

GIS-BASED FLOW ROUTING WITH THE DISTRIBUTED HYDROLOGICAL WETSPA MODEL IN THE ZIARAT RIVER BASIN - GORGAN, IRAN

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ABSTRACT. The GIS-based distributed hydrological model, WetSpa, whose flow routing method is described in this paper is suitable for flood prediction and watershed management on catchment scale. The model predicts outflow hydrographs at the basin outlet or at any converging point in the watershed, and it does so at a user-specified time step. The model is physically based, spatially distributed and time-continuous. This paper focuses on the GIS-based diffusive transport approach for the determination of rainfall runoff response and flood routing through a catchment. The watershed is represented as a grid cell mesh, and routing of runoff from each cell to the basin outlet is accomplished using the first passage time response function based on the mean and variance of the flow time distribution, which is derived from the advection–dispersion transport equation. The flow velocity is location dependent and calculated in each cell by the Manning equation based on the local slope, roughness coefficient and hydraulic radius. The hydraulic radius is determined according to the geophysical properties of the catchment and the flood frequency. The total direct runoff at the basin outlet is obtained by superimposing all contributions from every

grid cell. The model is tested on the Ziarat _Gorgan watershed with 4years of observed hourly rainfall and discharge data, and the results are in excellent agreement with the measured hydrograph at the basin outlet.

Key words: Diffusive wave; Unit hydrograph; Geographical information system; Flood modeling; WetSpa model.

INTRODUCTION

Determination of riverflow hydrograph is a main target in hydrology. Hydrological modeling deals with calculation of watershed hydrograph using hydro-meteorological information and terrain data, and processes of transforming rainfall into a flood hydrograph and the translation of hydrographs throughout a watershed. Flow routing subjects hydrograph transformation and translation through out a river basin.

Recent development of GIS and remote sensing technology makes it

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possible to capture and manage a vast amount of spatially distributed hydrological parameters and variables. Distributed parameter hydrological models are typically structured in characterizing watershed conditions such as topography, soil type, land use, drainage density, degree of soil saturation, and rainfall properties, for which it is advantageous to use the data currently available in GIS format (Liu, 2004).

The WetSpa model used in this study is a simple grid-based distributed runoff and water balance simulation model that runs on an hourly time step. It predicts hourly overland flow occurring at any point in a watershed, hydrograph at the outlet, and provides spatially distributed hydrologic characteristics in the basin, in which all hydrologic processes are simulated within a GIS framework (Bahremand, 2007). The WetSpa model was originally developed by Wang *et al.* (1997) and adapted for flood prediction by De Smedt *et al.* (2000) and Liu *et al.* (2003).

The model predicts peak discharges and hydrographs in any location of the channel network and the spatial distribution of hydrological characteristics in each cell. Darcy's law and a kinematic wave approximation are used to determine the amount of interflow generated from each cell, in function of hydraulic conductivity, the moisture content, slope angle, and the root depth. The routing of overland flow and channel flow is implemented by

the method of the diffusive wave approximation. This paper has focused on the flow routing component of the model.

Since the characteristics of hydrologic systems, as for instance precipitation and the generation of runoff, are extremely variable in space and time, the response of the system, i.e. the flow of water over the land surface and the river channels, is a distributed process in which the characteristics of the flow change both in time and space. This limits the use of the unit hydrograph model (Liu *et al.*, 2003).

In an attempt to find a physical basis for the IUH, Rodriguez-Iturbe and Valdes (1979) introduced the concept of a geomorphologic instantaneous unit hydrograph (GIUH), which relates the geomorphologic structure of a basin to the IUH using probabilistic arguments. This theory was later generalized by Gupta *et al.* (1980) and Gupta and Waymire (1983). The IUH is defined as the probability density function (PDF) of the droplet travel time from the source to the basin outlet.

Sivapalan *et al.* (1990) incorporated the effect of partial contributing areas, which recognizes that during a rainfall event, droplets contributing to the runoff are not uniformly distributed throughout the basin but are more likely to come from areas that are saturated close to stream channels. The saturated areas can be identified through topographic indices (Beven and Kirkby, 1979),

which can be easily obtained from DEM data.

