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Khatami, Sina; Khazaei, Bahram

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PO Box 117
221 00 Lund
+46 46-222 00 00

BENEFITS OF GIS APPLICATION IN HYDROLOGICAL MODELING: A BRIEF SUMMARY

Fördelar med GIS i hydrologisk modellering, en kort sammanfattning

by SINA KHATAMI^{1*} and BAHRAM KHAZAEI²

¹ Department of Water Resources Engineering, Lund University, Box 118, SE-221 00, Lund, Sweden

² Water Resources and Environmental Research Center, Ferdowsi University of Mashhad, Mashhad, Iran

* Corresponding author, e-mail Khatami.sina@gmail.com



Abstract

During recent years, Geographic Information Systems (GIS) as a powerful tool have had a tremendous impact on research techniques in the realm of geography 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 a interdisciplinary field requires modeling and analyzing data with different spatial resolutions. Therefore, GIS could definitely be utilized as a suitable tool for solving water resources problems from local to global scale. This paper tries to present the larger scheme of the benefits for the applications of GIS in water resources and hydrological modeling in particular. Certainly, within the few pages ahead only the surface is scratched and a more thorough and comprehensive review requires more time and effort. The fundamental reason for the need of integrating GIS and hydrological modeling is briefly discussed and different tools are introduced. Also, various examples of GIS application are presented to create a better understanding. Case studies such as the Wadi Madoneh Basin in Jordan, Kuronagi River in Japan and San Antonio River Basin in Central Texas, USA, are presented. The good agreement between the results from a fairly simple GIS model and observations in cases such as Kuronagi River and Wadi Madoneh is indicating a promising future for GIS application in hydrological modeling. Finally, the benefits of GIS utilization in the field are discussed and summarized.

Key words – GIS, hydrological modeling, surface hydrology, rainfall-runoff modeling

Sammanfattning

Geografiskt informationssystem, GIS, har under senare år vuxit fram som ett kraftfullt verktyg inom flera områden. Förmågan att lagra, manipulera, analysera och slutligen presentera alla möjliga rumsligt utbredda data har gjort GIS till ett attraktivt visuellt verktyg. Inom vattenresurshantering, som är ett multidisciplinärt område, gör just detta att GIS är attraktivt. Rätt använt kan GIS-metoder hjälpa till att lösa vattenproblem från lokal till global skala. Denna artikel presenterar fördelarna med GIS-baserade modeller inom hydrologi och vattenresurshantering. Självklart kan denna korta artikel inte täcka in alla användningsområden utan artikeln bör ses som en introduktion. Några exempel på lyckade användningar av GIS-modeller ges. Exempelen är hämtade från Wadi Madoneh Basin i Jordanien, Kuronagi River i Japan och San Antonio River Basin i Texas, USA. Resultaten är uppmuntrande. Artikeln innehåller också en diskussion och sammanfattning av GIS-baserade modeller inom vattenområdet.

1 Introduction

During the last decades, information technologies have been developed dramatically and have shaped a modern approach in problem solving. Among them, Geographical Information System (GIS) has drawn increasing at-

tention. 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 (Foote and Lynch, 2009).

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. Also, different related GIS tools are introduced. Afterwards, several case studies of GIS-based rainfall-runoff modeling are presented to explain the modeling procedure 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.

2 GIS and Water Resources

As a tool, GIS is very powerful 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 (Esri, 2012). 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 watershed management (Chen et al., 2004).

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 (Jordan, 2004).

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 parameter 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 can access and manipulate information associated with geographic features and look for spatial or temporal patterns and/or relationships in different layers of the GIS map (Jordan, 2004).

3 GIS and Hydrological Modeling

In simple words, hydrology as 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 (Heywood et al., 2006).

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 and in different directions. Such applications 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 by means of different products such as ArcGIS Hydrology Toolset, ArcGIS 3D Analyst, and add-ons like Arc Hydro, HEC-GeoHMS and HEC-GeoRAS supports surface water modeling. ArcGIS Hydrology Toolset contains Spatial Analyst tools used to model the water flow across a surface which requires the Spatial Analyst Extension. 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 (Esri, 2012).

