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Chapter 4

Applied Hydrological Modeling with the Use of Geoinformatics: Theory and Practice

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Additional information is available at the end of the chapter

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Abstract

Water resource management and catchment analysis are crucial aspects of the twenty-first century in hydrological and environmental sciences. Linked directly with studies and research about climate change effects in global resources (e.g., diminution of rainfall dynamic), as well as continuously growing extreme natural phenomena with catastrophic results (e.g., floods and erosion), hydrological modeling has become a key priority in modern academic research goals. 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. Thus, hazard assessment and risk evaluation modeling have become a strategic aim and an extremely useful tool for stakeholders, decision-makers, and scientific community.

Keywords: hydrological modeling, GIS, hydrology, unit hydrograph, floods

1. Introduction

The technological evolution during the last decades, especially in the field of geoinformatics, has offered new opportunities in hydrological modeling. The current efforts are targeted on optimizing existing models (setting some obsolete), evaluating them (with statistical methods, sensitivity analysis, field data, etc.), combining and comparing them, and most important recommending new ones based on original ideas and tools coming from developing technologies, techniques, and sciences. Part of these new technologies, perhaps the most important one, is occupied by Geographical Information Systems (GIS) and Remote Sensing (RS). These technologies stand on the cutting edge of modern geosciences, finding direct implementation in analysis and modeling of natural phenomena and research in key sectors like hydrology.

GIS-based hydrological analysis has a wide range of applications in (true) natural events that demand research, planning, and optimum management. An important aid to implement this methodology is the constantly increasing available free digital data (topographic, morphological, meteorological, land cover, spatially distributed data, etc.), offered by international projects (e.g. CORINE Land use/cover), new technologies such as RS (e.g., SRTM Aster Digital Elevation Model—DEM), national digital databases, and many other available sources. These data are continuously improving in volume, reliability, and spatial detail due to technological evolution, creating thus important databases (significant time series, spatial resolution, etc.) that along with freeware GIS software (e.g., QGIS and HEC-RAS) reduce cost, time, and improve efficacy in hydrological modeling.

Following not only new scientific trends but also contemporary demands and perspectives, the need for interdisciplinary approaches, in modeling natural processes and phenomena, is gaining more and more ground. For example, modeling runoff in a catchment via GIS can be implemented by a combination of satellite data, in situ measurements, time series data, etc., demanding thus a spherical perception of the study subject (e.g., hydrographic network characteristics, rainfall dynamic, and terrain characteristics) by combining various disciplines such as hydrology, geology, geomorphology, and hydrometeorology. Furthermore, the GIS-based modeling of natural processes requires a minimum understanding of data nature and limitations and processing of algorithms used by the software not only in order to implement the methodology but also to distinguish modeling errors and validate the analysis.

2. Literature review[1]

Novel environmental challenges have placed water resources management in high academic and research interest. Climate changes throughout the last decades, resulting in temperature augmentation, rainfall volume diminution, desertification, etc., and on the other hand in extreme events such as storms, flooding, landslides and soil erosion, threaten human lives and infrastructures. This constantly forming and alternating environmental regime has upgraded the need for scientific research on relevant disciplines like hydrology. Key goals of this effort are better methodological efficiency, optimum database management (as data volume is continually multiplying and demanding time-consuming data mining) and, more importantly, state-of-the-art modeling, as the understanding and forecasting of an event or a phenomenon are of utmost importance nowadays. Modern technologies based on Geoinformatics (e.g., GIS and RS, respectively) play a crucial role in this ongoing attempt.

[1] It must be mentioned that all referred and described publications were selected based, mostly, on their citations in an attempt to quote the ones with the highest impact in the disciplines discussed in this chapter. For this purpose Scopus citation index was used.

2.1. Applied hydrological modeling during 1970s

Many researchers have published (and keep publishing) their work on hydrological issues throughout the years, contributing to literature volume rise concerning this topic and scientific knowledge. A general publications recursion and description over the last 45 years in hydrological references could start with Nash et al. and their series of papers in 1970 in *Journal of Hydrology*. Nash and Sutcliffe [1] attempted to state the need for a more efficient transition from classical hydrology to applied hydrology. In the first part of their publication series, they tried to propose a number of principles for river flow forecasting through conceptual models, which were put to a test in their second and third parts by applying these principles in two case studies in Brosna Catchment at Ferbane [2] and Ray Catchment at Grendon Underwood [3].

As hydrological modeling started to flourish in scientific research, in the years that followed, many notable studies came to light. Among them, Beven's and Kirkby's work [4] was distinctive as they developed a hydrological forecasting model that combined the important distributed effects of channel network topology and dynamic contributing areas with the advantages of simple lumped parameter basin models. In the same year, Rodriguez-Iturbe and Valdes [5] attempted a unifying synthesis of the hydrological response of a catchment to surface runoff, by linking the instantaneous unit hydrograph (IUH) with the geomorphologic parameters of a basin. Closing the decade as it started, Kitanidis and Bras followed Nash and his colleagues (their work 10 years earlier) in setting a conceptual hydrological model for real-time short-term forecasts of river flows. Their first paper refers to an uncertainty analysis of the model, while the second to its applications and results [6, 7].

