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ROLE OF GEOGRAPHICAL INFORMATION SYSTEM (GIS) IN APPLICATION OF HYDROLOGICAL MODELING - A PLAUSIBLE REVIEW

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ABSTRACT

During recent years, Geographical Information Systems (GIS) as a powerful tool have had a tremendous impact on research techniques in the realm of hydrology and spatial analysis. The integrative ability of GIS to capture, store, manipulate, analyze, manage, and finally present all types of geographical spatial data, has drawn many attentions to it. Water Resources Engineering as an interdisciplinary field requires modeling and analyzing data with different spatial solutions. Therefore, GIS could definitely be utilized as a suitable tool for solving water resources problems from local to global scale. On a national or lower administrative level, the need for coping with natural disasters-affecting mainly human life, property, local economy, infrastructure, etc. – and the need to design management plans and projects for sustainable exploitation of natural resources set hydrological modeling in high demand by government organizations and local authorities. In this paper an attempt has been made by the author to present reviews of publications and the larger scheme of the benefits for the applications of GIS in water resource and hydrological modeling in particular field of specializations. The fundamental reason for the need of integrating GIS and hydrological modeling is briefly discussed and briefing of rainfall-runoff modeling. Also, various benefits of GIS utilization in the field are discussed and summarized

KEY WORDS: GIS, Hydrological Modeling, Rainfall-Runoff Modeling, Groundwater Hydrology

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INTRODUCTION

During the last decades, information technologies have been developed dramatically and have shaped modern approach in problem solving. Among them, Geographical Information System (GIS) has drawn increasing attention. GIS is a system designed to capture, store, manipulate, analyze, manage, and ultimately present all types of geographical spatial data. In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology [1]. Some of spatial analysts and intellectuals define as 'GIS is a computerized system that is used to capture, store, retrieve, analyze and display spatial data'-Clarke 1995 [2], Star and Estes 1990 [3] define 'GIS is an information system that is designed to work with data referenced by spatial or geographical coordinates', Duecker 1987 [4] define that 'GIS manipulates data about points, lines, and areas to retrieve data for ad hoc queries and analyses', Dangermond 1988 [5], stated that 'GIS consists of five basic elements: data, hardware, software, procedure and people' Maguire 1991 [6] define 'GIS comprises four basic elements which operate in an institutional context: hardware, software, data and liveware'.

Due to its powerful ability of spatial data analysis GIS has different applications and hence is of high interest in various fields of study. The need for a systematic approach for modeling, analyzing and/or present huge amounts of data (spatially and temporally distributed) could be answered by GIS. Water Resources Engineering as a multidisciplinary field requires modeling and analyzing spatially distributed data with different spatial resolutions. Therefore, GIS is indeed a suitable tool for solving water resources problems.

In light of the above, this article aims to present a brief review of GIS-based hydrological modeling and in particular rainfall-runoff modeling. In this regard, first, the necessity of the integration of hydrological modeling and GIS systems is discussed together with practical instances. Afterwards, GIS–based rainfall-runoff modeling and its benefits or challenges in detail. Good agreement between the results of fairly simple GIS-based models and observations is alluding to the promising future of such models. The paper ends by summarizing the benefits of GIS tools as a part of hydrological modeling.