GIS enables hydrologists to integrate various data (geographical spatial data), by different operations and applications into a manageable system. The suite of tools contained in the Arc Hydro facilitates the creation, manipulation, and representation of hydro-features within the ArcGIS environment. Arc Hydro is a set of data-based models and tools which operates within the ArcGIS to improve geospatial and temporal data analyses. Arc Hydro delineates and characterizes catchments as raster or vector structures, defines and then analyzes hydro-geometric networks, manages time series data, and configures and exports spatial data to numerical models (Esri, 2012).

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 sources 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 (Jordan, 2004).

3.1 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.

Hammouri and El-Naqa (2007) is applied GIS to model the rainfall-runoff process in the Wadi Madoneh ungauged basin in Jordan. The main objective of this study is to investigate the surface water potential for groundwater artificial recharge. Obviously, traditional methods for measuring surface discharge require sufficient and reliable hydrological and meteorological data. RS provides a source of input for hydrologic data such as soil, vegetation, drainage, as well as climatic data like precipitation, temperature, etc. GIS systems use data from RS and other sources to build new georeferenced databases in specific referable forms. In the rainfall-runoff analyses of Wadi Madoneh Basin, Hammouri and El-Naqa (2007) used a GIS-based model based on the Hydrologic Engineering Center model (HEC, 1998) and the Soil Conservation Service (SCS) curve number (USDA-SCS, 1972) method to estimate direct runoff volumes for different design storms.

The schematic procedure of constructing the rainfall-runoff model for Wadi Madoneh Basin is shown on Figure 1. A counter map, as a source, is used to provide input data for the model. ArcMap GIS 9.0 is utilized to

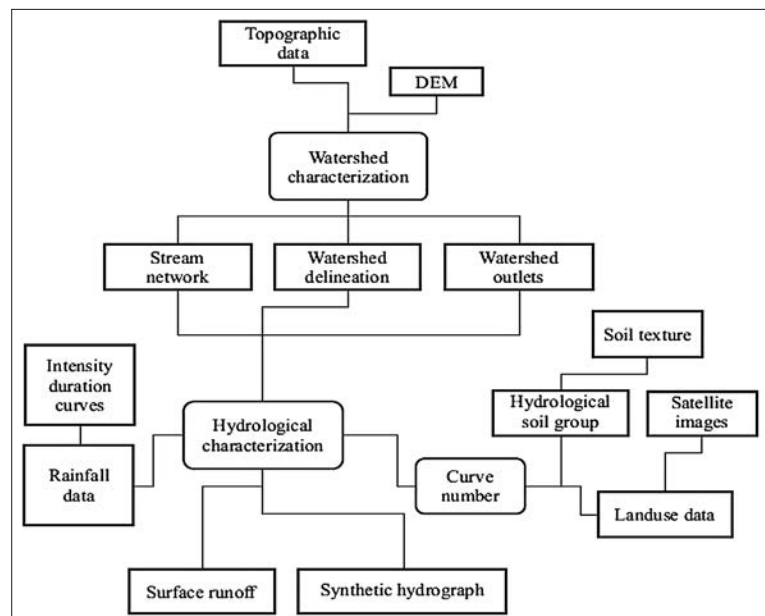


Figure 1. Flow chart of the GIS-based hydrological model for Wadi Madoneh basin (Hammouri and El-Naqa, 2007).

digitize the 50 counter interval to generate a Digital Elevation Model (DEM) with a 80 m cell size. Within the map conversion process, some cells might represent pits or holes. These cells should be removed before running the model otherwise water would accumulate in these cells when drainage patterns are being extracted. To define the flow direction, flow accumulation map is needed. By counting the number of cells contributed to upstream cells in DEM the flow accumulation is generated. The whole map forms a stream network which will define the flow direction and ultimately determine the outlets of the basin.

