structure. These problems were finally solved with development of the SWAT model (Arnold *et al*., 1994).

SWAT is a continuous time, basin-scale model that operates on a daily time step. It allows a basin to be divided into hundreds or thousands of grid cells or subwatersheds. It even allows a subwatershed to be further delineated into different hydrological response units to represent heterogeneous natural resource conditions in a watershed (Arnold *et al*., 1998). SWAT was developed to predict the impact of watershed management and best management practices on water, sediment and agricultural chemical yields in large ungaged basins. It consists of hydrology, weather, sedimentation, crop growth, nutrients, pesticides, and agricultural management components. Since SWAT embeds a very flexible configuration structure, which distinguishes the different activities within a watershed and provides a very flexible routing structure to control the movement of water flow, nutrients, sediment, and pesticides. It is well suited for evaluating alternative watershed management schemes. In recent years, SWAT has been extended to handle many watershed management problems beyond agricultural nonpoint source pollution. It has been applied to integrated watershed management worldwide. The current version of SWAT can be directly downloaded from either the USEPA web site (www.epa.gov/basins) or the USDA ARS Blackland Research and Extension Center web site in Temple, Taxes, USA (www.brc.tamus.edu/swat).

AGNPS

AGNPS (Young *et al*., 1987, 1989) is another process-based biophysical model that provides basic information on water quality to be used to classify nonpoint source pollution problems in agricultural watersheds. It was initially designed to be a spatially distributed, single-event watershed simulation model that subdivides complex watersheds into grid cells. The model provides outputs on runoff, upland erosion, channel erosion, and sediment yield, and nitrogen, phosphorus, chemical oxygen demand (COD) in runoff and sediment. Later, AGNPS was expanded to estimate pesticide movement in soil and runoff and allow continuous time steps in simulation. The USDA ARS National Sediment Laboratory in Mississippi, USA, currently maintains AGNPS. The most updated version of AGNPS can be downloaded from its web site (msa.ars.usda. gov/ms/oxford/nsl/agnps.html).

Besides HSPF, SWAT and AGNPS, there are many other watershed biophysical models developed in last two decades. Many of these models can be found in the USEPA web site (www.epa.gov/ceampubl). The Civil and Environmental Engineering Department at the Old Dominon University also hosts a web site (asellus.cee.odu.edu/ model) that collects many popular environmental, hydrological, hydraulic, water quality and water resource models. Biophysical models serve as a bridge that connects the best available sciences and integrated watershed management practices. To be useful to integrated watershed management, biophysical models have to be well supported and maintained by a core group of engineers to keep up with the increasing demand of watershed management practices and recent development in biophysical sciences. Development and application of HSPF, SWAT and AGNPS provide best examples that justify the importance of such support. On the other hand, TOPMODEL (Beven and Kirkby, 1979) and the Soil Moisture Routing (SMR) (Frankenberger, 1999) models are opposite examples. TOPMODEL and SMR are watershed-scale biophysical models that are based on the variable source area (VSA) hydrology (Betson, 1964; Tennessee Valley Authority, 1965; Amerman; 1965; Dunne and Black, 1970; Hewlett, 1982). The VSA hydrology argues that in humid regions such as the US Northeast, runoff is primarily generated in relatively small areas in a watershed where the soil has saturated to the surface. Even though the VSA hydrology is well recognized in the arena of basic or pure biogeoscience research and has great potential to improve efficiency and effectiveness of watershed management, it has almost invisible impacts on watershed management practices. One of the primary reasons for lacking such impacts is that the VSA-based hydrological models are not well developed (Beven and Kirkby, 1979; Wigmosta *et al*., 1994, Walter *et al*., 2000; Qiu, 2003).

Integration of GIS and Biophysical Models

Even though the biophysical modeling is an important information system for integrated watershed management as discussed above, the process of converting the biophysical data about watersheds into human understanding of biophysical process in the watersheds is not simple and easy. These models usually have complicated data structure and require extensive spatial and non-spatial input data. The output from those models is usually huge and not easy to read. With rapid development in computer capacities and GIS, integration of GIS and biophysical models becomes obvious solution to ease such difficulties. A GIS is a system of hardware, software and procedures designed to support the capture, management, manipulation, analysis, modeling and display of spatially-referenced data for solving complex planning and management problems. A GIS serves as an engine in the integrating process by creating user-friendly graphic interfaces to organize spatial and non-spatial watershed information, create scenarios, generate input data and process and display output for biophysical models and interface other models to make them easier to run.