GIS AND WATER RESOURCES

As a tool, GIS is very powerful tool for addressing different water resources issues such as water quality, ground water movement, ground water contamination, river restoration, flood prediction and management, and etc. on a local, regional, national or even global scale [7]. It could be used for different approaches such as analyzing the current situation, modeling and stimulating different scenarios for predicting the future, projecting new information, and enhancing decision making and water management [8]. As an example, within a given catchment, there could be thousands of groundwater monitoring wells, numerous streams reaches with gauges, along with snow measurements and weather stations. For making a suitable decision, the effects of land cover, vegetation, soil type, topography, geology, water quality, and other involving factors must be considered. In such cases, data are often available from different public agencies and or organizations, and usually in different coordinate systems, spatial references, at different scales, and or from different time periods or sources. The main challenge to frame a holistic view of the given watershed, therefore, would be to synthesize all these data [9]. The above challenge could suitably be carried out by GIS. GIS, as a smart map, together with a qualified user could assist with manipulation, analysis, and presentation of information tied to different locations. The critical parameters is the association of information with a location on the map. For example, a point representing a monitoring well may also have information such as well depth, screened interval, and lithological logs associated with it, along with a time series of water levels. By means of GIS, the user with geographic features and look for spatial or temporal patterns and or relationships in different layers of the GIS map [9]. A spectrum of domains for the application of GIS to water resources engineering are listed below:

- Surface water hydrology
- Ground water hydrology
- Water supply for municipalities and irrigation
- Wastewater and storm water
- Floodplains
- Water quality
- Monitoring and warning
- River basins

Planning and design in water resources engineering typically involve the use of maps at various scales and the development of documents in map formats. For example, in a river basin study, the map scale often covers a portion of a state and includes several countries and other jurisdictions. The river drains a certain geography having topographic, geologic (including types of soils), vegetative, and hydrologic characteristics. Cities and human-built facilities are located along the river and across the basin, and transportation and pipeline network link these together. All of these data sets must be established in a common geo-reference framework so that overlays of themes can be made the coincidence of features can be identified in the planning and design phase. The GIS is applied to manage all of these data.

It provides a comprehensive means for handling the data that could not be accomplished manually. The large amount of data involved requires a GIS, as there may be many thousands of features having a location, associated attributes, and relationships with other features. The GIS provides a means of capturing and archiving these data, and of browsing and reviewing the data in color-coded map formats. This data-review capability supports quality control, as errors can be more readily identified. Also, through visualization, the user can gain a better understanding of patterns and trends in the data in a manner not possible if the data were only in tabular format. The GIS provides an analysis capability as well. The database can be accessed by computer software and used as input to various modeling procedures to generate derived products.

In a river basin there are many applications of GIS, for example

- Defining the watershed and its hydrologic and hydraulic characteristics so that models of rainfall-runoff processes can be applied to examine the impacts of land-use changes
- Mapping land-use and population demographics in support of water and waste-water demand estimation procedures
- Interpolating groundwater contaminant concentrations given sampled data at observation wells spaced throughout an aquifer, or estimating snowpack amount at ungauged locations based on data obtained at gauged locations guided by factors of elevation and exposure.
- Managing public infrastructure, such as scheduling maintenance on a sewage collection system, notifying residents of water-pipe rehabilitation work, or identifying areas of potential low pressure during fire-response planning scenarios.
- Finding the coincidence of factors, such as erosion-prone areas having a certain combination of soil type, land-cover, and slope.
- Monitoring the occurrence and intensities of severe thunderstorms and providing tools for warning threatened populations of impending hazardous flood conditions.
- Providing the logical network structure for coordinating simulation and optimization models that schedule the interaction between basin water supplies, reservoirs, diversions and demands.

In addition to the physical scope of engineering planning and design activities, the organizational context within which the GIS exists is important. Whether it is a large federal agency seeking to establish water supplies for a region or a small municipality trying to keep up with rapid development, the GIS requires the establishment of procedures and standards. Often, the GIS will require a change in the way an agency's work is done. Advances in data collection and engineering measurement technologies, changes in data formats and report-generation capabilities, and requirements for data sharing across jurisdiction can be different from established historical practices. All of these factors can lead to improved practice, but they can also cause stress by requiring training and change.

In simple, words, hydrology is a branch of water resources refers to the movement, distribution, and quality of water on Earth (it could be on other planets as well). The hydrologic cycle, as the fundamental element of hydrology, describes the continuous movement of water above (surface hydrology) and below (hydrogeology) the surface of the Earth. As it could be understood from this general description, the hydrological cycle is essentially related to spatial variables [10].