To describe the flow through individual streams, Lee and Yen (1997) introduced the kinematic wave theory to determine the travel times of overland and channel flows, thus relaxing the linearity restriction of the unit hydrograph theory. The travel time from each cell to the watershed outlet is calculated by dividing each flow length by a constant velocity. Subsequently, a time area diagram based on the travel time from each grid cell is developed. A more elaborate flow model, which accounts for both translation and storage effects in the watershed, is presented by Maidment *et al.* (1996). De Smedt *et al.* (2000) proposed a flow routing method, in which the runoff is routed through the basin along flow paths determined by the topography using a diffusive wave transfer model, that enables to calculate response functions between any start and end point, depending upon slope, flow velocity and dissipation characteristics along the flow lines, and all the calculations performed with standard GIS tools (Liu *et al.*, 2003).

In this paper, the diffusive transport approach for flow routing in GIS-based flood modeling which has already been presented by Liu *et al.* (2003) has been applied to the Ziarat watershed located in the North of Iran. A response function is determined for each grid cell depending upon two parameters, the average flow time and the variance of

the flow time. The flow time and its variance are further determined by the local slope, surface roughness and the hydraulic radius. The flow path response function at the outlet of the catchment or any other downstream convergence point is calculated by convoluting the responses of all cells located within the drainage area in the form of the PDF of the first passage time distribution. This routing response serves as an instantaneous unit hydrograph and the total discharge is obtained by convolution of the flow response from all spatially distributed precipitation excess. The model is applied to the Ziarat_Gorgan watershed, for which topography and soil data are available in GIS form, and land use data is obtained from remote sensed images. River discharges are estimated on hourly basis from October 2007 to September 2010.

MATERIALS AND METHODS

The routing of overland flow and channel flow is implemented by the method of the diffusive wave approximation. This method has been used in some recent GIS-based flood models (Fortin *et al.*, 2001; Olivera and Maidment, 1999; Troch *et al.*, 1994). Liu *et al.* (2003) has presented the flow routing method of the WetSpa model in detail. A two-parameter response function, based on the average flow time and the standard deviation of the flow time, is proposed in this study. The flow time and its variance are determined by the local slope, surface roughness and the hydraulic radius for each grid cell. The flow path response function at the outlet of the catchment or

any other downstream convergence point is calculated by convoluting the responses of all cells located within the drainage area in the form of the probability density function (PDF) of the first passage time distribution. This routing response serves as an instantaneous unit hydrograph and the total discharge is obtained by a convolution integral of the flow response from all generated spatially distributed runoff.

Starting from the continuity equation and the St. Venant momentum equation, assuming one-dimensional unsteady flow, and neglecting the inertial terms and the lateral inflow to the flow element, the flow process can be modeled by the diffusive wave equation (Cunge *et al.*, 1980):

$$\frac{\partial Q}{\partial t} + c_i \frac{\partial Q}{\partial x} - d_i \frac{\partial^2 Q}{\partial x^2} = 0 \quad (1),$$

where Q is the discharge at time t and location x , t [T] is the time, x [L] is the distance along the flow direction, c [LT^{-1}] is the location dependent kinematic wave celerity and is interpreted as the velocity by which a disturbance travels along the flow path, and d [L^2T^{-1}] is the location dependent dispersion coefficient. Assuming that the bottom slope remains constant and the hydraulic radius approaches the average flow depth for overland flow and watercourses, c and d can be estimated by $c = (5/3)v$, and $d = (vH)/(2S_0)$ (Henderson, 1966), where v [LT^{-1}] is the flow velocity, calculated with the Manning equation, and H [L] the hydraulic radius or average flow depth. Parameters c and d are assumed to be independent of the discharge, Q . Hence, the partial differential Equation (1) becomes parabolic, having only one dependent variable, $Q(x,t)$. The hydraulic radius is determined by a power law relationship with an exceeding probability (Molnar and Ramirez, 1998), which

relates hydraulic radius to the controlling area and is seen as a representation of the average behavior of the cell and the channel geometry:

