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Abstract: Understanding and managing water resource problems involves complex processes and interactions within the watershed surface and subsurface. The imposition of total maximum daily load (TMDL) regulations on the pollutant influx to a watershed has created a strong demand for new assessment tools. The spatial scales relevant to transport of the pollutants may span many orders of magnitude, ranging from field plots to regional hydrological systems. As the demand for and development of watershed modeling capabilities have evolved, geographic information systems (GIS) in tandem with remote sensing technologies have played an essential role supporting both data collection and analysis. This paper reviews the current and future trends of GIS and remote sensing technologies in watershed modeling. The primary focus of this discussion is on spatial data availability and management, and further opportunities for model development.

Keywords: GIS; hydrologic processes; modeling; watershed; sensing

Introduction

As the need to improve our understanding and management of water resource problems has grown, analysts have focused on modeling hydrologic processes and interactions at the watershed surface and subsurface. A watershed model simulates hydrologic processes in a more holistic approach, compared to many other models which primarily focus on individual processes or multiple processes within a water body without full incorporation of watershed area (Oogathoo, 2006).

Most of the commonly used watershed models were formulated during the period between 1960 to 1990, including HEC-1 in 1967 at the Hydrologic Engineering Center in Davis, CA (USACE 1981), the Hydrologic Simulation Program in Fortran (HSPF) in the 1960's (Bicknell et al. 1993), and TOPography based hydrological MODEL (TOPMODEL) in 1974 (Kirkby and Weyman, 1974). After the initial release of models such as these, additional development work has focused on improving data management and utilization through graphical user interfaces (GUIs) with geographic information systems (GIS) and use of remotely sensed data (Borah and Bera, 2003). Furthermore, advances in modeling these processes offers an attractive framework for addressing many of these issues in a comprehensive manner.

Major watershed modeling capabilities, in tandem with GIS, are addressed and discussed within this paper in terms of a state-of-the-art critical review of current trends in watershed modeling. Each model's characteristics and features are highlighted to illustrate the types of applications being utilized by the watershed modeling community. This paper begins with a brief outline of several commonly used watershed modeling approaches and corresponding applications, addresses data availability and management within watershed modeling, and discusses GIS software products widely used in the water resource modeling community, and provides a glimpse into future trends for utilization of GIS technology in watershed modeling.

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Watershed Modeling Approaches

Watershed models can be classified based on the spatial and/or temporal scale used, the methods adopted for solving the equations, and how the underlying hydrologic processes are represented (Melone et al., 2005). The main features for distinguishing watershed modelling approaches are the algorithms (or solution methods) used, whether a stochastic or deterministic approach is taken to input or parameter specification, and whether the spatial representation is lumped or distributed. These classifications assist users in determining the applicability of a model to a given watershed.

With regard to spatial representation, the lumped modeling approach considers a watershed as a single unit for computations where the watershed parameters and variables are averaged over this unit. Homogeneous properties (e.g., climatic conditions, topography, geology, land use, and soil characteristics) are assumed for the single unit (Arabi, Govindaraju, and Hantush 2004). Components describing surface runoff are often extended in order to handle overland flow and erosion as functions of area and topographical data. Most models of this type use a simple hydrological model to describe the water balance for vertical water flow. In these models, infiltration is assumed to be "lost" to the system resulting in only basic inclusion of groundwater as a "sink" and possibly a "source" for some surface waters. As a result, this does not allow direct interaction between groundwater and surface waters (Refsgaard, 1996) which fails to consider lateral movement of groundwater and the complex processes that occur beneath the surface. Some common applications for these models include flow forecasting and shallow water table simulation (e.g., TOPMODEL).

Compared to lumped models, semi-distributed and distributed models account for the spatial variability of hydrologic processes, input, boundary conditions, and watershed characteristics (Liu and Weller, 2007). For semi-distributed models, the aforementioned quantities are partially allowed to vary in space by dividing the basin into a number of smaller sub-basins which in turn are treated as a single unit (Boyle et al., 2001). In the case of distributed models (e.g., TOPMODEL, ANSWERS, and GSSHA), spatial heterogeneity is represented at a resolution which is typically defined by the modeller (Melone et al., 2005). For TOPMODEL, this resolution is limited to a maximum grid-size of 50 m (Lancaster, 2010).