Hydrology is one of the burgeoning fields that recently employed GIS and GIS based models and Remote Sensing (RS) to tackle different issues within the field. The major reason for such integration stems from the fact that hydrological cycle and its related processes are dynamic systems which their elements are varying not just temporally but more importantly spatially. This inherent spatial dependency could be easily covered by GIS which provides various spatial data as an input for different variables needed for hydrological models. Involving a variety of spatial data could become very helpful as there would be no necessity to take many simplifying assumptions such as constant or linear slopes. In other words, the application of GIS allows one to cover a greater extent of reality. Further, it could enhance the possibility of a 3D approach for distributed models by which, for instance, the water movement could be monitored in several spatial locations could be employed for a flood management or control system.

To put it simply, hydrological modeling creates simplified conceptual models (mainly empirical mathematical equations that describe a phenomenon or a physical process) of a part of the hydrological cycle. Surface hydrology (surface water hydrology) is one of the most important domains of the hydrologic cycle which refers to all the surface waters of the globe: rivers. Lakes, wetlands, estuaries, seas, oceans, etc. ArcGIS Hydrology Toolset contains Spatial Analyst tools used to model the water flow across a surface. This toolset could be used to describe the physical components of a surface by identifying sinks, calculating flow direction and accumulation, delineating watersheds, and creating stream networks [7]. GIS enables hydrologists to integrate various data (geographical spatial data), by different operations and applications into a management system.

PUBLICATIONS REVIEW OF HYDROLOGICAL MODELING COUPLED WITH GIS

The most influential publications about empirical hydrological modeling and GIS integration as follows.

Closing the general reference on hydrological modeling, it would be inconsiderate not to mention Soil and Water Assessment Tool (SWAT), which is a conceptual, continuous time model that was developed in the early 1990s to assist water resource managers in assessing the impact of management and climate on water supplies and nonpoint source pollution in watersheds and large river basins. This tool was developed further in the 21st century (and keeps developing), and many research studies were based on its application. Some of the most indicative ones are the papers by Arnold and Fohrer [11], refers to SWAT2000 and its capabilities and research opportunities in applied watershed modeling. Abbaspour et al. [12] concerns an application of the model on hydrology and water quality in the prealpine/Alpine Thur watershed. Kalogeropoulos et al. [13] described the developing of a methodology of water resources exploitation, with the potential of creating small mountainous and upland reservoirs, by coupling hydrological analysis and SWAT model. Kalogeropoulos and Chalkias [14] were made an attempt of hydrological modeling incorporating SWAT model in a GIS environment in order to exam various scenarios of climate change in a Mediterranean catchment. Equally important are the RS-based approaches targeting hydrological-environmental modeling. Among the most important ones is NASA's Modern-era Restrospective Analysis for Research and

Applications (MERRA), the history of which as well as its contemporary development and applications are sufficiently described [15]. SWAT and other similar models along with RS is highly linked and coupled with GIS.

Fortin et al. [16] developed a methodology to relate urban growth studies to distributed hydrological model using an integrated approach of RS and GIS. US Environmental Protection Agency Office of Water developed Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system, which integrates GIS, watershed tools, and SWAT model [17]. **In** parallel, in order to analyzed land cover changes, a landscape assessment tool was developed by using a GIS that automates the parameterization of the SWAT and KINematic runoff and EROSion (KINEROS) hydrological models [18]. The first three years of the century closed with Liu et al. [19] proposing a GIS-based diffusive transport approach for the determination of rainfall runoff response and flood routing through a catchment, and with Al-Sabhan et al. [20], introducing a real-time hydrological model for flood prediction using GIS and the World Wide Web. Finally, one of the most interesting studies of 2003 was the work of Huggel et al. [21], which proposes a modeling approach, which takes into account the current evolution of the glacial environment and satisfies a robust first-order assessment of hazards from glacier-lake outbursts in the Swiss Alps. Knebl et al. [22] published their work on regional scale flood modeling that integrates NEXRAD level III rainfall, GIS, and hydrological model HEC-HMS/RAS, applied on San Antonio River Basin in Central Texas, USA, for a specific storm event. Furthermore, among the most distinguished papers of 2005 was the study of Kyoung et al. [23] in which two digital filter-based separation modules, the BELOW and Eckhardt filters, were incorporated into the Web-based Hydrograph Analysis Tool (WHAT) system, whose Web GIS version accesses and uses US Geological Survey (USGS) daily streamflow data from the USGS web server. Jia et al. [24] developed the WEP-L, a physically based distributed hydrological model, which couples simulations of natural hydrological and water use processes, with the aid of RS data and GIS techniques. Wolski et al. [25] on modeling of the flooding in the Okavango delta, Botswana, using a hybrid reservoir-GIS model, which is a semi-distributed and semi- conceptual approach.