2.2. *Applied hydrological modeling during 1980s*

During the 1980s new ideas were published, establishing for good the digital era in hydrological modeling, as well as ones relevant to the rising need for evaluation and improvement of physically based models. In 1984, O'Callaghan et al. [8] carried forward to the scientific community their method for extracting drainage networks from digital elevation data, and 5 years later, Hutchinson [9] proposed a new procedure (the ANUDEM algorithm) for gridding elevation and stream line data. In the years between, and specifically in 1986, the Danish Hydraulic Institute along with the British Institute of Hydrology and SOGREAH (France) published their work on "Systeme Hydrologique Europeen" (SHE). This model was developed under the perception that conventional rainfall/runoff models are inappropriate to many demanding hydrological problems, especially those related to the impact of man's activities on land-use change and water quality, and that only through the use of models which have a physical basis and allow for spatial variations within a catchment can these problems be tackled. This work was described in two chapters in *Journal of Hydrology*, where the first covered the evolution and general philosophy and the second the structure of the model [10, 11]. At the end of the decade, Beven expressed his criticism about problems in the application of physically based models for practical prediction in hydrology, focusing on limitations and lack of theory in specific aspects, practical constraints, and dimensionality issues [12].

2.3. *Applied hydrological modeling during 1990s*

In the years between 1990 and 2000, there is a research outburst concerning hydrological modeling. The studies published in this period cover a wide range of topics referring either directly or indirectly to the discipline of hydrology. Environmental, climatic, and natural hazard issues became extremely important this decade (fact that continued if not increased until today), boosting scientists to direct their interests in aspects such as hydrological modeling interaction with soil erosion, landslides, and vegetation. Attempting a brief overview over these matters, a small number of relevant publications will be cited in the following paragraphs.

Maidment proposed a methodology based on GIS raster structure in order to extract a spatially distributed single hydrograph by calculating flow velocities for each cell in the study area. Subsequently, this flow velocity layer is calculated by the influx time of the water in each cell, at the river mouth, by dividing the flow length to velocity. Then, the isochronous curves are constructed (equal confluency time) together with the time-area chart (catchment surface which reflects the increasing extent of the basin that contributes to runoff through time). The unit hydrograph of the basin results from the slope of cumulative runoff surface. The velocity field is permanent, meaning that it is constant over time throughout the duration of the precipitation [13].

Daly et al. [14] proposed Precipitation-elevation Regressions on Independent Slopes Model (PRISM) trying to meet the demand for climatological precipitation fields on a regular grid, as ecological and hydrological models became increasingly linked to GIS that spatially represent and manipulate model output. Montgomery and his colleagues described their model for the topographic influence on shallow landslide initiation, by coupling digital terrain data with near-surface through flow and slope stability models. More specifically, they used "TOPOG" hydrological model in order to predict the degree of soil saturation in response to a steady-state rainfall for topographic elements defined by the intersection of contours and flow tube boundaries, which was later used by the slope stability component to analyze the stability of each topographic element for the case of cohesionless soils of spatially constant thickness and saturated conductivity [15, 16]. In parallel, Wigmosta et al. [17] presented their distributed hydrology—vegetation model that included canopy interception, evaporation, transpiration, and snow accumulation and melt, as well as runoff generation via the saturation excess mechanisms.

Sellers et al. [18] completed the revision of their first model Simple Biosphere ("SiB") model creating the new edition "SiB2", which belongs to a wider group of models that are called General Circulation Models (Atmospheric—"GSMs"). "SiB2" includes canopy photosynthesis—conductance model, use of satellite data to describe the vegetation phenology, a hydrological submodel for describing baseflows and calculate interlayer exchanges within the soil profile, and other tools covering aspects like snowmelt [19]. Morgan et al. [20] published European Soil Erosion Model ("EUROSEM"), which is a dynamic distributed model, able to simulate sediment transport, erosion, and deposition over the land surface and its outputs include total runoff, total soil loss, storm hydrograph, and storm sediment graph.

Many researchers have applied the spatially distributed unit hydrograph with spatially variable rainfall, included losses of rain by using the method of curve numbers (Curve Number, USDA), which is particularly suitable for use in a GIS environment, resulting in successful simulated hydrographs that had arisen from actual measurements [21].

In 2000, Iverson tried via a mathematical model to evaluate the effects of rainfall infiltration on landslide occurrence, timing, depth, and acceleration in diverse situations [22]. Finally, the same year, Vörösmarty et al. issued a critical review on global water resources arguing on their vulnerability from climate change and population. The point of views that they expressed was derived by co-evaluation, analysis, and combination of climate model outputs, water budgets, and socioeconomic information along digitized river networks. In few words, they resulted in the opinion that a large proportion of the world’s population is currently experiencing water stress and that rising water demands greatly outweigh greenhouse warming in defining the state of global water systems to 2025. They also stated that the consideration of direct human impacts on global water supply remains a poorly articulated but potentially important facet of the larger global change question [23]. These ideas strengthened the need for hydrological research and sustainable management of water resources, setting thus hydrological modeling as an important priority, and laid the carpet for the 21st century’s scientific goals.

Focusing purely on hydrological modeling and analysis, during the decade 1990–2000, it is highly noticeable that new technologies begin to occupy significant space in this field. For example, RS techniques start to define their part as a useful, modern, and continuously evolving scientific trend in environmental sciences and therefore, in hydrology. In short reference, Houser et al. [24] wrote their paper on integrating soil moisture RS and hydrological modeling, while Jackson et al. [25] used microwave radiometry in an attempt to map soil moisture in regional scales. Another parallel trend, on hydrological modeling, these years was neural network modeling. Dawson and Wilby made their approach to rainfall—runoff modeling via Artificial Neural Networks (ANN) [26, 27], and Govindaraju [28, 29] followed them in 2000 with his two papers about ANN in hydrology.