Many of these types of models are now commonplace in a variety of applications (Vieux, 2004). Typical examples of applications include aquifer vulnerability mapping, surface water and ground water quality remediation, floodplain studies, assessment of surface water impact from groundwater withdrawal, water supply design, river basin management and planning, assessment of catchments changes due to land use changes and irrigation, and run off predictions in ungauged watershed (Graham and Butts, 2006).

Watershed-scale models can be further divided into event-based or continuous-process models. Event-based models simulate individual precipitation-runoff events with a focus on infiltration and surface runoff, while continuous-process models explicitly account for all runoff components while considering soil moisture redistribution between storm events (Melone et al., 2005).

Watershed-Scale Models

There are numerous watershed hydrologic models and systems available for watershed management at different scales. A widely used conceptual runoff model, Hydrologiska Byråns Vattenbalansavdelning

(HBV) is a computer simulated model used in operational hydrological forecasting and water balance studies (Bergstrom, 1976). Consisting of three main modules – snow accumulation and melt, river routing and response, and soil moisture accounting – HBV requires input data that is readily available for most applications. The benefits of models such as HBV lie in their ability to assist water resource and watershed managements with a variety of applications, including analysis of future sediment loading and runoff, evaluation and development of total maximum daily loads (TMDLs), evaluation of the effects of farming and land use on soil erosion and sediment delivery for small, agricultural field-sized watersheds, flood hazard mapping, large scale hydrologic and hydraulic studies, drainage studies, and spill/contaminant prediction. A brief description of the main characteristics and features of the most commonly used watershed models is presented in Table 1.

Data Availability and Management

A majority of the watershed models listed in Table 1 are considered to be distributed or semi-distributed, with fully developed capabilities to model the three primary areas of interest for watershed simulation: hydrology, sediment transport, and fate and transport of contaminants. Very often, the type of model selected for an application is dictated by the availability of data (Singh and Woolhiser, 2002). Data needed to support watershed modeling typically include hydrometeorologic (e.g., rainfall, snowfall, temperature, radiation, and humidity), geomorphologic (e.g., elevation contours, river networks, drainage areas, slopes, and slope lengths), agricultural (e.g., vegetative cover, land use, treatment, and fertilizer), pedologic (e.g., soil type, soil particle size diameter, soil moisture content, capillary pressure, and saturated hydraulic conductivity), geologic (e.g., stratigraphy and lithology), and hydrologic (e.g., flow depth, base flow, interflow, stream-aquifer interaction, and water table).

Advances in remote sensing technologies have assisted with efficient and timely data acquisition, diminishing the problem of scarce data experienced during early watershed modeling efforts. Radar systems such as Next-Generation Radar (NEXRAD) and Weather Surveillance Radars-88 Doppler have been used to gather spatial and temporal rainfall volumes and intensity in near real-time and at fairly high resolution (Vijay P. Singh and Woolhiser, 2002; Vieux, 2004). Rainfall data in this format has proven to be extremely useful for distributed models. For example, Knebl et al. (2005) perform regional scale flood modeling using NEXRAD rainfall and HEC-HMS for the San Antonio River Basin using data from a 2002 storm event. Moon et al. (2004) also demonstrated that the Surface Water Assessment Tool's (SWAT) streamflow estimates improved with NEXRAD precipitation input instead of rain gauge inputs.

The National Oceanic and Atmospheric Association (NOAA) (2008) is also able to utilize an Advanced Very High Resolution Radiometer (AVHRR) and Geostationary Operational Environmental Satellites (GOESs) to generate maps showing snow cover for over 4,000 river basins in the United States which in warmer weather may contribute to flow in the local watersheds. Some of the future satellite research efforts relevant to watershed management and modeling will focus on programs to acquire and improve satellite data for temperature, humidity, vegetation, and soil moisture. For the land use/land cover maps, various products obtained from satellite imagery and local field surveys are readily available. One popular data source is the land use/cover (LULC) database which is available from US Geological Survey's (USGS) Center for Earth Resources Observation and Science (EROS, 2008). The US Department of Agriculture (USDA), through the National Resource Conservation Service (NRCS), also provides widely used soil maps for the entire United States in the form of two data products: STATSGO2 and SSURGO (NRCS, 2008a;b). Other satellite systems have provided alternative sources for generating additional data needed to map and classify soils, land use, and vegetation cover (Vieux, 2004).