Basin delineation process is the final step that rests on flow direction and flow accumulation map. It is also dependent to a threshold value which is the minimum number of pixels desired to be delineated in each sub-basin. This threshold value is decided by user. Wadi Madoneh Basin with its sub-basins and stream network is illustrated on Figure 2.

Simulated runoff is compared to the measured runoff at this basin for the two return periods of 10 and 50 years (see Figure 3). Modeled and observed hydrographs

for a 10-year return period are in good agreement, but for the 50-year return period the model has overestimated the hydrograph. However, the results indicate that the generated model is not biased in overpredicting/underpredicting the runoff.

Baiyinbaoligao et al. (2011) 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. They used Esri's ArcView 8.3 and its Spatial Analyst extension module to carry out the flow direction, flow accumulation, and stream network as features.

They used a 50 m DEM spatial data issued by Japan Geographical Survey Institute in 1996 to produce the digital basin of the Kuronagi River. They also utilized the Arc Hydro Tools to divide the catchment into 27 sub-catchments and then to calculate the slope area, average slope and river's length, and slope for each sub-catchment (see Figure 4).

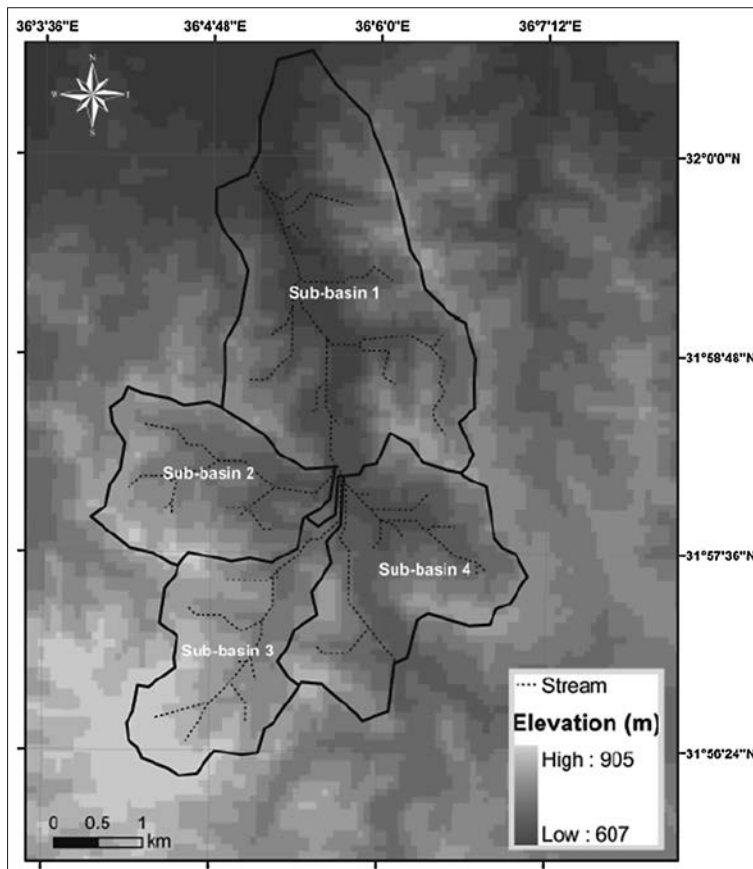


Figure 2. Delineation of Wadi Madoneh Basin and stream network (Hammouri and El-Naqa, 2007).