Nevertheless, the most distinctive and influential research topic of 1990s was the coupling of Digital Elevation Model (DEMs) analysis and raster-based hydrological modeling, which consolidated the use of GIS in hydrology. In 1991, there were many authors that directed their interests toward raster modeling. Tarboton et al. [30] wrote about the extraction of channel networks from digital elevation data, Moore et al. [31] published a review on hydrological, geomorphological, and biological applications through digital terrain modeling, Quinn et al. [32] attempted a prediction of hillslope flow paths using DEMs, and finally, Fairfield and Leymarie [33] worked on deriving drainage networks from grid DEMs. Three years later, Zhang and Montgomery examined the effect of DEM’s grid size in landscape representation and hydrological simulations [16], and Tarboton [34] proposed a new method for the determination of flow directions and upslope areas in grid DEMs. Bates and De Roo [35] closed the century with their raster-based model for flood inundation simulation.

2.4. *Hydrological modeling during the period 2001–2015*

The 21st century started with the place and significance of GIS, RS, and other modern technologies in hydrological modeling well established. New scientists targeted in developing new ideas based on the previous works and tools. Free software packages were developed and distributed, huge global digital data banks were created and various research projects took place. The evolution and revolution of hydrological modeling via modern technologies still flourish, finding constantly new applications, meeting continuously growing demands, and inviting more and more new scientists to work on this field. In the following paragraphs, a short literature review of the last 15 years will be presented, starting with a brief reference on hydrological modeling in general and followed by a wider review on the main topic of this chapter.

Beven continued his critical reviews on hydrological modeling with a discussion concerning the problems of distributed models [36]. In the same period, Dawson and Wilby applied ANN, a highly emerging field of research, for rainfall-runoff modeling and flood forecasting [27]. Simultaneously, Thiemann et al. coped with the problem of uncertainty of hydrological modeling, which is the compound effect of the parameter, data, and structural uncertainties associated with the applied model. They presented the framework for a Bayesian recursive estimation approach to hydrological prediction that can be used for simultaneous parameter estimation and prediction in an operational setting [37]. A similar attempt was made a few years later by Ajami et al. [38] with their integrated hydrological Bayesian multimodel combination framework, which also tried to confront the uncertainties in hydrological predictions.

As new ideas and techniques dominate the field, Hock [39] approached a different aspect of hydrological modeling, with direct reference on environmental and climate change. It was none other than temperature index snow or ice melt modeling. Also, Döll et al. expressed their interest on global environmental issues by introducing Water GAP Global Hydrology Model (WGHM), which computes surface runoff, groundwater recharge, and river discharge at a spatial resolution of 0.5 and is a submodel of the global water use and availability model WaterGAP 2, which was also introduced in the same year [40, 41].

One of the most innovative ideas published in 2004 was that of Nayak et al. [42], concerning the combination of ANN and fuzzy logic approaches, creating thus a neuro—fuzzy hybrid computing technique for modeling hydrological time series. Finally, the Distributed Model Intercomparison Project (DMIP) was selected as a last reference for 2004, due to its distinctive concept, as it was formulated as a broad comparison of many distributed models among themselves and to a lumped model used for operational river forecasting in the US [43].

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

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indicative ones are the papers by Arnold and Fohrer [44], by Abbaspour et al. [45], by Kalogeropoulos et al. [46], as well as by Kalogeropoulos and Chalkias [47]. The first refers to SWAT2000 and its capabilities and research opportunities in applied watershed modeling, while the second concerns an application of the model on hydrology and water quality in the prealpine/Alpine Thur watershed. The third one was 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. The fourth one was 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 retrospective analysis for research and applications (MERRA), the history of which as well as its contemporary development and applications are sufficiently described [48]. SWAT and other similar models along with RS is highly linked and coupled with GIS, as shown below.

2.5. *GIS and hydrological modeling, 2001–2015*

The last part of this literature review aims at identifying the most influential publications of the last 15 years, about empirical hydrological modeling and GIS integration.

In 2001, Weng [49] developed a methodology to relate urban growth studies to distributed hydrological models using an integrated approach of RS and GIS. Following a similar concept, Fortin et al. [50] proposed HYDROTEL, a distributed watershed hydrological model compatible with 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 [51]. In parallel, in order to analyze 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 [52]. The first three years of the century closed with Liu et al. [53] 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. [54], 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. [55], 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 southern Swiss Alps.

In the next three years, a lot of significant papers were published. Lan et al. [56] used hydrological modeling and GIS for spatial analysis and prediction of landslide hazard in the Xiaojiang watershed, Yunnan, China. During the same year, a grid or cell-based process-oriented distributed rainfall-runoff model, capable of handling the catchment heterogeneity in terms of distributed information on landuse, slope, soil, and rainfall, was developed and applied to isolated storm events in several catchments by Jain et al. [57]. Knebl et al. [58] 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. [59] in which two digital filter-based separation modules, the BFLOW 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. [60] 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. At the same time, Olivera et al. [61] presented ArcGIS-SWAT, a geodata model and GIS interface for the SWAT. The final reference for 2006 concerns the work of Wolski et al. [62] on modeling of the flooding in the Okavango Delta, Botswana, using a hybrid reservoir-GIS model, which is a semidistributed and semiconceptual approach.