With the spatial variation found in watersheds, it is essential that similar variation be captured in the data input for distributed watershed models whenever possible. The use of structure elevation data is one of the most important aspects for achieving this task. Digital terrain models that provide elevation data are triangulated irregular network (TIN) grids or digital elevation models (DEMs) and contour-based networks (Singh and Woolhiser, 2002); of these, DEMs are most widely used in the watershed modeling community. It is also important to note that many DEMs are derived from existing contour maps or imagery generated from various remote sensing options discussed earlier. Many of the models listed Table 1 have been designed to utilize DEMs.

Use of DEMs and other digital datasets in watershed modeling requires efficient data management and processing tools. GIS technology has played a vital role in serving this purpose. For example, GIS can assist in generation of DEMs from a variety of elevation sources, model parameter preparation (e.g., delineate watershed and extraction of parameters such as soil properties from soils maps), performing overlays between different digital datasets and improving the display of watershed modeling output with existing spatial data. Most of the models discussed earlier contain a GIS component or are part of another system that integrates GIS functionality. A more detailed discussion on the use of GIS in watershed modeling follows.

Watershed Modeling and GIS

Advancements in GIS and remote sensing techniques have influenced the trend in watershed modeling. For example, remote sensing techniques (e.g., radar and satellite imaging) can be utilized for obtaining spatial information on land use and soil type at regular grid intervals with repetitive coverage. Central to this advancement is the contribution GIS technology has offered hydrologists by providing additional capabilities for reducing computation times, efficiently handling and analyzing large databases describing the heterogeneities in land surface characteristics, and improving display of model results (Jain et al., 2004). With the increasing availability of fairly detailed spatial datasets and flexible GIS capabilities, watershed modeling has undoubtedly advanced to a more distributed representation by accounting for the spatial and temporal variations in parameters such as soil, land use and precipitation. As a result, distributed models are becoming commonplace in a variety of applications (Noto and Loggia, 2007).

Early GIS software packages existed as isolated software programs with unsophisticated user interfaces and limited processing capabilities (Clarke, 2003). This was influenced by fairly unsophisticated operating systems possessing minimal flexibility. These systems were difficult to manipulate and did not have a large group of users. GIS software products have since improved immensely, primarily due to improvements in operating systems and processing power in microcomputer environments. For example, Microsoft Windows® has a programming environment for creating user-friendly GUIs and performing multi-tasking where sessions can run several software programs simultaneously. The increase in processing power for desktop computers has also enhanced the performance of GIS operations (e.g., buffering) for large datasets.

Table 2 provides a list of desktop and professional GIS software products which are widely used in the water resource modeling community. Most of these GIS products have a Microsoft Windows®-like appearance with typical pop-up and pull down menus. In addition, they offer basic GIS functionality for capturing, storing, retrieving, managing, analyzing, and displaying vector and raster formats. Some GIS software packages also have tools for converting this data into a format that is compatible for water resource models (e.g., ArcHydro, WMS).

As an extension of desktop GIS, Internet or web-based GIS has emerged as an attractive platform for effectively distributing GIS data and applications to a wider audience (Peng and Tsou, 2003). Many of the leading GIS software developers are now tapping into this market by releasing their web mapping products. Government agencies are also gradually making this the standard for disseminating environmental data on surface waters nationwide. The US Environmental Protection Agency (USEPA) is leading the effort with EnviroMapper, Surf Your Watershed and Window to My Environment (WME) websites. EnviroMapper allows users to dynamically display information about various types of environmental information, including air releases, drinking water, toxic releases, hazardous wastes, water discharge permits, and Superfund sites. Surf Your Watershed enables a user to dynamically display information about national watersheds and other water resources, generate customized maps that portray the national surface waters and collect environmental data. WME is a web-based tool that provides a wide range of federal, state, and local information about environmental conditions and features in a selected area. USGS (2009) also publishes a web-based national atlas and the National Map Viewer, which provide an extensive range of products and services to meet the diverse needs of people who are searching for relevant maps and geographic information. Ecotrust (2008) is one of several non-governmental organizations (NGOs) who complement federal and state efforts by providing alternative web mapping tools for disseminating watershed-delineated datasets (e.g., Google-based watershed locator).