There are many examples that integrate GIS with the popular biophysical models in literature. Tim and Jolly (1994) developed an integrated ARC/INFO GIS and AGNPS to evaluate agricultural nonpoint source pollution. He *et al*. (1993) integrated AGNPS and GRASS to evaluate the impacts of agricultural runoff on water quality in the Case River, a subwatershed of Saginaw Bay. Mitchell *et al*. (1993) developed an integrated AGNPS/GRASS system to validate AGNPS for predicting runoff and sediment delivery from small watersheds of moderate topography. Srinivasan and Engel (1995) integrated AGNPS and GRASS GIS to assess agricultural nonpoint source pollution. Fulcher (1996) integrated ArcInfo GIS with AGNPS to evaluate the economic and environmental impacts of land management activities designed to reduce agricultural nonpoint source pollution. Osmond *et al*. (1997) developed the information-based WATERSHEDSS (Water, Soil, and Hydro-environmental Decision Support System) model to assist watershed managers in defining water quality problems and selecting appropriate pollution control measures. WATERSHEDSS provides rich information resources on watershed management and contains a GIS-based biophysical simulation model for evaluating water quality impacts of alternative land treatment scenarios. Other integrated information systems include AQUATOOL (Audreu *et al*., 1996), Water Ware (Fredra and Jemieson, 1996; Jamieson and Fredra, 1996a and 1996b), and LOADSS (Lal *et al*., 1991).

The USEPA developed the most comprehensive information system called the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) that integrates ArcView GIS with nationally derived watershed and water quality data in the US and biophysical models for integrated watershed management. It comprises of nine interrelated components for performing various aspects of environmental analyses at watershed scale. The nine components include (1) nationally derived watershed and water quality data with *Data Extraction* tools and *Project Builders*, (2) assessment tools (*Target*, *Assess*, and *Data Mining*) that address large and small scale watershed characterization needs, (3) utilities to facilitate organizing and evaluating watershed data, (4) tools for *Watershed Delineation*, (5) utilities for classifying DEM, land use, soils, and water quality observations, (6) *Watershed Characterization Reports* that facilitate compilation and output of information on selected watersheds, (7) an instream water quality model, QUAL2E, (8) two watershed loading and transport models, HSPF and SWAT discussed above, and (9) PLOAD, a simplified GIS based model that estimates nonpoint pollution loads on an annual average basis (Lahlou *et al*., 2001). Working together, these components address several specific aspects of integrated watershed management by (1) identifying and prioritizing impaired waters, (2) supplying data characterizing point and nonpoint source pollution and their magnitudes and significance, (3) integrating point source and nonpoint source loadings and fate and transport processes, (4) evaluating and comparing the relative impacts of potential pollution control strategies and watershed management alternatives, and (5) visualizing and communicating environmental conditions to the public through tables, graphs, and maps. BASINS has been widely used to support watershed management and development of the total maximum daily load (TMDLs) in impaired watersheds in the USA TMDL specifies the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and allocates pollutant loadings among point and nonpoint pollutant sources. The current version of BASINS 3.0 can be downloaded from the USEPA web site (www.epa.gov/ost/basins).

Spatial Decision Support System

Rapid advances in computer capacities, information technologies and biophysical modeling allows the development of spatial decision support systems (SDSS) that integrate multi-disciplinary knowledge and information for solving watershed-based environmental problems. Walsh (1993) defined 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 incorporating modeling capabilities with database resources to assist and improve decision-making processes. Decision makers can interact with the system using intuitively designed easy-to-use graphical user interfaces. A SDSS is a knowledge-based system that integrates data, information and models for the purpose of identifying and evaluating solutions to complex problems involving spatially distributed information. Leipnik *et al.* (1993) defined SDSSs as integrated environments, which utilize the databases that are both spatial and non-spatial models, decision support tools like expert systems, statistical packages, optimization packages, and enhanced graphics to offer the decision makers a new paradigm for analysis and problem solving. As suggested by Densham and Goodchild (1989), a SDSS should include the following five key modules: (1) database management system that integrates locational, topological and thematic data and supports cartographic display, spatial query, and spatial modeling, (2) analytical models that process data and decisions, (3) graphical display and report generation that offers the capabilities of generating a set of graphical and tabular reports, (4) graphic user interfaces that effectively connects data, models, users decision preferences and other components of SDSS, and (5) expert knowledge system that synthesizes environmental, procedural and structural knowledge in various ways to solve problems during different stages of decision-making process.