Melesse and Graham proposed a GIS-based model on calculating the routing time. They perceived the flow within the basin into two major types of flow: the flow into the main river channel and the overland flow (flow onto the slopes of the catchment). Here, the flow time for each cell is the sum of the flow times of all the cells along the path of the water (from each cell until the mouth of the catchment). Instead of the unit hydrograph, they proposed the calculation of a direct flood hydrograph, resulting directly from the sum of the volumetric flow rates of all the confluent cells at each time step. This model was a fixed time spatially distributed direct hydrograph approach [63].

The need to exploit hydrological models for researching various environmental aspects and hazards lead Pandey et al. [64] 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. [65] 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 (covering thus another sector of hydrology) in shallow aquifer in Aligarh, India, was made by Rahman [66], using a GIS-based DRASTIC model. Jonkman et al. [67] 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. [68], Chen et al. [69], Milewski et al. [70], and Sheikh et al. [71] stood out. The first 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. The third paper concerns applied methodologies for rainfall-runoff and groundwater 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, while the fourth one introduced Bridge Event and Continuous Hydrological (BEACH) model (developed in GIS), used for predicting soil moisture.

Du et al. [72] proposed a spatially distributed model similar with the model of Melesse and Graham [63], but they took into account the temporal variability. The improvement 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 [73]). This model was named time variant spatially distributed direct hydrograph.

At the end of the decade, Van der Knijff et al. [74], 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. [75] used an uncalibrated hydrological model and radar rainfall data for flash flood prediction in a Mediterranean watershed. Also in 2010, Kourgialas et al. [76] 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. In the year that followed, Paiva et al. [77] presented a large-scale hydrological model with a full one-dimensional hydrodynamic module to calculate flow propagation on a complex river network, while Lei et al. [78] developed an efficient and cost-effective distributed hydrological modeling tool (MWEasyDHM) based on open-source MapWindow GIS. Furthermore, Fugura et al. [79] 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. [80] 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 southeastern Iran, which were selected as an example of hazardous regions [81].

Despite the significant volume of previous research, the publication list in this topic 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 uses and land abandonment along with GIS in the Estanque de Arriba catchment (Spanish Pre-Pyrenees) [82]. Paiva et al. [83] 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 Solimões River basin. Tehrany et al. [84] 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. Another published novel idea of the year was that of Formetta et al. [85], who described the structure of JGrass-NewAge: a system for hydrological forecasting and modeling of water resources at the basin scale. Furthermore, among the published papers of 2014, the integration of RS and GIS occupies a rather special place, with the most influential works on this topic. Chen et al. [86] 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 [87] 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. Finally, Fiorillo et al. [88], published a model for simulating recharge processes of karst massifs and Krysanova et al. [89] used Soil and Water Integrated Model (SWIM) to model climate and land-use change impacts (four different application studies were made and analyzed). Both research works couple GIS and hydrological modeling.

In conclusion, from the references presented above, it can be easily deduced that hydrological modeling occupies a distinguished place in environmental modeling and research. The latest trends in the field are RS techniques and GIS coupled with hydrological modeling. The development and application of this coupling is expected to flourish the following years in scientific research.

3. Applied hydrological modeling—An empirical paradigm

3.1. A general description of the methodology

As mentioned earlier, GIS-based hydrological analysis has a very wide variety of applications in natural events and natural disasters. This part of the chapter intends to highlight the contribution of GIS in hydrological analysis and simulation by presenting an empirical analysis.

The basic aim of this simulation is to estimate the peak flood discharge, derived by an extreme rainfall event, as well as the critical time to reach this peak right after the rainfall peak. In order to do that, a synthetic Unit Hydrograph (UH) is obtained by estimating the time-area curve. The curve (histogram) of time-area shows the spatiotemporal relationship during time at which water flows within the basin. This curve can be expressed with a reclassification of time concentration at specific time intervals. These time periods are distinguished by isochrones. These are the lines within the catchment where runoff has the same travel time to reach the outlet of the basin.

According to the theory of the UH, the duration of the flood is the same for any given amount of active rainfall duration, while the ordinates of the hydrograph on the joint duration (time base flood) is directly proportional to the amount of rain (Chow et al., 1988). Thus, the discharge at the outlet of the basin is resulting from the superposition (addition) of instantaneous UH produced by active rain at each time step. UHs in hydrological practice are exported with numerical techniques from observed hydrographs. Many scientists have used GIS technology in order to construct rainfall-runoff model for UH attainment [13, 21, 63, 72].

In order to estimate the magnitude of a flood, a routing model was designed in a GIS context [63, 72, 90, 91]. The choice of the specific model was based mainly on its ability to be created entirely in a GIS environment. Accordingly, this model is very flexible to changes and connection with other models. Also, it is expandable, and it can be easily used in different areas.