GIS Watershed Functionality

GIS technology is playing a significant role in advancing the application of watershed models. Four distinct areas where GIS is applied in watershed modeling are hydrologic assessment, model setup, parameter determination, and modeling within GIS (Garbrecht, et al., 1991; Ogden et al., 2001; Eldho et al., 2007).

Hydrologic Assessment and Model Setup

Hydrologic assessment refers to the use of GIS for the analysis of various hydrologic factors for the purpose of assessing risk or susceptibility to pollution (Ogden et al., 2001), flood, drought, erosion, etc. This type of assessment uses weighted indexing schemes to quantify the relative influence of various factors in contributing to flow of water (and often pollutants) throughout a basin. Model setup involves defining the topography, boundaries, and drainage networks of a watershed so as to form the basic framework for applying both lumped and distributed watershed models (Vieux, 2004). DEMs are the primary data structure utilized for this task. Within the context of hydrologic assessments and model setup, GIS offers watershed model developers and managers several valuable tools for data creation and management, automated feature extraction and watershed delineation.

Data Creation: In some instances, limited or no viable grid-type data is available for a watershed under investigation. Collecting elevations or other attributes (e.g., rainfall) at field data points using global positioning systems (GPS) or using digital contour maps are often employed to generate new DEMs datasets when none exist for the area of interest. DEMs can be created by interpolating rainfall data or from aerial photography to measure snowfall (Lee et al. 2008) which is also used in the watershed analysis as hydrologic sources. In some cases, contour data stored on paper-based maps can be extracted and converted to digital format using GIS digitizing tools. GIS automated tools based on basic and geostatistics interpolation techniques (e.g., inverse distance weighting, splines, and kriging) can be used to generate new DEMs or other raster datasets from point and contour datasets.

*Automated Feature Extraction: V*arious GIS software packages offer automated routines for delineating watershed boundaries, and draining divides, extracting surface drainage channel networks, and generating other hydrography data from DEMs (Maidment, 2002) (e.g., WMS, ArcHydro). The D-8 method is one of the most widely used DEM processes in these routines. Features are typically displayed as a raster image consisting of strings of cells with a unique code (DeBarry et al., 1999).

A recent application of automated feature extraction utilized MapWindows TauDEM (Terrain Analysis Using Digital Elevation Models) (EMRG, 2008) and the GIS Weasel (An Interface for the Development of Spatial Parameters for Physical Process Modeling) (Viger and Leavesley, 2006). Also notable is ESRI's ArcView ArcHydro, which supports independent hydrologic models by providing a geospatial and temporal data structure for describing surface water hydrology and hydrogarphy (Maidment, 2002). Researchers and system developers continue to use these and other tools in more recent watershed model formulations (Noto and Loggia, 2007).

For channel network extraction, it is important that individual channel links and adjacent contributing areas are explicitly identified and associated with topographic information for upstream and downstream connections (DeBarry et al., 1999). Routines within GIS may be applied to index channel links and network nodes, and organize the channels into a sequence for cascade flow routing (Vieux, 2004).

Data Management: The application of watershed models with GIS usually requires assembling data with different formats from a variety of sources into a common coordinate space for efficient processing or display. This presents some inherent data management problems. First, these sources are often generated by various agencies that may have adopted different coordinate systems. One of the most well known of these is the Universal Transverse Mercator (UTM) coordinate system, which is widely used across the United States (Leavesley et al., 1983). In addition, the State Plane coordinate system is commonly used and may have one or more zones defined for each state. Datasets (both raster and vector) with different coordinate systems will not have their features drawn in the correct location when displayed in GIS; this can generate inaccuracies during data creation and features extraction, as well as in performing other operations such as the display of watershed model results. Most GIS software provides manual or automated tools that assist with transforming datasets into a common coordinate space. The ability to document the coordinate systems for each dataset using metadata records is essential.