$$H = a_p [(A_i)]^{b_p} \quad (2),$$

where H [L] is the hydraulic radius, A_i [L^2] is the drained area upstream of the cell, which can be easily determined by the flow accumulation routine in standard GIS, a_p [-] is a network constant and b_p [-] a geometry scaling exponent both depending on the discharge frequency. The parameters a_p and b_p can be estimated based on the watershed characteristics. An approximate solution to the diffusive wave equation in the form of a first passage time distribution was proposed by Liu *et al.* (2003), relating the discharge at the end of a flow path to the available runoff at the start of the flow path:

$$U_i(t) = \frac{1}{\sqrt{2 \frac{\pi \sigma_i^2 t^3}{t_i^3}}} \exp \left[-\frac{(t-t_i)^2}{2 \frac{\sigma_i^2 t}{t_i}} \right] \quad (3),$$

where $U_i(t)$ [T^{-1}] is the flow path unit response function, t_i [T] is the flow time, and σ_i [T] is the standard deviation of the flowtime. The parameters t_i and σ_i are spatially distributed, and can be obtained by integration along the topographic determined flow paths as a function of flow celerity and dispersion coefficient:

$$t_i = \sum_{j=1}^N \left(\frac{1}{c_j} \right) l_j \quad (4)$$

$$\sigma_i^2 = \sum_{j=1}^N \left(\frac{2d_j}{c_j^3} \right) l_j \quad (5)$$

It can be proven that the skewness of the sum of the independent variables is equal to the sum of their skewnesses:

$$SKW(Y) = 12 dx \quad (6)$$

The direct flow hydrographs at the basin outlet or any downstream

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convergent point are obtained by a convolution integral of the flow response from all contributing cells:

$$Q(t) = \int_A \int_0^t V(\tau) U(t - \tau) d\tau dA \quad (7),$$

where $Q(t)$ [L^3T^{-1}] is the direct flow hydrograph, $V(\tau)$ [L^{-1}] is the surface runoff input in a grid cell, τ [T] is the time delay, and A [L^2] is the drainage area of the watershed.

For the purpose of model parameter optimization and sensitivity analysis, a watershed unit response function is proposed in this paper based on the flow path redistribution function described above. The watershed IUH differs from the traditional GIUH, which uses the drainage basin hill slope function weighted by the channel network width function (Troch *et al.*, 1994), because it integrates the flow path response functions in the basin weighted by the spatially distributed runoff coefficient:

$$UH(t) = \frac{\int_A CU(t)dA}{\int_A CdA} \quad (8),$$

where $UH(t)$ [T^{-1}] is the IUH of the catchment or subcatchment, and C [-] is the default runoff coefficient of the grid cell, which is assumed to depend upon slope, soil type and land use. Values of the default runoff coefficient can be collected from the literature (Kirkby, 1978; Chow *et al.*, 1988; Browne, 1990; Mallants and Feyen, 1990; Pilgrim and Cordery, 1993). The numerator on the right hand side of Eq. (8) serves as the direct runoff hydrograph at the outlet resulting from a unit volume of rainfall but spatially distributed surface runoff, while the denominator is the total volume of the runoff. The watershed IUH described in Eq. (8) can also be used in lumped or semilumped rainfall runoff models to predict outlet hydrographs with an average excess precipitation input on subcatchment or catchment scale.

Interflow is assumed to contribute to the surface runoff at the outlet of each cell, and routed to the catchment outlet together with surface runoff without redistribution among downslope cells for simplicity. Groundwater flow is modeled with a linear reservoir method on small subcatchment scale, while a nonlinear reservoir method is optional in the model with storage exponent of 2. The groundwater outflow is added to any runoff generated at the subcatchment outlet to produce the total streamflow. Hence, the flow routing consists of tracking runoff along its topographic determined flow path, and evaluating groundwater flow for each small subcatchment. In order to consider the damping effect of the river, overland flow and interflow are routed firstly from each grid cell to the main channel, and joined with groundwater flow at the subcatchment outlet. Then the total hydrograph is routed to the basin outlet by the channel response function. The total discharge is the sum of the overland flow, interflow and groundwater flow (Liu, 2004).

