Simulation of Basin Runoff due to Rainfall and Snowmelt

Zeinivand, H. [1, 2], F. De Smedt [1] and A. Bahremand [3]

[1] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussels, Belgium
[2] Lorestan University, Khorram Abad, Lorestan, Iran
[3] Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran
Email: Hossein.Zeinivand@vub.ac.be

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EXTENDED ABSTRACT

The prediction of peak flow and the simulation of flood hydrographs in a stream or river is a very complex process. An application of a spatially distributed hydrologic model WetSpa working on a daily time scale is presented in this paper. The model combines elevation, soil and landuse data within a GIS framework, and predicts flood hydrograph and the spatial distribution of hydrologic characteristics through a watershed. The hydrological processes considered in the model are precipitation, interception, depression, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow, and water balance in the root zone and the saturated zone. This version of the WetSpa model uses a modified rational method to calculate runoff and an energy balance approach to estimate the snowmelt runoff based on temperature data. The main focus of the paper is on discussing the simulation of a flood hydrograph as consequence of rainfall and snowmelt. 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 model is applied to the Hornad river basin located in Slovakia. Daily hydrometeorological data from 1993 to 2000, including precipitation, temperature, evaporation, and windspeed, are used as input data to the model. For the simulation of hydrographs at the basin outlet and at the flow monitoring stations inside the catchment, the basin was divided into 223 subcatchments, corresponding to the threshold value of 1000 cells when delineating the stream network based on topographic flow accumulation. The calibration process is mainly performed for the global model parameters, whereas the spatial model parameters are kept as default values. The initial global model parameters are specifically chosen according to the basin characteristics as discussed in the documentation and user manual of the model. Results of the simulations show a good agreement between calculated and measured hydrographs at the outlet of the basin (Nash-Sutcliffe efficiency is equal to 74%). An interesting period, with snow accumulation followed by snowmelt producing a flood is discussed in detail.

1. INTRODUCTION

In applied hydrology, the prediction of peak flow and the simulation of flood hydrographs in a stream or river is a very complex process, because the hydrological variables vary both in space and time as a function of the meteorological inputs, spatial variability of topography, land use and soil types (Liu and De Smedt 2004). The WetSpa model used in this study is a simple grid-based distributed runoff and water balance simulation model that runs on daily time step. It predicts overland flow occurring at any point in a watershed and the resulting hydrograph at the outlet. It also provides spatially distributed hydrologic characteristics in the basin, in GIS form. The input of the model includes observed data of precipitation, evaporation, temperature (minimum, mean and maximum), and windspeed together with parameters derived from topographic, land use and soil maps in digital raster format. Stream discharge data is optional for model calibration. In this paper emphasis is given to the simulation of runoff from rainfall and snowmelt. The model is applied for a rather large catchment located in Slovakia by comparing calculated and observed daily discharges for an 8 years period.

2. WETSPA MODEL AND RUNOFF PRODUCTION

WetSpa is a grid-based distributed hydrological model for water and energy transfer between soil, plants and atmosphere, which was originally developed by Wang *et al.* (1996). For each grid cell, four layers are considered in the vertical direction, i.e. vegetation zone, root zone, transmission zone and saturated zone. The hydrological processes considered in the model are precipitation, interception, depression, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow, and water balance in the root zone and the saturated zone. The total water balance for a raster cell is composed of the water balance for the vegetated, bare-soil, open water and impervious parts of each cell. A mixture of physical and empirical relationships is used to describe the hydrological processes in the model (De Smedt *et al.* 2004, Liu *et al.* 2004).