3.2. The proposed method: data and methods

3.2.1. Data

The basic concept of the simulation is the runoff analysis in a GIS environment given a specific storm. The initiate data which is needed for this simulation is

3.2.1.1. The rainfall

The model can incorporate various types of rainfall data. More specifically, data derived by rainfall stations can be used. In this case, the use of them depends on the number of meteorological gauge stations. So, for example, if there is only one rainfall station in the river basin (i.e., the study area), the rain data is entered into the model (the simulation) as cumulative rainfall (single number). The distribution of rainfall is used after the modeling to construct the flood hydrograph. This simulation is taking into account only the time distribution of the rainfall (time modeling).

If the study area has more than one meteorological gauge stations, then the best way to handle all the rainfall data is to proceed to the tessellation of the data, e.g., with the creation of Voronoi (Thiessen polygons) geometries. In this way, the simulation is taking into account, besides time, the spatial context of the rainfall distribution (semispatiotemporal modeling).

Nowadays, the use of radar for record rainfall, or the use of data that are provided by Atmospheric Simulation Model, has provided the ability to incorporate in the hydrological modeling both the spatial and temporal variation of rainfall (spatiotemporal modeling).

In each case, the best way to simplify the hydrological modeling is to modify the total rainfall in terms of the part of rainfall which finally becomes surface runoff (excess rainfall). This data can be extracted from Atmospheric Simulation (the rainfall grid values can be only the excess rainfall). Otherwise, techniques such as Curve Numbers CN can be established in order to be used as a layer in the process of simulation [72].

Figure 1 presents the most common types of rainfall data which can be used in the model. **Figure 1a** shows a study area which is covered from only one rain station. **Figure 1b** presents a study area which is covered from many rain gauge stations (that is why the Thiessen polygons are used), and **Figure 1c** shows six different raster presentation of a 3-h cumulative rainfall (each one) and all together (in a row) cover the entire flood event.

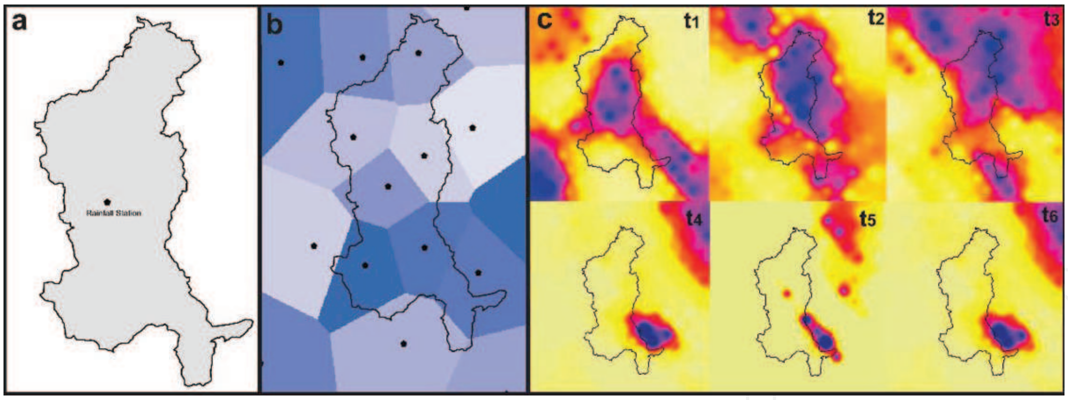

Figure 1. (a) One weather station—time modeling, (b) many weather stations—semi-spatiotemporal modeling (dots represents meteorological stations), (c) use of atmospheric simulation data—spatiotemporal modeling (t_1–t_6 are time snapshots of 3-h cumulative rainfall, blue color indicate high values of cumulative rainfall & yellow color indicate low values of cumulative rainfall).

3.2.1.2. A Manning's n roughness coefficient layer

In order to perform the simulation a Manning's roughness coefficient layer is needed. The construction of such a layer requires a land use/land cover (LULC) map of the study area.

Each type of LULC is assigned to Manning's roughness coefficient values using suitable lookup tables like the one in **Table 1** (for more details see reference [92]).

Description	Manning's n
Forest/Forest mixed	0.1
Urban/Urban mixed	0.015
Pasture/Pasture mixed	0.03
Permant Crop/Permant crop mixed	0.035
Arable Crop/Arable crop mixed	0.03
Olive/Olive mixed	0.15
Vineyard/Vineyard mixed	0.05

Table 1. Lookup table to assign Manning's roughness coefficient values to LULC.

After pairing the values of each LULC type to Manning's *n* values, the roughness coefficient layer (grid) is constructed.

3.2.1.3. A Digital Elevation Model (DEM)

The digital elevation models have been used, during the last decades along with the development of GIS, in order to derive hydrological and hydro-geomorphological properties such as streams, basins, flow direction, flow accumulation, flow length, and stream order. Nowadays, the development in satellite technology provides very high accuracy for remotely sensed data in terms of landscape topography. Alternatively, data generated from digitization of topographic maps can be used after applying the suitable algorithms in order to create a DEM, e.g., the algorithm ANUDEM.[93]. This specific algorithm produces a coherent grid which maintains the integrity of the topography [94]. Another way of constructing DEM is to use data derived from the use of Laser Scanners. The elevation point cloud is converted to Triangulated Irregular Network (TIN) and then is converted to DEM.

In GIS-based hydrological analysis, the use of DEM is exceptional and of critical importance. The cell size of a DEM largely determines the accuracy of the analysis that is carried out each time.