One of the disadvantages of DEMs is the large amount of data redundancy in areas of uniform terrain and the subsequent inability to change grid sizes to reflect areas of different complexity of relief (Burroughs, 1986). However, most GIS software offers a variety of data compression routines (e.g., quadtrees and run-length) to reduce this problem and improve processing time (Clarke, 2003).

Parameter Determination

A key aspect of modeling watershed processes is the ability to determine various parameter inputs. Information on precipitation, soil properties, and land use/cover is of critical importance to watershed modelers and managers. Unlike data creation, where you may be required to collect elevations or other attributes and input them into your model, parameter determination involved deriving the necessary inputs from available data in various forms. Many of the commonly used soil and LULC maps are disseminated within the model in vector format and facilitate the storing of multiple attributes or properties for each soil unit and land use/cover class. Satellite imagery is also another popular option for land use/cover. Ground-based radar systems provide valuable raster data expressed as reflectivity values for estimating rainfall.

Before utilizing these data sets, a series of pre-processing GIS operations are required to estimate the necessary parameters and reclassify the map (similar to data creation). While the data may exist, it is necessary to extract the appropriate information in proper format for use in the model. In the case of vector data formats, conversion operations are required to generate the desired grid/raster format.

Soil properties are useful for estimating infiltration, while land use/cover is valuable for estimating hydraulic roughness coefficients which are used to predict surface runoff from channel and overland flow areas in a watershed. In the case of infiltration, it is possible to apply infiltration equations and estimate infiltration rates for each soil unit based on soil attributes. For example, the Green-Ampt equation can be formulated in GIS and its required parameters (effective porosity, wetting front suction head, and saturated hydraulic conductivity) can be calculated and used to estimate infiltration rates values (Vieux, 2004). One model that utilizes each of these parameters for Green-Ampt calculations is TOPMODEL (Lancaster, 2010). GIS also provides the necessary tools to reclassify soils maps based on infiltration rates and convert them to the preferred raster format for model input. LULC maps undergo a similar operation where known hydraulic roughness values are assigned to each LULC class and reclassified according to these values.

Several GIS tools are available for parameter extraction. For example, the GIS Weasel uses US Geological Survey (USGS) DEMs, STATSGO soils, and USDA Forest Service gridded vegetation type and density data to estimate spatially distributed parameters including elevation, slope, aspect, topographic index, soil type, available water-holding capacity of the soil, vegetation type, vegetation cover density, solar radiation transmission coefficient, interception-storage capacity, stream topography, and stream reach slope and length (Leavesley et al., 2006; Usery et al., 2004). Another example is Watershed Modeling System (WMS), which is capable of processing both raster and vector data for land use, soil type, rainfall zone, and flow path networks in order to develop important modeling parameters such as curve numbers, infiltration parameters, rainfall intensities, and water course travel times (lag time and time of concentration) (Nelson et al., 2004).

Often, established reflectivity-rainfall relationships are used to estimate rainfall from reflectivity values generated by NEXRAD's radar grid datasets (e.g., Vieux, 2004). Again, GIS makes it possible to apply routines based on these relationships to generate new grid datasets with rainfall rate estimates which are then utilized by distributed models. Kalin and Hantush (2003) were able to demonstrate, through the use of ArcView GIS tools, that the spatially distributed precipitation data obtained through radar reflectivity measurements is a viable alternative to rain gauge measurements.

Model-GIS Interface

A common feature of GIS software packages is the Microsoft Component Object Model compliant architecture, which allows watershed system developers to utilize macros and object-oriented programming environments (e.g., Visual Basic for Applications-VBA, C++) to create user-friendly GUIs and applications for interfacing GIS and water resource models. Beginning in the early 1990s, interfacing water resource models with GIS environments has been explored and examined in great detail by many researchers (Fedra, 1993; Gurnell and Montgomery, 2000; Martin et al., 2005). Water resource models are typically interfaced within GIS environments with linked, coupled, or integrated/embedded techniques.