RESULTS AND DISCUSSION

The WetSpa model has been applied in several studies, e.g. the Barebeek catchment in Belgium (De Smedt *et al.*, 2000), the Alzette river basin in Luxembourg (Liu *et al.*, 2003), the Hornad watershed in Slovakia (Bahremand *et al.*, 2005), the Tisza river basin (Corluy *et al.*, 2005), the Jajrood watershed in Iran (Zeinivand, 2009), the Gorganrude basin in Iran (Kabir and Bahremand, 2011), the DMIP project for Oklahoma region in USA (Safari *et al.*, 2012) with different success. The

model has been used for assessing landuse and climate change impacts and river restoration effects on flooding in several studies (e.g. Gebremeskel, 2003; Liu, 2004; Bahremand *et al.*, 2006). Those studies showed that the model is capable to simulate stream flow, to predict floods, and to assess the effects of landuse and climate changes on hydrologic processes and floods. Also, the model has been adopted and applied for simulation of runoff and phosphorus transport, i.e. for the Margecany catchment in Slovakia (Liu *et al.*, 2006). The application of the physically based distributed unit hydrograph method derived from the

diffusive transport approach (Liu *et al.*, 2003) is presented in this paper for GIS based modeling on catchment scale of the Ziarat watershed. The topography and soil data of the catchment are available in GIS form, and land use data was obtained from remote sensed images. The average elevation in the 95.15 km² watershed is 1915 m, with an average basin slope of 41.4%. *Fig. 1* shows the topographic elevation map of the Ziarat catchment, and *Fig. 2* shows the land use map of the study area. This catchment is partly located in Iran and in the Gorgan.

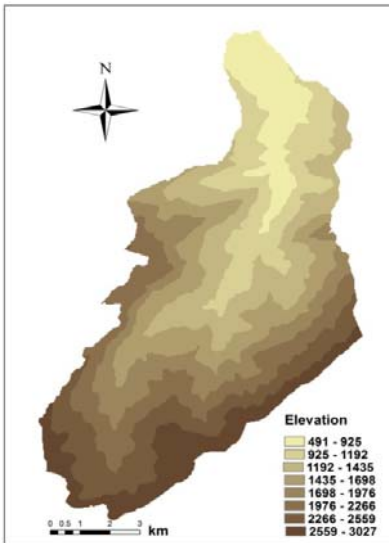


Figure 1 - DEM of the study area

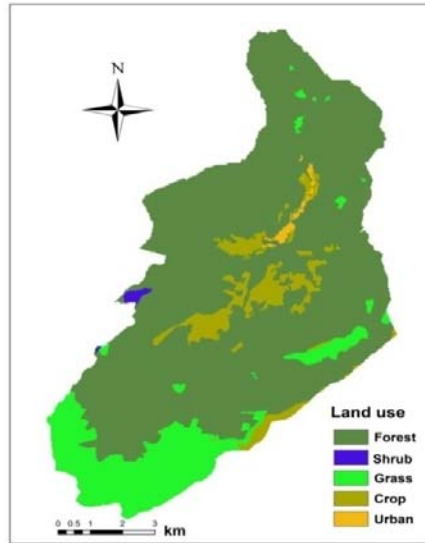


Figure 2 - Land use map of the study area

The dominant soil textures are and sandy loam, loamy silt, loamy clay and loamy clay silt.

High runoff occurs in winter and low runoff in summer due to the

higher evapotranspiration. flood happen frequently because of saturated soils and low evapotranspiration. The average annual precipitation in the region 425

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mm and maximum moisture varies between 71% and 75%. A total of 4 years of hourly precipitation, discharge and potential evapotranspiration data are available. The average flow during the monitoring period is $0.18 \text{ m}^3/\text{s}$, with flows ranging from 0.001 to $2.09 \text{ m}^3/\text{s}$.