The model predicts peak discharges and hydrographs, which can be defined for any numbers and locations in the channel network, and can simulate the spatial distribution of catchment hydrological characteristics. For each grid cell, the root zone water balance is modeled continuously by equating inputs and outputs (Liu, 2004):

$$D\frac{d\theta}{dt} = P - I - S - E - R - F \qquad (1)$$

where D (m) is the root depth, θ ($m^3\ m^{-3}$) is the soil water content in the root zone, t (d) is the time, P ($m\ d^{-1}$) is the rainfall intensity, I ($m\ d^{-1}$) is the initial loss due to interception and depression storage, S ($m\ d^{-1}$) is the surface runoff resulting from snowmelt and rainfall, E ($m\ d^{-1}$) is the evapotranspiration from the soil, R ($m\ d^{-1}$) is the percolation from the root zone, and F ($m\ d^{-1}$) is the amount of interflow. The surface runoff is calculated using a moisture-related modified rational method with a potential runoff coefficient depending on land cover, soil type, slope, the magnitude of rainfall, and antecedent soil moisture (Liu 2004, Zeinivand and De Smedt 2007):

$$S = C(P - I + M)(\theta/n)^{\alpha} \qquad (2)$$

where M ($m\ d^{-1}$) is the rate of snowmelt, n ($m^3\ m^{-3}$) is the soil porosity, and C (-) is the potential runoff coefficient. The values of C are taken from a lookup table, linking values to slope, soil type and landuse classes (Liu, 2004). The exponent α (-) in the formula is a parameter reflecting the effect of rainfall intensity on the surface runoff. The value is higher for low rainfall intensities resulting in less surface runoff, and approaches one for high rainfall intensities (Bahremand *et al*, 2005). Because a large part of the annual precipitation is in the form of snow, a model based on daily temperature data is used to simulate snow melt. Physical processes within the snowpack involve mass and energy balance as well as heat and mass transport. Snowmelt is basically an energy driven process (Parajka, 2001). The energy balance of a snowpack is given by (Tarboton and Luce 1996, Walter *et al.* 2005, Zeinivand and De Smedt 2007):

$$\frac{dU}{dt} = S_n + L_a - L_t + H + E_l + G + Q_p - Q_m \qquad (3)$$

where U is the internal energy of snowpack and the upper frozen part of the soil ($kJ\ m^{-2}$), S_n is the net short wave solar radiation ($kJ\ m^{-2}\ d^{-1}$), L_a is the atmospheric long wave radiation ($kJ\ m^{-2}\ d^{-1}$), L_t is the terrestrial long wave radiation ($kJ\ m^{-2}\ d^{-1}$), H is the sensible heat exchange ($kJ\ m^{-2}\ d^{-1}$), E_l is the energy flux associated with the latent heat of vaporization and condensation at the snowpack surface ($kJ\ m^{-2}\ d^{-1}$), G is ground heat conduction to the snowpack ($kJ\ m^{-2}\ d^{-1}$), Q_p is heat advected by precipitation ($kJ\ m^{-2}\ d^{-1}$), and Q_m is the amount of heat removed by snowmelt ($kJ\ m^{-2}\ d^{-1}$).

The water balance of a snowpack is given by (Tarboton and Luce 1996, Zeinivand and De Smedt 2007):

$$\frac{dW}{dt} = P_r + P_s - E_s - M \tag{4}$$

where W is the snowpack's water equivalence (m), P_r is the precipitation as rainfall (m d^{-1}), P_s is the precipitation as snowfall (m d^{-1}), and E_s is the sublimation from the snowpack (m d^{-1}). When the internal energy of snowpack energy U is positive, heat becomes available for snowmelt. The heat required to melt all the snow is λW. Hence, when U is positive but smaller than λW, only part of the snow can melt i.e.

$$M = \frac{1}{\lambda}\frac{dU}{dt} \tag{5}$$

Where λ is the volumetric latent heat of fusion ($3.35\ 10^5$ kJ m^{-3}).

The routing of overland flow and channel flow is implemented by the method of the diffusive wave approximation of the St. Venant equation and a linear approximate solution to the diffusive wave equation in the form of a first passage time distribution is applied (Liu *et al.* 2003), relating the discharge at the end of a flow path to the available runoff at the start of the flow. Because, groundwater movement is much slower than the movement of water in the surface and near surface water system, and little is known about the bedrock, groundwater flow is simplified as a lumped linear reservoir for each GIS derived subcatchment. Considering the river damping effect for all flow components, 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. One advantage of this approach is that it allows the spatially distributed runoff and hydrological parameters of the basin to be used as inputs to the model, and all hydrological processes are simulated within a GIS framework; more details can be found in Liu (2005).