3.2.2. The methodology

The methodology which is presented in this paradigm is actually based on the estimation of concentration time in order to construct a layer of isochrones. Accordingly, calculations were carried out for flow time within the basin, both for channel and overland flow. In order to discrete these two types of water flow, a suitable threshold on flow accumulation must be selected. This can be done by several iterations until the stream layer reflect reality. Hence, the two types of flow are separated, and it also results in drainage network determination and mapping. As mentioned before, the topography of the land surface (expressed by a DEM) is one of the most fundamental elements for this simulation. Thus, DEM construction and analysis is the first step in order to execute the current rainfall-runoff model. There are various derivatives from the hydrological analysis of a DEM such as the slope (surface analysis), flow direction, flow accumulation, and flow length (hydrological analysis).

By extracting the flow accumulation layer (from the above DEM analysis), the discharge within the channel (Q_{ch} in m^3/s) of the river is calculated according to Eq 1:

$$Q_{ch} = \frac{R \times Flow.accumulation \times cell.size^2}{T_R} \tag{1}$$

where R is the amount of rainfall (in meters) and T_R is the duration of rainfall (in seconds). If the rainfall comes from only one meteorological station, R is actually a number which represents the amount of rainfall throughout the duration of the event. If the rainfall comes from several gauge stations, R is a grid layer which corresponds to closest gauge station. Lastly, if the rainfall comes from several grid layers which represent the spatiotemporal distribution of the rain, the discharge within the channel must be calculated as many times as the number of the separate grids. Then, these grids are added to give the total discharge within the river network.

The velocity of the water within the channel (V_c in m/s) can be estimated according to the combination of Manning's equation with the continuity equation by using the following Eq 2:

$$V_c = K \times S_0^{3/8} \times Q_{ch}^{1/4} \times n^{-3/4} \quad (2)$$

Where $S_0^{3/8}$ is the surface slope (m/m), Q is the cumulative discharge (m^3/s) which is calculated above, and n is the Manning's roughness coefficient. K is a coefficient that is determined after the calibration of the model and corrects the simulation errors of slope and n. Measurements of real discharge (Q) are very helpful and highly desirable in order to calibrate the model. The value "1" of K is a good starting point for ungauged basins.

Likewise, the overland flow velocity (V_0 in m) can be estimated according to Eq 3:

$$V_c = S_0^{3/8} \times l^{2/5} \times i_e^{2/5} \times n^{-3/5} \quad (3)$$

where S_0 is the surface slope (m/m), l is the length of the slope (m), i_e is the vertical net incoming flux (m/s), and n is the Manning's roughness coefficient. The combination of the above two types of velocities provides the final velocity, since the final velocity is calculated for each cell off the basin (using conditional algorithms).

The travel time (T in s) in each cell was computed from the travel distance using as a weight raster the 1/V grid as illustrated by Eq 4:

$$T = Flow.Length \times \frac{1}{V} \quad (4)$$

All the above equations can be calculated with the use of map algebra in a GIS software package. Map Algebra is a language that defines a syntax for combining map themes by applying mathematical operations and analytical functions to create new map themes. In a map algebra expression, the operators are a combination of mathematical, logical, or Boolean operators (+, >, AND, tan, etc.), and spatial analysis functions (slope, shortest path, spline, etc), and the operands are spatial data and numbers.

Finally, in order to estimate the flow time and isochrones (i.e., curves that connect areas of the basin where the runoff needs the same time to reach the exit of the basin), it is necessary to reclassify the values of travel time T.

The flow chart of the methodology is presented in **Figure 2**.

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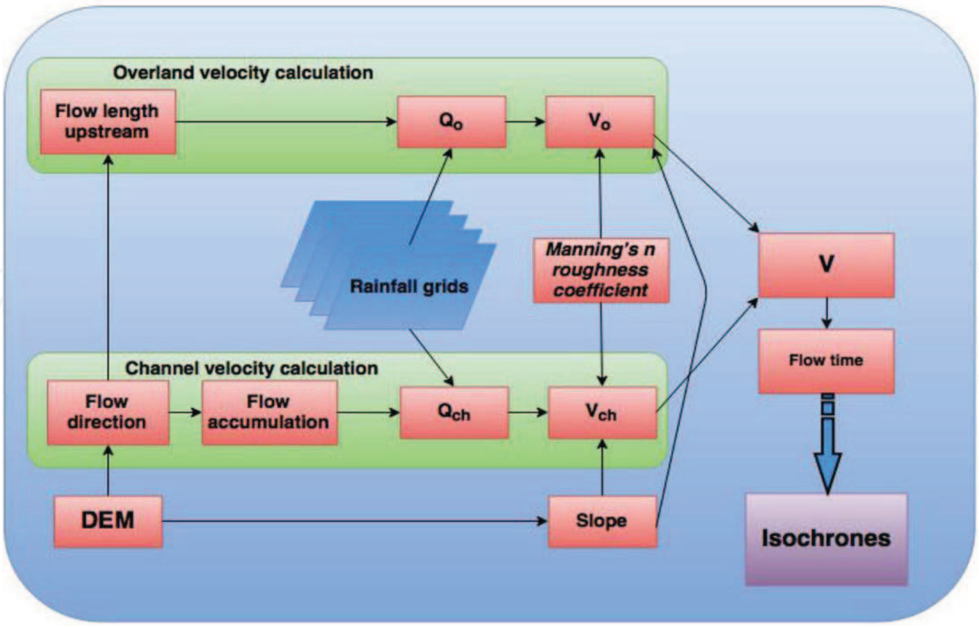
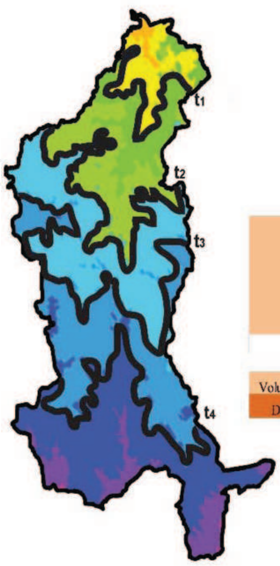


Figure 2. The flow chart of the methodology.