Model parameters are identified using GIS tools and lookup tables, which relate default model parameters to the base maps, or a combination of the base maps. Starting from the 30 by 30 m^2 pixel resolution digital elevation map, hydrologic features including surface slope, flow direction, flow accumulation, flow length, stream network, drainage area and subbasins are delineated. The threshold for delineating the stream network is set to, 100 i.e. the cell is considered to be drained by ditches or

streams when the total drained area becomes greater than 9 ha. A map of Manning's roughness coefficients is derived from the land use map, and a map of potential runoff coefficients is calculated from the slope, soil type and land use class combinations (Liu *et al.*, 2002). Impervious areas have significant influence on the runoff production in a watershed, because these can generate direct runoff even during small storms. Due to the model 30 m grid size, cells may not be 100% impervious in reality. In this study, the percentage of impervious area in a grid cell is computed based on land use classes, with 30% for residential area, 70% for commercial and industrial area and 100% for streams, lakes and bare exposed rock. The map of the potential runoff coefficient of the study area is given in Fig. 3a.

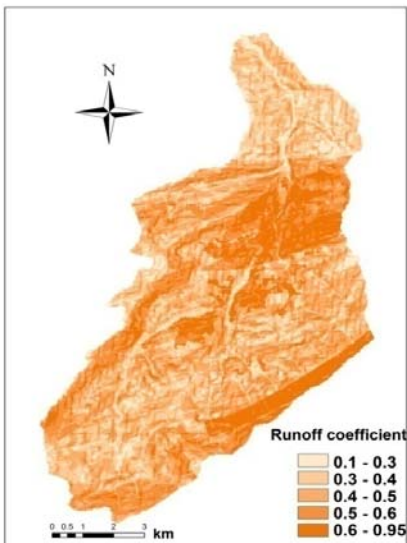


Figure 3a - Distribution of potential runoff coefficient



Figure 3b - Distribution of hydraulic radius for a flood with a 2-year return period

For calculation of the spatially distributed flow velocity and dispersion coefficient, both parameters are assumed to depend on local slope, hydraulic radius and vegetation type. This differs from previous work, where the flow velocity and dispersion coefficient are considered to be uniform distributed over the hill slope and the channel networks and estimated by model calibration (Van Der Tak and Bras, 1990; Troch *et al.*, 1994; Gyasi-Agyei *et al.*, 1996; Olivera and Maidment, 1999). In this study, the roughness coefficients for river courses and different land uses are obtained from literature (Chow, 1964; Yen, 1991; Ferguson, 1998), while the hydraulic radius is determined by a power law relationship with an exceeding probability (Molnar and Ramirez, 1998), which relates hydraulic radius to the drained area and is seen as a representation of the average behavior of the cell and the channel geometry, Eq. (2)

Consequently, the hydraulic radius for each grid cell in the basin is calculated with Eq. (2). In this study, the exceeding probability p is set to a 2-year return period for normal floods.

The minimum hydraulic radius for overland flow to be 0.002 m and the maximum hydraulic radius for channel flow 0.45 m at the basin outlet. *Fig. 3b* shows the spatial distribution of the hydraulic radius for a flood with a 2-year return period.

Because the local slope in some cells derived from the DEM can be

very small and even can reach zero particularly in the river valleys in the flood plain area, he calculated flow time and its variance become very large and the computed flow path IUH is unrealistic. Therefore, a threshold for the minimum slope should be fixed, in order to make the flow path IUH more reasonable. In this study, the threshold of the minimum slope is set to 0.01%, i.e. the local slope is considered to be at least 0.01%. Thereafter, by combining the maps of the hydraulic radius, Manning's roughness coefficient, and surface slope, the average flow velocity in each grid cell can be calculated using Manning's equation, which results average velocities is 0.1m/s. *Fig. 4a* shows the spatial distribution of the average flow time to the basin outlet from each grid cell, and *Fig. 4b* shows the spatial distribution of the standard deviation of the flow time. The average flow time is 5.5 h and the maximum flow time of Ziarat catchment as the time of concentration of the watershed is 10.57 h for area, and the average standard deviation is 3.16 h.

With the above information, the flow path unit response functions are calculated for each grid cell to the basin outlet using Eq. (3), and the watershed unit response function can be calculated using Eq. (8), weighted by the spatially distributed runoff coefficient. The calculated watershed IUH is shown in *Fig. 5*.