3. APPLICATION

3.1. Study area

The Hornad River is located in Slovakia and emerges in the Tatras Mountains. The drainage area is 4262 km^2 up to Zdana station. A multi purpose reservoir called Ruzin is located in the centre of the basin (Fig.1). Figure 1 shows the Hornad basin, the Ruzin reservoir with topography and location of precipitation stations indicated. The basin is mountainous with elevations ranging from 171 to 1945 m. The mean elevation is 580 m and the mean slope about 17.6%. A digital elevation model (DEM) of the basin was obtained from the Slovak Hydrometeorological Institute (SHMU), and converted to a 100 m grid size DEM. Land cover data were obtained from Landsat-7 Enhanced Thematic Mapper (ETM) satellite data, acquired on August 20th, 2000. The final land-use map for this study is composed of 5 different types of land cover: 51.8% of the basin is covered by forest, 22.7% by grassland and pasture, 22.5% by agriculture areas, 2.9% by urban area, and about 0.1% by water surfaces which are mainly reservoirs (Fig. 2). There are 10 different soil textures in the catchment. The dominant soil texture is loam, which covers about 43% of the basin, and sandy loam and silt loam about 27% and 17% respectively (Fig. 3). January is the coldest month and July is the warmest month of the year. The highest amount of precipitation occurs from May to August while in January and February there is usually only snow; more details can be found in Bahremand *et al.* (2005). The mean annual precipitation of the watershed based on 8 years data of 36 stations within it is 675 mm, ranging from about 560 mm in the valley to more than 1200 mm in the mountains. The mean temperature of the catchment is about 6.5˚C. The annual potential evapotranspiration based on 8 years observations by the Water Research Institute of Slovakia at Spisske Vlachy located in the catchment, is about 560 mm. All other data for this study were obtained from SHMU. The data set include, daily precipitation in 36 stations, temperature (minimum, mean and maximum) in 14 stations, and daily discharge data at 8 gauging stations. All data are available for an 8 year period from 1993 to 2000. Daily discharge data are available at 8 locations inside the catchment, but only the watershed outlet station at Zdana is used for model calibration.

3.2. Results and discussion

For the simulation of hydrographs at the basin outlet and at the flow monitoring stations inside the catchment, the basin was divided into 223 subcatchments, corresponding to the threshold value of 1000 cells when delineating the stream network based on topographic flow accumulation. The areas of the GIS derived subcatchments range from 0.02 to 122.51 km^2 with an average subcatchment area of 19.08 km^2.

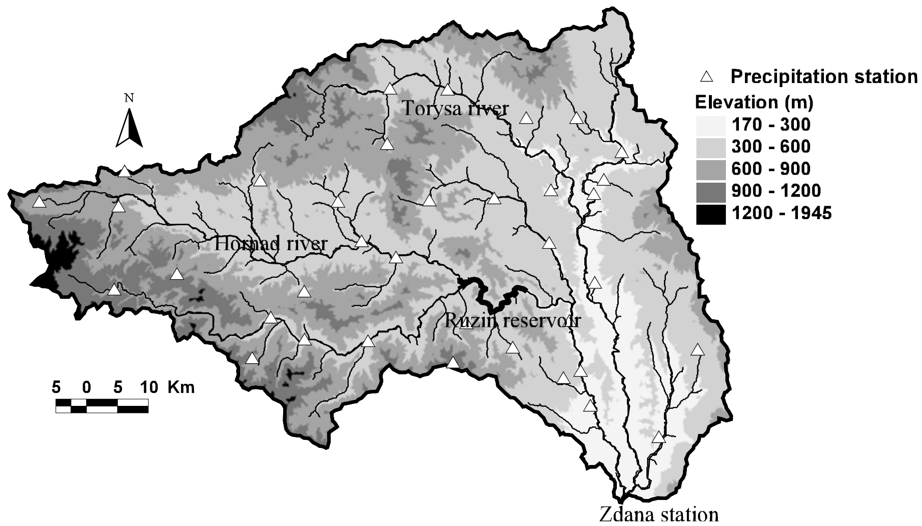

Figure 1. Detailed map of Hornad watershed upstream of Zdana station showing stream network, topography, location of precipitation stations, and Ruzin reservoir.