The need to exploit hydrological models for researching various environmental aspects and hazards lead Pandey et al. [26] on an attempt to identify the critical erosion prone areas of Karso watershed of Hazaribagh, Jharkhand, in India, using Universal Soil Loss Equation (USLE), RS technology, and GIS technologies. Simultaneously, Miller et al. [27] presented an open-source toolkit for distributed hydrological modeling at multiple scales called the Automated Geospatial Watershed Assessment (AGWA) Tool, which uses commonly available GIS data layers to fully parameterize, execute, and visualize results from both the SWAT and KINematic Runoff and EROSion model (KINEROS2). In 2008, an approach for groundwater vulnerability assessment in shallow aquifer in Aligarh, India, was made by Rahman [28], using a GIS-based DRASTIC model. Jonkman et al. [29] tried to cope with the problem of flood damage in the Netherlands, by integrating hydrodynamic and economic modeling via GIS, offering thus a new approach and perspective in the analysis of this natural phenomenon. During 2009, various interesting papers were published, among them the studies of Maksimovic et al. [30], Chen et al. [31]. These two papers dealt with urban flooding via GIS modeling combining various techniques, tools and data, like high-resolution Digital Elevation Model data collected by the LiDAR technique and GIS-based Urban Flood Inundation Model (GUFIM), respectively. Milewski et al. [32] concerns and applied methodologies for rainfall-runoff and ground water recharge computations that heavily rely on observations extracted from a wide-range of global RS datasets (TRMM,SSM/I, Landsat TM, AVHRR, AMSR-E, and ASTER), using the arid Sinai Peninsula and the Eastern Desert of Egypt as test sites. Sheikh et al. [33] described about the paper, like introduced Bridge Event and Continuous Hydrological (BEACH) model developed in GIS, used for predicting soil moisture.

Du et al. [34] proposed a spatially distributed model, the improvements relates to the calculation of the variation of flow time in each cell, due to the velocity variance, regarding the uneven distribution of rainfall over time. This model also incorporated the rainfall losses by using the Curve Number methodology (Soil Conservation Service [35]). This model was named Time Variant Spatially Distributed Direct Hydrograph. Van der Knijff et al. [36], described the spatially distributed LISFLOOD model, which is a hydrological model specifically developed for the simulation of hydrological processes in large European river basins.