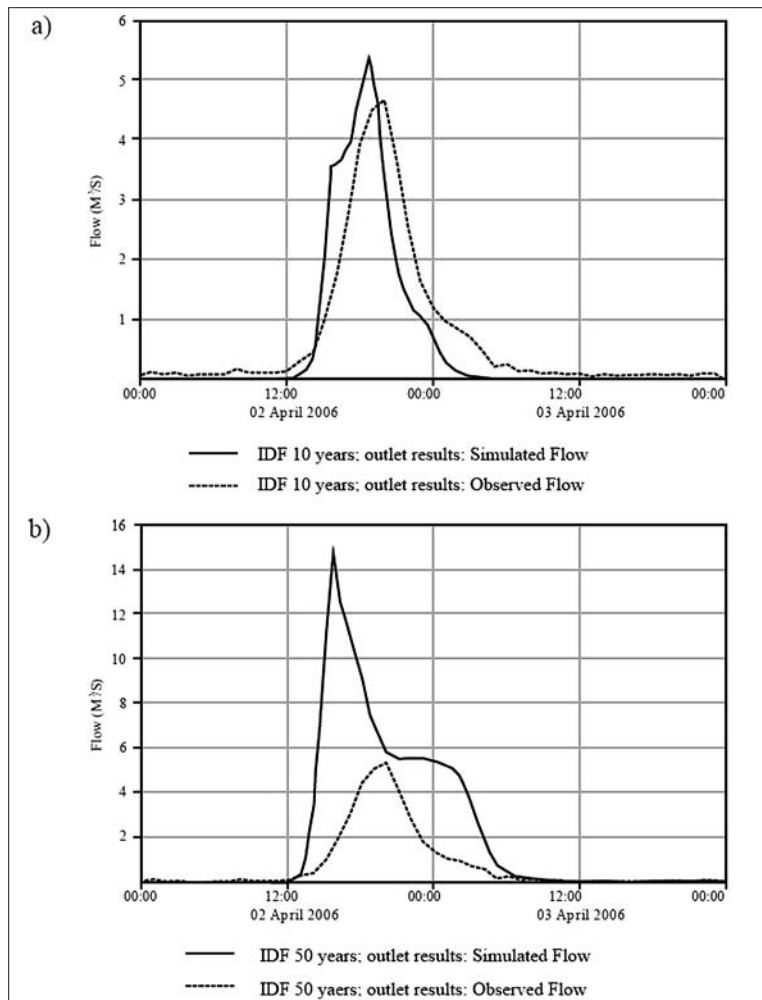


Figure 3. Comparison of observed and simulated hydrographs for 10-year (a) and 50-year (b) return periods based on precipitation data from IDF curves, Wadi Madoneh Basin (Hammouri and El-Naga, 2007).

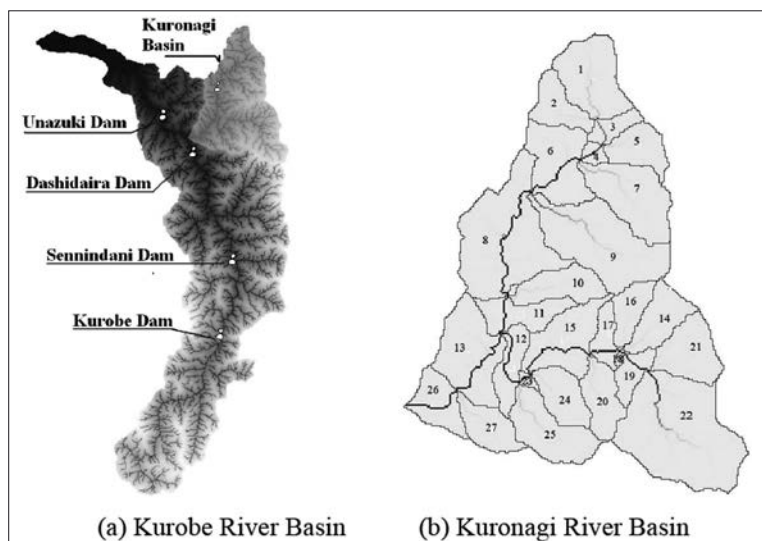


Figure 4. Digitalization of Kuronagi River Basin (Baiyinbaoligao et al., 2011).

Due to the fact that using only two rainfall stations is problematic considering the entire area of catchment, they interpolated 84 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. They assumed a loss rate of 3 mm/h within 8 h after each rainfall event. Therefore, the part of the rainfall excluding this 24 mm was assumed to be the effective rainfall.