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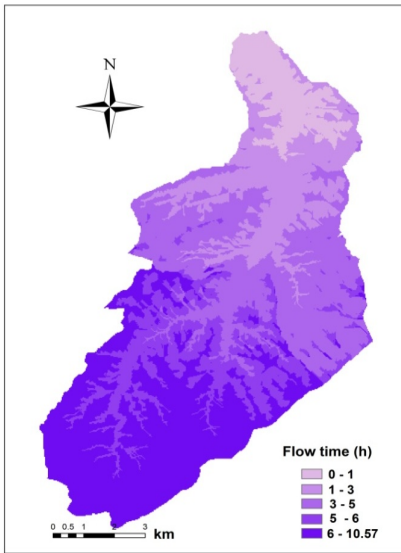


Figure 4a - Average flow time to the basin outlet

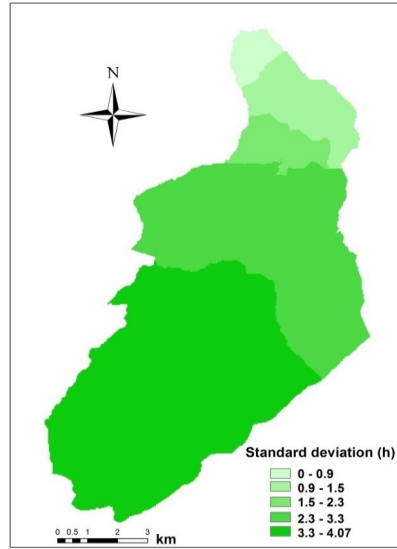


Figure 4b - Standard deviation of the flow time

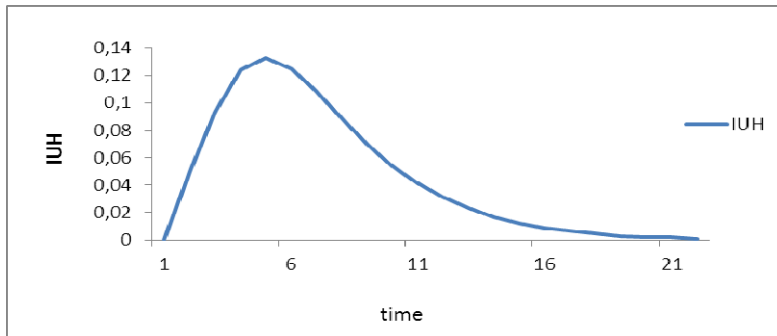


Figure 5 - Calculated watershed IUH

A linear relationship is assumed between the actual surface runoff and the soil moisture content in the root zone, where wet soils tend to generate more runoff and dry soils tend to generate less or even no runoff. The soil moisture content in each cell is further simulated on the basis of a soil water balance on hourly time scale,

which relies on the rate of the infiltration, percolation, interflow and evapotranspiration in and out of the root zone. Finally, the hydrograph at the basin outlet is obtained by the convolution integral of the excess precipitation and the flow path IUH from all cells in the watershed with Eq. (7).

In order to evaluate the performance of the diffusive wave approximation method for the routing of surface runoff, 4 years observed hourly discharge data at the station in the Ziarat catchment are selected for the model verification. The baseflow is separated from the total hydrograph by the nonlinear reservoir algorithm (Wittenberg and Sivapalan, 1999), in which the baseflow is assumed to be proportional to the square of the groundwater storage as:

$$Q_g = kS^2 \quad (9),$$

where Q_g [$L^3 T^{-1}$] is the baseflow, S [L] is the groundwater storage, and k [LT^{-1}] is a reservoir recession coefficient, which is related to the area, shape, pore volume and transmissivity of the watershed, and can be derived from the analysis of the recession curves. Combined with the soil water balance equation, the groundwater storage can be determined and used for baseflow separation with Eq. (9). It turns out that the computed surface runoff hydrographs compared very well with

the observations. As a typical example, we show the results for a flood event that occurred from January 25 to February 28, 2010, shown in Fig. 6, where the baseflow volume takes about 96% of the total flood volume, and the direct flow about 4%.