As flood management became more and more important due to climate change and other environmental and human factors, many researchers pointed their work toward these issues. In this frame, Rozalis et al. [37] used an uncalibrated hydrological model and radar rainfall data for flash flood prediction in a Mediterranean watershed. Also in 2010, Kourgialas et al. [38] published a very interesting case study about koiliaris River Basin, located east of the city of Chania on the island of Crete in Greece, proposing an integrated framework for the hydrological simulation of this complex geomorphological river basin that includes a two-part Maillet Karstic model, a GIS-based Energy Budget Snow Melt model, an empirical karstic channel model and the Hydrological Simulation Program– FORTRAN (HSPF) model. Lei et al. [39] developed an efficient and cost-effective distributed hydrological modeling tool (MWEasyDHM) based on open-source MapWindow GIS. Furthermore, Fugura et al. [40] coupled hydrodynamic simulation with a well-developed digital surface and terrain model (DEM), derived by aerial photogrammetry, to map flood extent in Kuala Lumpur, Malaysia. Kia et al. [41] developed a flood model, using various flood causative factors, ANN techniques, and GIS to model and simulate flood-prone areas in the southern part of Peninsular Malaysia. Sarhadi et al. linked GIS techniques (HEC-GeoRAS, IRS-P6 satellite images, etc.) with frequency analysis, aiming at probabilistic flood inundation mapping of ungauged rivers and more specifically of the Halilrud basin and Jiroft city in south-eastern Iran, which were selected as an example of hazardous regions [42].

Based on the abundant volume of previous research, the publication list in this domain is still increasing. Lopez-

Vicente et al., used the modified version of the revised Morgan, Morgan and Finney (RMMF) model to predict the hydrological connectivity and the rates of soil erosion under four different scenarios of land use and land abandonment along with GIS in the Estanque de Arriba catchment (Spanish Pre-Pyrensees) [43]. Paiva et al. [44] published their validation work for the implementation of MGB-IPH hydrological model, which uses full Saint Venant equations, a simple storage model for flood inundation and GIS-based algorithms to extract model parameters from digital elevation models, on large-scale hydrological modeling in the Amazon and specifically in the Solimoes River basin. Tehrany et al. [45] proposed a novel methodology for flood susceptibility mapping, where weights-of-evidence (WoE) model was utilized first to assess the impact of classes of each conditioning factor on flooding through bivariate statistical analysis (BSA) and then, these factors were reclassified using the acquired weights and entered into the support vector machine (SVM) model to evaluate the correlation between flood occurrence and each conditioning factor. Chen et al. [46] developed a methodology for regional estimates of potential floodwater retention under floodplain inundation, from ecologically significant flood return periods, by coupling RS and GIS technologies with spatial hydrological modeling. Mahmoud [47] estimated the potential runoff coefficient (PRC), using GIS, based on the area's hydrologic soil group (HSG), land use, slope, and determined the runoff volume in Egypt. Mahmoud SH. Mint: Investigation of rainfall-runoff modeling for Egypt by using remote sensing and GIS integration. Catena. 2014;120:111-121. A research work couple with GIS and hydrological modeling by Fiorillo et al. [48] published a model for simulating recharge processes of karst massifs. The other research work by Krysanova et al. [49] used Soil and Water Integrated Model (SWIM) to model climate and land-use change impacts (four different application studies were made and analyzed).

GIS has a great ability to integrate data from multiple sources as long as they all have the same spatial reference. For instance, it can combine data from source such as boreholes and wells, subsurface isopach maps, structure contour, surface geology maps, and satellite imagery. This ability allows all of these data to be used simultaneously to develop a more comprehensive model. Such models could assist geographers to gain a deeper understanding of the movement of different surface (or subsurface) waters and their interactions [9].

GIS APPLICATION IN RAINFALL-RUNOFF MODELING

One of the most useful applications of ArcGIS is in rainfall –runoff modeling i.e. calculation of runoff based on precipitation in a given catchment or region. A GIS based model for rainfall-runoff calculation should be constructed and then calibrated for each case, separately. Although general parameters such as soil type, topography and precipitation are the same and just need the specific data sets of the particular case as an input, but from case to case other influencing parameters could emerge. For instance, monsoon precipitations or floods in semi-arid regions need to be identified and employed. Also, the weight of these influential parameters could be different from case to case.

Hammouriand El-Naqa [50] is applied GIS to model the rainfall –runoff process in the Wadi Madoneh ungauged basin in Jordan. GIS systems use data from RS and other sources to build new geo-referenced databases in specific referable forms. The general schematic procedure of constructing the rainfall-runoff model is shown in Figure 1.