The results of this modeling are in good agreement with the observations (see Figure 5). 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 (Baiyinbaoligao et al., 2011).

In a more sophisticated study, Knebl et al. (2005) developed a framework integrating GIS and HEC-HMS/RAS based on Next-Generation Radar (NEXRAD) Level III rainfall inputs to model flood events in San Anto-

nio River Basin in Central Texas, USA. In this study, the authors attempt to present a modeling process in which floodplain outputs are generated based on rainfall inputs. The outcome of such studies could provide more reliable rainfall-runoff models for researchers, as well as, positive modification in flood forecasting systems in areas like Texas counties. In this regard, a new Map-to-Map tool developed by Robayo et al. (2004) is being used to combine NEXRAD precipitation datasets with GIS and hydrological models to produce a floodplain map.

Daily rainfall of NEXRAD Level III data have been collected into a 4 km gridded format obtained from Texas' West Gulf River Forecast Center. Other topographic and physiographic required information is collected from USGS (U.S. Geological Survey) and NRCS (Natural Resources Conservation Service) databases and they have been provided into 10 m and 30 m resolution DEMs. Thereafter, precipitation-runoff process is being adjusted using, Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), version 2.2.1., developed by the US Army Corps of Engineers. In a

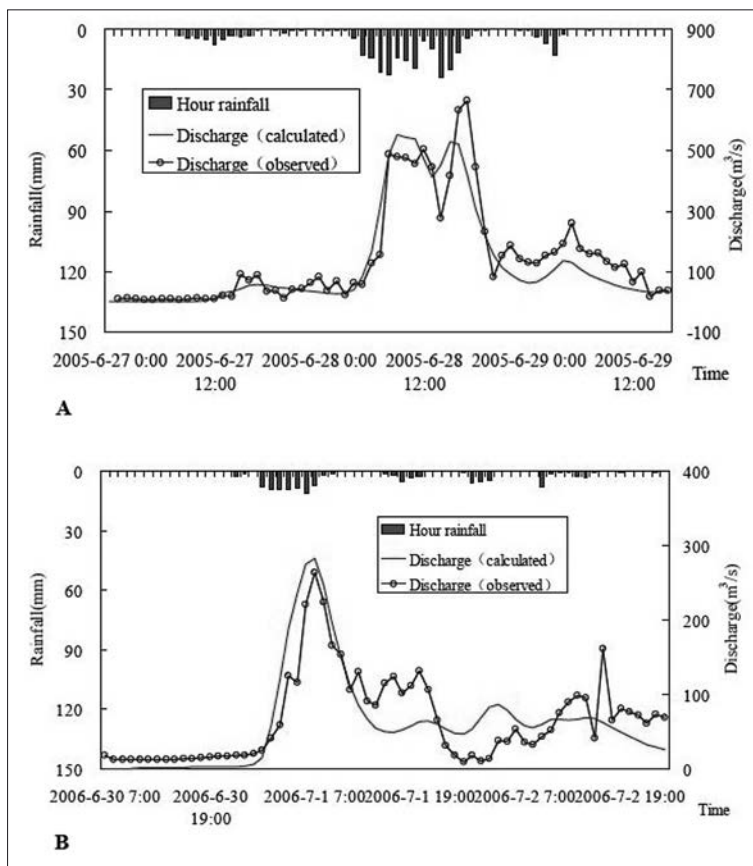


Figure 5. The discharge hydrographs for 27–30 June 2005 (A) and 30 June–2 July 2006 (B) at estuary of Kuronagi River (Baiyinbaoligao et al., 2011).