Linking: GIS and model linking typically uses data generated within GIS as inputs to the model, and model outputs are transferred back to GIS for display and spatial analysis. While many water resource models have fixed file formats for organizing input data, this process is facilitated by GIS data structures (vector or raster) which allow data transfer in both ASCII and binary file formats (Martin et al., 2005). An example of successful linking is MIKE SHE with ArcView (Borah and Bera, 2004). Linking offers the simplest interface option and requires the least programming effort. The discrete file transfer allows for modular interchange of model outputs; however, key drawbacks include limited GIS functionality, a dependency on the GIS or model output format, incompatibility between operating system and model environments, and the use of multiple interfaces (Martin et al., 2005).

Combining: Combining differs from linking because information is passed between the model and GIS via memory-resident data models (using client-server programs available in most GIS software) rather than external files (Martin et al., 2005). An example of a successful combining effort is the Water Erosion Prediction Project (WEPP) and ArcGIS 9.x (Minkowski and Renschler, 2008). Combining these retains GIS functionality, offers flexibility interface that allows exchange between models, and improves computational performance and interactivity. Nonetheless, the main drawbacks are the requirement of increased programming efforts and creation of a final system that may require multiple user interfaces.

Integration: The integration or embedding technique is concentrated on incorporating GIS and model components with each other, thus eliminating the need for intermediate transfer software. To be considered integration a seamless interaction is required where many processes and data sources of the model and GIS are shared in order to reduce redundancy within the system (Liao and Tim, 1997). An example of such an effort is the integration of SWAT and GRASS/GeoMedia (Jones et al., 2002). Jain et al. (2004) were also able to develop a completely integrated GIS based distributed rainfall-runoff model to predict temporal variation of the spatial distribution of flow depth and runoff over eleven different watersheds. DOE (2008) has ongoing research regarding the development of a fully integrated GIS-based system with 3-D visualizations that is tied to dynamic watershed models and watershed data.

Typically, these systems have a single interface where data transfer between the model and GIS is transparent to the user and all GIS functionality is maintained. The key drawbacks include the possible requirement for GIS and model simplification, complex programming and necessary data management requirements to ensure full integration (Martin et al., 2005).

Future Trends

The utilization of GIS technology in watershed modeling has brought great value and presents future potential benefits for watershed managers. The literature on this topic shows that the capabilities in applying GIS in watershed modeling are growing among watershed stakeholders (e.g., Brooks et al., 2006). This is evident by the efforts of government agencies to disseminate watershed information to stakeholders and an overall commitment to improving GIS-based watershed modeling tools. The success of these efforts will be heavily dependent on the effectiveness of GIS-watershed model interface developers in producing user friendly systems. Earlier discussions on interfacing techniques suggest that the integration would offer maximum benefits; however, a lack of established conventions for interfacing GIS and simulation models has limited the development of protocols and guidelines for such efforts (Martin et al., 2005). Problems with spatial scale and managing massive amounts of data has been a limiting factor in the full integration of GIS and watershed models (Noto and Loggia, 2007). As a result, linking and combining dominate GIS interfaces for watershed scale models to date. Despite these limitations, this does not prevent efforts to integrate GIS with watershed models from continuing. Future trends in GIS in watershed modeling applications are expected to be heavily influenced by the emergence of hybrid systems, open-source GIS software and Web-based GIS systems, as well as the availability of real-time data.

Hybrid Systems: Even though distributed systems are becoming more prevalent, they tend to be computationally expensive and require significant amounts of data. According to Aral and Gunduz (2006), more interest is being given to semi-distributed hybrid modeling systems which adopt other approaches such as artificial neural network and rule-based methods. GIS lends itself to facilitating this kind of system development since it has a flexible environment for managing and integrating diverse processes and data. For example, Noto and La Loggia (2007) were successful in developing new procedures that improved the classic unit hydrograph theory using GIS and remote sensing. This proposed procedure can be adopted as a component in hybrid systems.

Open Source GIS: Many examples of GIS-model interfaces use proprietary software such as ArcView. Typically, proprietary software requires annual maintenance fees to ensure that users keep pace with GIS version updates. In addition, there are cases where other fees are required for distributing applications based on proprietary software. This makes commercial software less attractive and significantly hinders the ease of dissemination of applications. Open Source GIS software products provide a more cost effective option. For example, MapWindow GIS is an open source product that is becoming increasingly popular with federal agencies, primarily due to its free use and the ability to redistribute to clients and other end users without the need to purchase a user license (GIS, 2007). USEPA made the decision to migrate its GIS-based watershed system, BASINS, from ArcView to MapWindow, making it independent of proprietary GIS products (USEPA, 2007). The Idaho National Laboratory (INL) is also listed as a collaborating institution for MapWindow GIS, where the software is used to implement a Virtual Infrastructure and Site Tour System (VISiTS) as part of INL's Critical Infrastructure Protection Test Range (INL, 2007).