3.3. Results

The time-area unit hydrograph theory, as it known, inaugurates a specific association between the travel time *T* and a part of the upper catchment that may contribute runoff during this travel time *T*. The area which is closest to the catchment outlet will contribute to the runoff hydrograph sooner than the other areas which are on the catchment boundary. This method indicates that the catchment is divided into areas of approximately travel time (isochrones).



Flow time (isochrones)			Area	(km^2)
t1	→	1h	A_{t01}	3.2
t2	→	2h	A_{t12}	6.3
t3	→	3h	A_{t23}	8.1
t4	→	4h	A_{t34}	6.7
			A_{t4-}	9.4

	R1	R2	R3	R4	R5	R6	← snapshots of 3-hour cumulative rainfall
Area (m^2)	0.01	0.025	0.005	0.01	0.015	0.007	← Rainfall in meters
3200000	32000	80000	16000	32000	48000	22400	
6300000	63000	157500	31500	63000	94500	44100	
8100000	81000	202500	40500	81000	121500	56700	
6700000	67000	167500	33500	67000	100500	46900	
9400000	94000	235000	47000	94000	141000	65800	

	Palm 1	Palm 2	Palm 3	Palm 4	Palm 5	Palm 6	Palm 7	Palm 8	Palm 9	Palm 10
Volume of water (m^3)	32000	143000	254500	333000	413000	466400	279600	251200	187900	65800
Discharge (m^3/s)	26.6667	119.167	212.083	277.5	344.167	388.667	233	209.333	156.583	54.8333

Figure 3. Reclassified travel time (time zones, isochrones).

These lines of equal travel time are known as isochrones. Hence, the time-area histogram is actually converted to a hydrograph. **Figure 3** presents a common type of isochrones for the needs of this current empirical paradigm.

The total amount of rainfall for the examined flood event is 72 mm (0.072 m) within 18 h. From **Figure 3** it is obvious that the distribution of rainfall is presented in 3-h cumulative rainfall snapshots (R_1 = 10 mm, R_2 = 0.025 mm, R_3 = 0.005 mm, R_4 = 0.01 mm, R_5 = 0.015 mm, and R_6 = 0.007 mm). The area of each time zone (0 t_1, t_1 t_2, t_2 t_3, t_3 t_4, t_4 end) is A_1 = 3.2 km^2, A_2 = 6.3 km^2, A_3 = 8.1 km^2, A_4 = 6.7 km^2, A_5 = 9.4 km^2, respectively (thus, the whole area of the catchment is 33.7 km^2).

The main goal is the calculation of the discharge that is reaching the outlet of the basin in order to construct the synthetic UH (the so-called "palm of discharge"). For this reason, the amount of water that falls onto each time zone is calculated. Thus, for the first time zone (t_1), the amount of water during the first 3 h is V_{11} = R_1*$A1$ = 0.01 m*3,200,000 m^2 = 32,000 m^3, for the second time zone (t_2) is V_{21} = R_2*A_1 = 0.025 m*6,300,000 m^2 = 80,000 m^3, etc.

The next step is the calculation of the total volume for each palm of water discharge that reaches the outlet of the basin. Thus, the volume of the first palm is V_{palm1} = V_{11} = 32,000 m^3 (the first purple cell in **Figure 3**), the volume of the second palm is $V_{palm}2$ = $V21$ + $V12$ = 80,000 m^3 + 63,000 m^3 = 143,000 m^3 (the sum of the first red cells in **Figure 3**) etc.