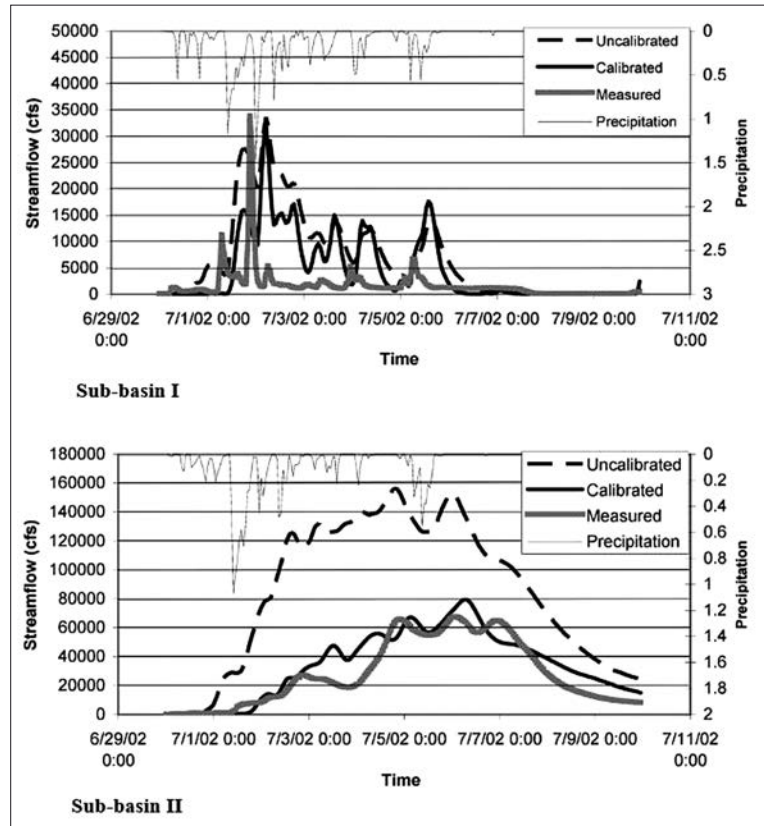


Figure 6. Comparison of measurements and hydrologic model results (calibrated and uncalibrated) for two different sub-basins of the San Antonio River (precipitation time series are also included for reference) (Knebl et al., 2005).

same way, HEC's River Analysis System (HEC-RAS), version 3.1, is utilized to build hydraulic models based on one-dimensional flow (HEC, 2000). The model is considered for major streamlines in the study area. Geometric features of the channels are defined through DEMs and are available cross sections of USGS.

To run the model, firstly, all information will be gathered into a whole using ArcView GIS 3.2. Then the stream network will be delineated by HEC-Geo HMS. An integration of inputs, parameters and stream networks will result in output stream hydrographs at considered points. By running the hydraulic model in HEC-RAS and importing stream features simultaneously, output floodplains will be extracted. To improve the model performance, model calibration is necessary in basin scales. In this study, infiltration coefficients, time of concentration, and baseflow are calibrated and modified in a way that a better fitness between model and observations could be formed. Finally, input data from San Antonio River Basin are imported into the model and results are generated.

Figure 6 presents comparison between modeled and observed results of stream flow time series for two sub

basins in the study area captured between June 29 and July 11, 2002. Difference between results of simulated and observed stream flows is the consequence of extreme variations of watershed characteristics such as topographical and physiographical diversity in the study area. It is expected that result of calculations and observations converge in basins with more homogeneous hydrological features. The authors mention that in larger areas the model accuracy might probably decrease. Possibly, a considerable amount of error is originated from different data resolutions used in model as inputs. It should be noted that cloud shadows might be misinterpreted as water and flooded areas. Finally, it is concluded that the proposed methodology seems appropriate in flood forecasting at different regional scales.

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 (Schultz, 1996, Saghafian et al., 2002, Jain et al., 2004, Patil et al., 2008, Nourani et al., 2009, Fry et al., 2013). The key point of GIS application in the realm of hydrologic modeling is its effectiveness and proficiency in problem solving.

4 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 perception 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 commands 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 analyses (Heywood et al., 2006).

Another aspect of the benefits of 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 of 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 a 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 to understand and comfortable for future alterations.

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