Internet GIS: As Internet GIS continues to evolve, it will no doubt influence the next generation of watershed model-GIS interface architecture. Racicot (2006) identified two trends that support this notion. First, the software domain is providing more functionality through web services. Second, web-based decision support tools are emerging as a viable solution to fulfill environmental management decision support needs, while addressing the desire for platform independent web-based interfaces. One noteworthy example is the Catastrophic Level Event Emergency Response (CLEER) emergency impact simulator, which accesses chemical and live weather data, simulates a range of emergency impact scenarios (e.g., release chemical vapor into the air or tire/oil fires that produce harmful smoke), and displays the results against the backdrop of Google's interactive map or, when available, satellite/aerial imagery (CLEER, 2008). It is also possible to enter an address and determine if it is within the projected impact zone. Even though Google Maps is becoming an extremely popular web mapping tool, it is not considered to have full Web-GIS functionality. However, it offers some of the basic web GIS tools necessary to meet the overall purposes of a decision support system.

Early research efforts considered developing web-based watershed modeling systems. For example, work by Parson (1999) led to the development of an Internet Watershed Educational Tool which utilizes hydrologic modeling to help educate local government officials and concerned citizens. Within the watershed management community, research efforts have focused on developing more advanced and sophisticated web-based GIS watershed modeling systems (e.g., Al-Sabhan et al., 2003; Cate et al., 2006; Choi and Engel, 2008). For example, Cate et al. (2006) created DotAGWA – a web-based interface for AGWA which is currently under development. The interface allows users to have online access to the same functionality of AGWA without purchasing expensive GIS software or downloading and projecting data.

Real-time: While modeling techniques and capabilities continue to grow, the need for real-time decision support based on those models is no longer a desire, but instead a necessity. This has led to the confluence of web-based GIS technology with real-time modeling techniques (Racicot, 2006). Real-time data acquisition is increasingly important in water resource modeling, but the retrieval of this data can be quite expensive (Al-Sabhan et al., 2003). Real-time data can be spatial or non-spatial and made available at fixed time intervals or after the completion of a specific event, such as a flood. Two notable national real-time data services that are relevant for watershed modeling are USGS's National Water Information System (USGS, 2009) and NOAA's National Weather Service (NOAA, 2008), which provide real-time data on national daily streamflow conditions at 15 to 60 minute intervals and surface weather conditions (e.g., temperature, precipitation), respectively. Each source also provides these data services in Rich Site Summary (RSS) or Extensible Markup Language (XML) online feeds which are fairly easily processed and converted to database formats.

As more real-time data becomes available, this may present some problems for traditional watershed models and GIS-based models. Conventional GIS models, such as data modeling, data management, and software design and engineering, may not allow current GIS systems to meet the requirements of real-time applications effectively (Al-Sabhan et al., 2003). For example, FORTRAN and other traditional programming technologies of many models (e.g., HSPF, HEC-1) are not suitable for the representation of dynamic geographical systems (Al-Sabhan et al., 2003). Moreover, many of the current GIS and hydrological models lack a direct connection with external sensors and devices, resulting in limited access to real-time data. These deficiencies can lead to hard-coding of data directly into the system, making updating of existing data particularly difficult. Like the CLEER Impact system, it is expected that more web-GIS watershed modeling research will explore and improve efficient connections to available real-time data services.

Conclusions

An essential element of watershed management is the utilization of watershed-scale modeling. The benefits of using these models include the ability to assist with a variety of applications, such as future sediment loading and runoff, evaluation and development of TMDLs, flood hazard mapping, and computing peak flows. Major advances in watershed modeling rely on spatial datasets (e.g., DEMs, LULC), GIS, and remote sensing technologies (e.g., NEXRAD, LiDAR) to understand and represent these processes. GIS technology has made a significant impact on enhancing watershed modeling efforts by offering the necessary tools to perform hydrologic assessments, model setup tasks, parameter extraction, user friendly interfaces, and dissemination of watershed and related information via the Internet to various stakeholders. Future trends suggest that GIS will continue to influence watershed modeling by providing flexible platforms to support hybrid watershed modeling system development, real-time data collection and deployment of web based watershed modeling applications. Open-source GIS software appears to be leading this movement and it is showing great promise as a cost effective alternative to traditional commercial GIS.