The diffusive flow routing model is then applied with spatially distributed excess rainfall as input and the hydrograph at the basin outlet as output and observed peak discharge of $2.09 \text{ m}^3/\text{s}$, while the simulated peak flow is $1.94 \text{ m}^3/\text{s}$. As can be seen in the figure, the predicted hydrograph is in good agreement with the observations. For assessing the model performance, two evaluation criteria were applied to the simulation results for the whole simulation period: (1) the model Nash Sutcliffe efficiency (Nash and Sutcliffe, 1970) for reproducing the direct discharges is 71%, and (2) the average correlation coefficient between the measured and predicted hydrograph is 57%.

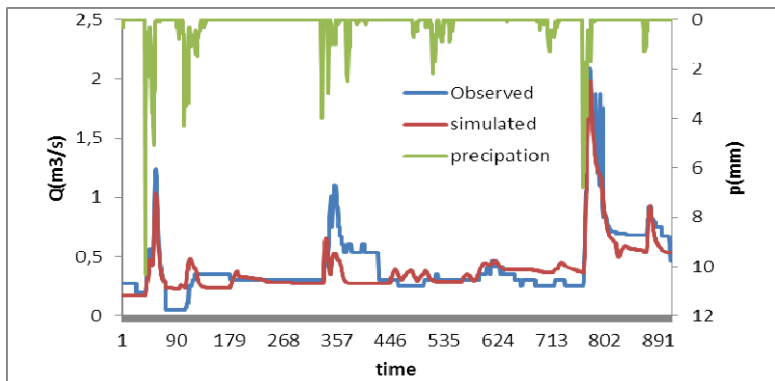


Figure 6 - Observed and predicted stream flow

CONCLUSIONS

The application of the physically based distributed unit hydrograph method derived from the diffusive transport approach (Liu *et al.*, 2003) is presented in this paper for GIS based modeling on catchment scale of the Ziarat watershed located in the North of Iran. The method differs from the previous works in that it is based on a location dependent velocity field. The basic modeling approach is to use raster GIS functions to calculate the travel time from each point in the watershed to the outlet by determining the flow path and the travel time through each cell along the path. The flow velocity in each grid cell is calculated by the Manning equation. The travel time through each individual cell along the flow path is integrated to obtain the cumulative travel time to the outlet. Based on the mean and the variance of the flow time, the first passage time distribution density function is applied as a flow response function. Runoff is routed over the surface flow path, and accounts for the differences in runoff amount and velocity, due to changing slope, land use, soil type and other surface conditions. Finally, the total direct discharge at the downstream convergence point is obtained by superimposing all contributions from every grid cell. The watershed IUH is calculated based on the flow path functions and the spatially distributed runoff coefficient, and can be used for model parameter sensitivity analysis

or as the IUH for lumped prediction models. Model parameters based on surface slope, land use, soil type and their combinations are collected from literature, and can be prepared easily using standard GIS techniques (Liu *et al.*, 2003).

The model was tested on the Ziarat catchment in Golestan with 4 years of observed hourly rainfall and discharge data, where the spatially distributed surface runoff was generated by the WetSpa model. The results show an excellent agreement with the measured hydrograph at the basin outlet.

The diffusive wave transport approach assumes a unique relationship between flow and stage at each point for both overland flow and channel flow, and so does not require the specification of a downstream stage. It also generally operates satisfactorily with less detailed ditch and channel geometry information than required by dynamic wave models and is much more stable and easy to use in GIS based flood modeling. Moreover, this approach allows the spatially distributed excess precipitation and hydrologic parameters of the terrain to be used as inputs to the model, and is especially useful to analyze the effects of topography, and land use or soil cover on the hydrologic behavior of a river basin. The method is worth to be applied in flood modeling for a wide range of slopes from flood plains to the hilly areas. However, accuracy of the diffusive wave approach increases with increasing slope, and it cannot be

used in situations where flow reversals occur. Application of the methodology suggests that simulations of the hydrologic response based on diffusive wave approximation and GIS specification of the topographical network are validated in the study area. This is sustained by a proper adjustment of the parameter values characterizing the flow travel time and its variance, which is deemed to cover most cases of engineering interest.

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