Baiyinbaoligao et al. [51] has employed GIS for modeling the rainfall-runoff process in the Kuronagi River based on two rainfall stations. Since rainfall-runoff could be modeled based on different methods, they engaged the distributed Kinematic Wave hydrological model to calculate the two rainfall-runoff events in 2005 and 2006.

Due to the fact that using only few rainfall stations is problematic considering the entire area of catchment. In such a case they interpolation method to be adopted of rainfall stations in the basin and its surroundings. For the interpolation, the Inverse Distance Weighted (IDW) method as a local interpolation was used calculating the areal average of rainfall per hour in each sub-basin. In addition to this, assume a loss rate within few-hours after each rainfall event. Therefore, the part of the rainfall excluding this assumed rainfall to be the effective rainfall. The results of this modeling are in good agreement with the observations. This study shows that the progress of rainfall observation techniques and computational methods together with the development of digital land information could be utilized by GIS technology. Subsequently, a relatively simple rainfall-runoff model can produce results with high precision.

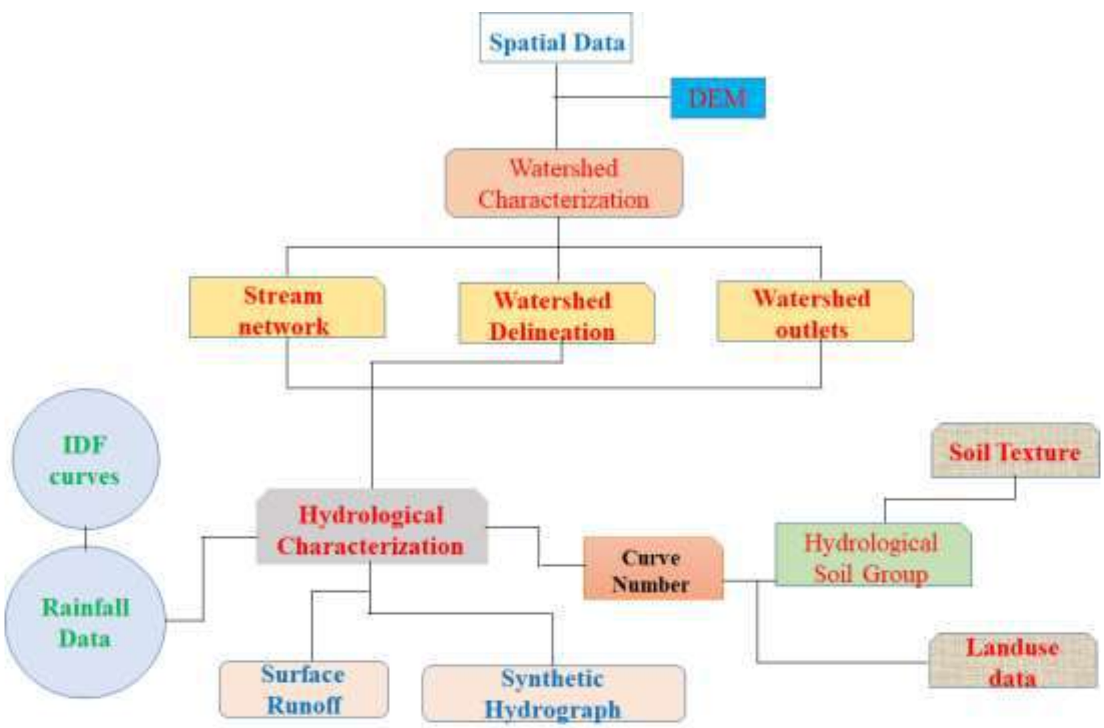

Fig.1 Schematic procedure of constructing Rainfall-Runoff Modeling

BENEFITS OF GIS APPLICATION IN HYDROLOGICAL MODELING

GIS (and GIS-based models) could be beneficial for different hydrological modeling such as rainfall-runoff. For instance, to calculate runoff or flood in a particular region, one can build up a GIS-based model. For that model one can set parameters such as soil type, topography, vegetation, and so on (which are not changing throughout time rapidly) and then calibrate them based on historical time series. The calibrated model, afterwards, could project new data (e.g. flood movement) for different scenarios of future climate and climate change. Using such models in a fairly user friendly environment of GIS, one can get rid of dealing with lots of equations and calculations of different parameters.