Although the integration of GIS with biophysical models has frequently been entitled as SDSS for integrated watershed management, most of them do not capture the human dimension of watershed management. Integration of GIS with biophysical models significantly improves the efficiency of biophysical modeling for evaluating the environmental impacts of watershed management decision, and therefore, improves the efficiency of watershed management decision process. However, it captures nothing about how watershed decision is made by the watershed managers, stakeholders and the public. The distinguished characteristics of the integrated watershed management framework are that it: (1) takes a problem- and watershed-based approach that focuses on the primary threats to human and ecosystem health with the watershed, (2) allows great participation of communities and stakeholders to identify watershed management problems and take actions collectively and, (3) integrates science and technology of watershed management with local knowledge to take corrective action in a comprehensive and integrated manner (USEPA, 1993). Useful SDSS must incorporate the watershed management decision process that captures broad participation of stakeholders with multiple interests in the watershed. Lack of human behavior components in the development of SDSS greatly limits applications of SDSS in integrated watershed management and policy analysis.

Qiu and Prato (2000) specifically emphasized the importance of behavioral modeling in watershed management and presented a general framework on how economic optimization and environmental models can be integrated in a SDSS. Their SDSS extended previous efforts of integrating GIS with an enterprise budget generator called Cost and Revenue Estimator (USDA, 1988), and biophysical models AGNPS and SWAT (Fulcher, 1996; Zhou and Fulcher, 1997) by incorporating multi-criteria decision making frameworks to capture farmers' behavior in response to changes in agricultural policy and watershed management goals. Through friendly graphic user interface in the integrated system, users can define farming systems or best management practices, evaluate their economic impacts through the budget generator and environmental impacts through biophysical models, and incorporate these impacts with users' preferences over different watershed management goals or changes in agricultural policy to select the most preferred farming systems and/or BMPs in the watershed. Since watershed management usually carries multiple objectives and stakeholders have very diverse concerns and interests during the process, multi-criteria decision making is viewed as an appropriate model that should be incorporated into SDSS for integrated watershed management (Lovejoy *et al.*, 1997; Prato, 1999; Qiu, 2003). Integrated behavioral and environmental modeling in a SDSS contributes to a better understanding of stakeholders' behavior and interrelationships among social, economic and biophysical processes in watershed management.

Web-based Spatial Decision Support System

Rapid development in Internet technologies over the past decade has brought up new ways to development of information systems for integrated watershed management. As discussed previously, Internet warehouses store a large repository of biophysical, social and economic data about the watershed. Communication between and among the professionals and the decision-makers has been improved to the degree that sharing of ideas, experiences, and information about solving problems has become a common place (Wallace *et al.*, 2001). Information systems such as SDSS were traditionally developed for single users, which require data management, model management, and the user interface component to reside on the same machine. Since traditional SDSSs are usually platform-specific, costly, and not extensible, few small businesses have enough resources to develop and maintain their own SDSSs (Regmi, 2002). Advances in Internet technologies, especially the development of web-based GIS such as ArcView IMS and Arc IMS make it possible to develop and maintain SDSS through Internet, i.e. the web-based SDSS (WSDSS). WSDSS provides opportunities to increase involvement of stakeholders in the decision-making and planning process by providing knowledge and data through a widely accessible, fast, cost-effective, and easy-to-use medium (Regmi, 2002).

Benefits of WSDSSs include accessibility, efficient distribution, efficient administration, and cross-platform flexibility (Molenaar and Songer, 2001). In a WSDSS, computational and data-intensive applications run in a powerful server and management scenarios are created and output reports are viewed by users in their web browsers. As data are located in the server, data input to models can be verified and thus input data errors can be minimized. Since the models are stored in a single location, maintenance and distribution of models also become easy and all users access the same version of system. Unlike traditional SDSS, users of WSDSS donot need to purchase specialized hardware or software (Regmi, 2002).

Built upon the previous effort of developing a standard SDSS by Dietz (2000), Regmi (2002) developed a multi-disciplinary WSDSS for the effective management of watershed development called WebL2W. WebL2W integrates hydrologic, economic, and biological models in a single shell by using ArcIMS as a common platform for database and interface management. A user can access the system over the web and choose pre-selected land development patterns to create a 'what if' scenario. The embedded hydrologic model HSPF simulates effects of the scenario on annual runoff volume, flood peaks of various return periods, and groundwater recharge. The economics model evaluates the changes in land value, tax revenue, and government expenditures as a result of the new land development scenario. The biologic model evaluates effects of new land uses to fish habitats in the watershed. The distinguished characteristic of this WSDSS is to generate both biophysical and economic information to watershed managers and stakeholders for solving the watershed issued in a holistic manner. WebL2W is specifically applied to evaluate economic and environmental impacts of different land development patterns in the 145 km^2 Back Creek watershed, Virginia, USA. The model can be accessed through the Internet (webl2w.ce.vt.edu).