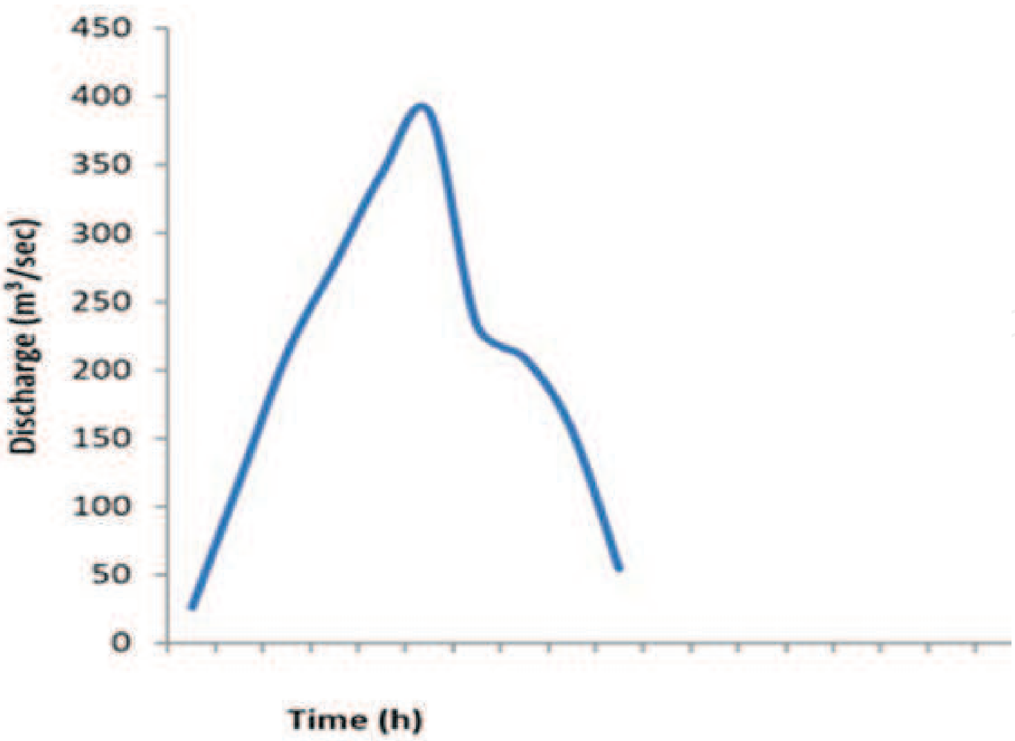


Figure 4. The synthetic unit hydrograph (UH).

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The final step is the reduction of each volume to time, which is actually the calculation of the discharge. By plotting these values of discharges against time the synthetic UH is constructed. This synthetic UH is presenting on **Figure 4**. This UH reveals two vital values of the flood hydrographs which are the critical time and the maximum (peak) value of the discharge. For this empirical paradigm, these values are T_c = 18 h and the Q_{peak} = 388.667 m^3/s.

3.4. Conclusions

This methodology attempts to analyze the physical processes of a rainfall event in a hypothetical study area. Thus, a rainfall-runoff model is used for estimating the spatially distributed synthetic UH for the outlet of the catchment.

The form of the model-derived synthetic UH for the outlet of the basin can be used in a variety of cases. There are two crucial values derived from a UH, the critical time (time difference between peak rainfall and maximum discharge) and the peak value of the discharge. The development of such hydrographs can be used for extreme rainfall magnitudes in order to design constructions such as bridges and roads.

Also, UH can be used in order to extrapolate flood flow records based on rainfall records and for the development of flood forecasting and warning systems. Additionally, each UH shows the response of the catchment-study area, i.e., they provide also evaluations of extreme discharges while they are giving the opportunity to design UH (in rivers and streams) with lack of meteorological and hydrometric stations (by applying modeling on rainfall and hydrological data using GIS).

The empirical modeling described earlier has also some limitations. It undertakes uniform distribution of rainfall over the catchment and uniform intensity during the duration of rainfall excess (in case of rainfall data from rain gauge stations). In practice, these conditions are not satisfied during a real storm event. Under specific situations of nonuniform aerial scattering and disparity of intensity, UH, still, can be used if the spatial distribution is constant between different flood events. In addition, in some cases, when the rainfall data comes from meteorological stations, the catchment size levies a superior limit on the pertinency of the UH implementation due to rainfall distribution. In this case, a very big river basin needs to be tackled as the sum of smaller subcatchments. Thus, this obligation noises for an assortment of flood events of so slight a period which would generally yield a strong and approximately unchanging effective rainfall. Also it would yield a distinct single peak of hydrograph of short time base. UHs that are having the same time base are unswervingly relative to the total amount of runoff given by each hydrograph (linearity).

Usually, in hydrological modeling and especially in modeling of flash floods, there are some definite assumptions. For instance, the effects of evapotranspiration, as well as the synergy between the aquifer and the rivers, are ignored. This could also be overlooked due to the fact that the amount of evapotranspiration during the time, in which the flood occurs, is insignificant when compared to other fluxes such as infiltration. Furthermore, the effect of the aquifer-river synergy is commonly disregarded due to the response time of overland flow versus the flow within the channel. Similarly, effects of the rest of hydrological procedures such as interception and depression storage are also ignored.

3.5. Discussion

Despite the assumptions/limitations of the model, the proposed modeling provides a meaningful estimation of the maximum value of discharge and the peak time of a flood event.

The introduction of GIS technology led researchers to develop data processing automations and to produce reliable simulation models. They appreciate the standing and welfares of such a technology that empower them to evaluate data, contend with complications, generate instinctive visualization approaches, and make conclusions with a higher effectiveness.

The objective of this chapter was to present the extended history of GIS modeling and to converse the modern observes in terms of integration of GIS with the hydrological modeling, and also to discuss the problems, the assumption, and the limitations of GIS-based hydrological models. Generally, four different approaches have been widely proposed and used in terms of integrating GIS with the hydrological modeling. These are (a) embedding GIS-like functionalities into hydrological modeling software, (b) embedding hydrological modeling into GIS software, (c) loose coupling (add-on), and (d) tight coupling which actually is to customize applications into a GIS software [95].

Therefore, these models can be used as tools for policy makers in order to take decisions for the construction of artificial dams (i.e., containment barriers) and halting water projects in general. Thus, rainfall-runoff models together with the GIS technology are used as integrated systems of assessing potential impacts for various rainfall events. Hence, the GIS technology has the capability to postprocess the results which are obtaining from a model and sublimate them into policy.

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