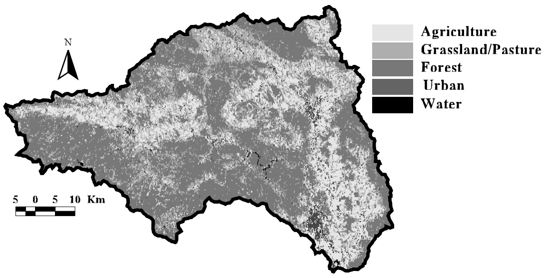

Figure 2. Landuse map of the Hornad watershed.

Figure 3. Soil map of the Hornad watershed.

The 8 years (1993–2000) measured daily precipitation, temperature (minimum, mean and maximum), PET, windspeed, and discharge data are used for model simulation. The calibration process is mainly performed for the global model parameters, whereas the spatial model parameters are kept as default values. The initial global model parameters are specifically chosen according to the basin characteristics as discussed in the documentation and user manual of the model (Liu and De Smedt 2004). The initial groundwater flow recession coefficient is estimated by analyzing the baseflow, which is separated from the observed hydrograph. Adjustment of this parameter is necessary in accordance with the fitting of baseflow and the total flow volume. The interflow scaling factor is adjusted for the peak and recession part of the flood hydrograph, which is sensitive for both high and low flows. The additional two parameters controlling the amount of surface runoff, i.e. the surface runoff exponent for a near zero rainfall intensity and the rainfall intensity corresponding to a surface runoff exponent of 1, are adjusted mainly for small storms, for which the actual runoff coefficients are small due to the low rainfall intensity. The initial soil moisture and active groundwater storage are adjusted by comparison of the hydrographs and water balance for the initial phase. The maximum active groundwater storage controls the amount of vapor transpirated from the groundwater, and therefore can be adjusted by comparison of the flow volume during dry periods (Bahremand *et al.* 2005). The calibrated values of global parameters are listed in Table 1.

Table 1. The model global parameters

Parameter	Value
Interflow scaling factor (-)	1.620
Initial soil moisture (mm)	0.970
Correction factor for PET (-)	1.025
Groundwater recession coefficient (d^{-1})	0.00015
Initial active groundwater storage (mm)	60.12
Maximum active groundwater storage (mm)	853.11
Moisture or surface runoff exponent (-)	2.712
Maximum rainfall intensity (m)	103.75

Every year snow accumulation starts around November and snowmelt occurs around April depending upon the air temperature. For discussion we select an interesting period with snowmelt and rainfall flood, which is from the beginning of November 1995 to May 1996. All relevant information for this period is given in Fig 4. The simulated snow accumulation and melt is shown in Fig. 4a. In the beginning of November '95 temperatures dropped below zero and only snowfall occurred until the end of March '96. During this period several moderate snow events occurred, and the snowpack gradually accumulated and built up to reach about 80 mm of water equivalent on average March '96. But on 15, 16 and 17 November '95 temperature became positive and around 10 mm of snow melted. From 15 March '96 onwards the temperature rose steadily above zero and the whole snowpack melted in about four weeks. In figure 4b the graphical comparison between observed and calculated daily flow is given for the same period at Zdana station. At the start of the simulation period the basin discharge was about 10 to 12 $m^3 s^{-1}$ which seems to be drained only from groundwater storage. From 16 to 21 November '95 there was a little bit rainfall and about 10 mm snowmelt which resulted in runoff of about 23 $m^3 s^{-1}$ on 18 November. From 21 November '95 onwards there was no considerable direct runoff and the basin discharge was only maintained by groundwater discharge. From 15 to 25 March '96 about 30 mm snow melted and as a consequence basin discharge increased from 12 $m^3 s^{-1}$ to between 40 and 50 $m^3 s^{-1}$. Then river discharge decreased to 25 $m^3 s^{-1}$ on 30 March because there was no heavy rainfall or any snowmelt. On 1st and 2nd April '96 there was a large storm with 12 and 4 mm d^{-1} respectively, while at the same time and around one week thereafter there was 50 mm snowmelt, which together led to a huge flood with a peak discharge of 100 $m^3 s^{-1}$ which last for almost one week. The peak discharge and shape of the flood wave is well simulated by the model as compared to the observed hydrograph.