Table 1: Watershed Models - Main Characteristics and Features

Model	Suited Applications	Main Components	Spatial Scale	Temporal Scale	Watershed Representation	Availability
ANSWERS	Agriculture watersheds; Designed for ungauged watersheds	Runoff, infiltration, subsurface drainage, soil erosion, interception & overland sediment transport	D	E	Square grids; 1-D simulations	Public
ANSWERS-2000	Medium-sized agriculture watersheds; Designed for ungauged watersheds; Useful in evaluating the effectiveness of BMPs; Capable of simulating transformation & interactions between four nitrogen pools	Runoff, infiltration, water/river routing, drainage & chemical/nutrient transport	D	C	Grid/Cells	Public
AGNPS	Agriculture watersheds	Runoff, infiltration & soil erosion/sediment transport	D	E	Homogeneous land areas	Public
Ann AGNPS	Agriculture watersheds; Widely used for evaluating a wide variety of conservation practices & other BMPs	Hydrology, sediment, nutrients & pesticide transport; DEM used to generate grid & stream network	D	C - Daily or sub-daily steps	Homogeneous land areas, reaches & impoundments	Public
GSSHA/CASC2D	Agriculture or urban watersheds; Diverse modeling capabilities for various climates & watersheds with complex spatial datasets	Spatially varying rainfall; Rainfall excess & 2-D flow routing; Soil moisture, channel routing, upland erosion & sediment transport	D	E; C	2-D square overland grids; 1-D channels	Proprietary
HEC-1/HEC-HMS	Urban watersheds; Widely used for modeling floods & impacts on land use changes	Precipitation, losses, baseflow, runoff transformations & routing	SD	E	Dendritic network or grid	Public
HSPF	Agriculture or urban watersheds; Diverse water quality & sediment transport at any point on the watershed	Runoff/water quality constituents, simulation of pervious/impervious areas, stream channels & mixed reservoirs	SD	C	Pervious/impervious land areas, stream channels & mixed reservoirs; 1-D simulations	Public
HBV	Agriculture or urban watersheds; Designed for ungauged watersheds; Computer simulation of river discharge & water pollution; Used for hydrological forecasting & inflow prediction	Runoff; Water/river routing, soil moisture & water balance; Climate change	SD	C - Daily steps	Catchments/zones/ basins; Grid/Cells input	Public
TOPMODEL	Catchments with shallow soils & moderate topography; Cannot handle long dry periods	Simulates hydrologic fluxes of water, infiltration, subsurface flow, evapotranspiration, groundwater/surface water interactions & channel routing	D	E	2-D overland grid (size limited to </= 50m	Public

Spatial Scale: Semi-Distributed - SD; Distributed – D **Temporal Scale:** Continuous - C; Event-base - E

Table 2: Leading GIS Software Packages

Vendor	Desktop/Professional GIS Products	Internet GIS Products
Environment Research Systems Institute (ESRI)	ArcView 3x, ArcGIS 9.x (ArcView, ArcEditor, ArcInfo)	ArcIMS, ArcServer
Auto Desk	Autodesk Map	MapGuide Open Source
U.S. Army Construction Engineering Research Laboratories (CERL)	Geographic Resources Analysis Support System (GRASS)	---
Caliper Corporation	Maptitude, TransCAD	Maptitude/TransCAD for the Web
Intergraph Corporation	GeoMedia, GeoMedia Professional	GeoMedia WebMap
Clark University	IDRISI	---
MapInfo Corporation	MapInfo	MapExtreme
Microsoft®	MapPoint	MS Virtual Earth
ERDAS, Inc.	ERDAS IMAGINE	---
	Map Window	MapServer
Open Source	Quantum GIS	---
	Integrated Land and Water Information System (ILWIS)	---

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