Engaging such models, the modification and updating of the model parameters (data sets) would be easy and straight forward and the user is not dealing with equations but the visualized results that could enhance the precipitation and understanding of different plausible scenarios. It should be noted that the user has to be qualified and aware of the algorithms and mathematical functions behind different command and operations in the GIS. Lack of sufficient knowledge could lead to a misleading and incorrect solution for the working issue. GIS-based hydrologic models can provide a spatial element that other hydrologic models lack. This could be done with the analysis of variables such as slope, aspect and watershed or catchment area. Since water always flows down a slope, terrain analysis is fundamental to hydrology. As basic terrain analysis of a DEM involves calculation of slope and aspect, DEMs are very useful for hydrological analysis [52].

Due to promising outcome of GIS application in hydrologic modeling, it has been applied in a wide range of rainfall-runoff modeling problems and for different purposes by taking different approaches. The key point of GIS application in the realm of hydrologic modeling is its effectiveness and proficiency in problem solving.

Another aspect of the benefits if GIS-based approaches in hydrological modeling is that one can combine different layers of geographic data and create new integrated information which is quite useful for creating dependent or independent hydrological variables; for example, generating evaporation from temperature and Relative Humidity (RH). Temperature and RH could be stored in different layers as dependent variables and then the combination of these two layers could generate the evaporation layer. It should be noted that combining different layers needs all of the sources to be projected into the same coordinate system and scale. Moreover, users should be aware of different operations for combining layers otherwise the generated information could be far from the reality or might not be the wanted information. The final stage every research, i.e. the presentation of results, might be of less importance to many researchers. In most cases, however, both classification and presentation of results could be serious challenge due to huge amount of spatial information as the outcome. In some cases poor presentation of the results could become even misleading and could lead to misinterpretations. Well-structured representation of results will enhance the possibility of better understanding and obtaining a perception closer to the reality. GIS as a smart map and by means of different generalizations, for example simplification and symbolization, and with the aid of different visualization methods could produce efficient maps and figures which are not only comprehensive but also easy understand and comfortable for future alterations. The use of GIS permits integration of spatial, non-spatial and ancillary data into hydrologic models and thus significantly strengthens hydrologic modeling capability.

A number of formidable challenges still remain before GIS achieves more of its potential in hydrology.

- The standardized data bases that are generally available are applicable to regional scale analysis of fairly large watersheds. Considerable database development is still needed within cities to support analysis at the scale of small urban watersheds. Probably, 80% of hydrologic modeling is done to solve problems in urban areas, so this limitation is critical.
- Various methods for creating GIS- based models of hydrologic processes are emerging but they have not yet been standardized to the point that they are being applied widely. There is a great need for dispersion of knowledge so that more people can use what is available.
- The integration of hydrologic processes, particularly integration of surface and groundwater flow, is not yet solved very well. Integration of processes across scales of space and time is not well understood. A map can be drawn at any scale, but it is unclear to what extent models can be applied at different scales.
- The impact of water utilization facilities, such as pumping stations and reservoirs, on flow through the landscape, is not well described in spatial hydrology models yet.
- Subsurface representation of hydro-geologic properties of aquifers is embryonic. There are no standardized databases of hydrogeology, like the ones that exist for soils. A 3-D GIS system has not really emerged yet.
- Water quality modeling in rivers and lakes is sufficiently complex that it is still largely being done in traditional simulation models supported by GIS data. There is not yet much intrinsic water quality modeling within GIS.

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