Another example of WSDSS is the Web-based Woody Draw Management Model (WDMM) developed by CARES at the University of Missouri, USA, to evaluate economic and environmental impacts of alternative uses of woody draws in Long Branch watershed, Missouri, USA (http://www.cares.missouri.edu/cares/projects/Geoeconomic.asp). Woody draws are small natural drainage areas covered by trees, shrubs and grasses that are formed in landscape by cumulative overland flow. They are natural habitat for many wildlife species, important for water quality improvement and carbon sequestration, valuable for constructed wetlands, grass waterways and woody buffers, and provide shelter for cattle. Maintaining its natural use becomes very important to the integrity of a watershed (Qiu *et al.*, 2002). WDMM is empowered by ArcView IMS and integrates a biophysical model called APEX and a cash flow model to evaluate pre-determined three agricultural and four alternative uses of woody draws. The cash flow model is used to compare economic impacts of uses of draws and APEX is used to evaluate the interaction between a woody draw and the contributing upland area and simulate the environmental impacts of uses of draws. The WDMM allows users to visualize the spatial information, delineate the study area, select and compare scenarios easily through their web browser.

Although WSDSS shows great potential for improving watershed management process, it does have some limitations. First, developed WSDSSs are usually site-specific. It is not an easy task to apply the developed WSDSSs to a new watershed, which requires re-collaboration or re-validation of the models that are embedded in the WSDSSs. Second, WSDSSs run much slower than their desktop counterpart even though the computing power of Internet keeps increasing. It is not expected to run WSDSS through dial-up Internet connection. Third, the scenarios evaluated in most WSDSSs are simple and most of them are predetermined. Fourth, almost all models embedded in the WSDSS originally use the desktop computer as the computing platform. Although several computer languages, such as Java and Perl can be used to link them together in a seamless fashion, the integrated modeling system is not as flexible as the individual models when simulating management scenarios. In general, WSDSSs are in the infancy development stage. Technological breakthrough in Internet communication and model development will stimulate the future development of WSDSS.

Concluding Remarks

Integrated watershed management is a holistic framework for solving problems related to water resources and processes in a given watershed. The success of integrated watershed management relies on efficient and effective delivery and processing of watershed information about the biophysical, social and economic processes to the watershed managers and stakeholders. This paper overviews five types of information systems and their applications for integrated watershed management: (1) watershed information clearinghouse, (2) biophysical modeling, (3) integration of GIS with biophysical models, (4) spatial decision support system, and (5) web-based spatial decision support system. As discussed above, these information systems assemble critical watershed information for watershed managers and stakeholders to encourage broad participation and make watershed management decisions. Recent developments in computer and information technology such as powerful computer, Internet, and GIS significantly improve the efficiency and effectiveness of information delivery and processing in watershed management.

However, there are still great information gaps between the needs of watershed management decisions and current states of watershed knowledge. USNRC (1999) identified three types of information barriers for successfully implementing integrated watershed management. These are (1) gaps in knowledge of watershed processes, (2) gaps in data and information, and (3) gaps in simulation modeling and decision support systems. The information gaps provide great opportunities for future development of the information systems for integrated watershed management. First, watersheds are complex systems with numerous components and complex relationship between those components, and too often our human understanding of watersheds is one-dimensional and overly simplistic (USNRC, 1999). Fundamental research on the natural and human processes and their interactions in watersheds is the basis for constructing efficient and effective information systems for integrated watershed management. Second, better and more user-friendly biophysical models should be developed to transfer the scientific knowledge of watershed into human understating of biophysical processes. These models should incorporate the newest developments in the watershed science, computer sciences, information technologies, and Internet capacities. Current biophysical models are generally designed for experts and are too complicated for the general users such as stakeholders who do not have substantial knowledge in the specific areas. Future model design should accommodate such needs. Third, current information systems primarily emphasize the biophysical processes of a watershed and almost ignore the social and economic processes in the watershed. Lack of understanding of the social and economic processes explains many failures of integrated watershed management efforts. Future information systems should focus more on providing social and economic information of the watershed and the social and economic consequences of watershed management decisions. Fourth, future information systems should have well-tested decision models to help watershed managers and stakeholders to use available information in their watershed management decision. Current information systems such as SDSS and WSDSS began to incorporate decision models to capture the behaviors of stakeholders, but usually lack the inputs from stakeholders. Broad participation of stakeholder is strongly encouraged to develop efficient and effective information systems for integrated watershed management.

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