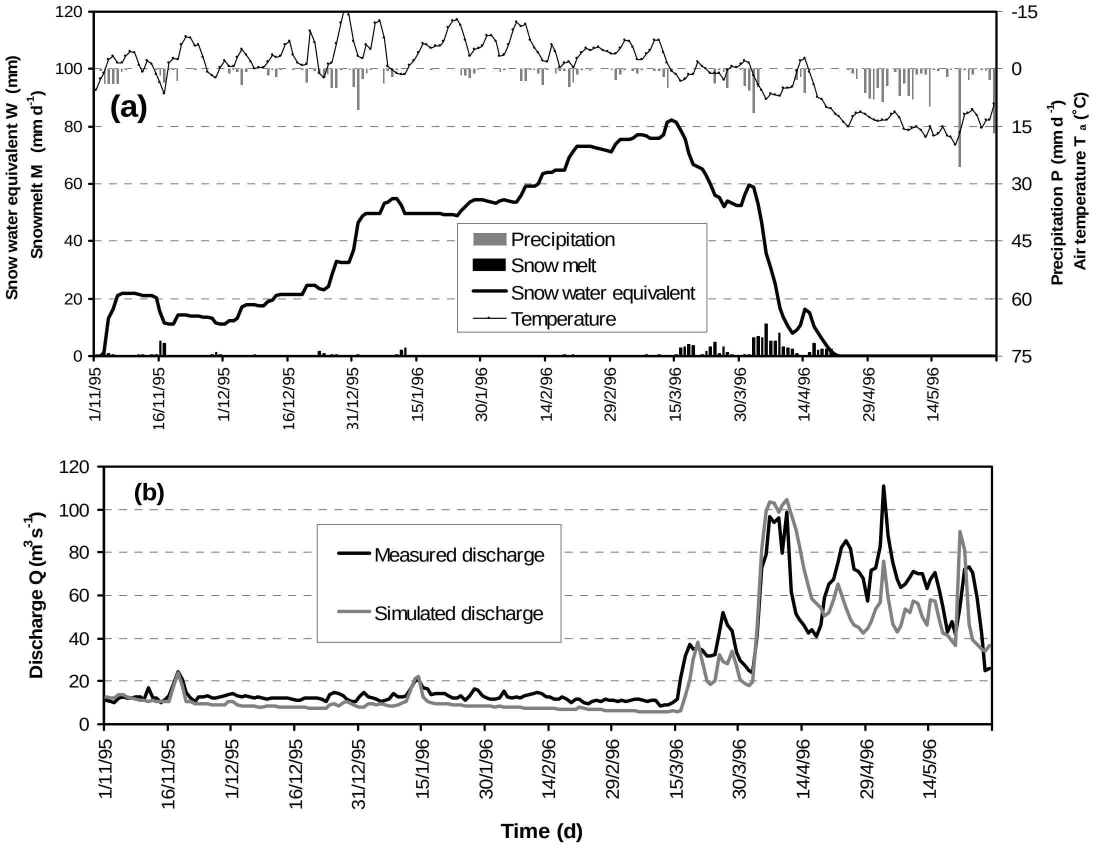

Figure 4. Daily average precipitation, temperature, snow layer water equivalent, and snowmelt (a) and graphical comparison between observed and simulated flow at Zdana between 1/11/1995 and 28/5/1996 of the simulation period (b).

At the second half of April and during May '96 all remaining snow melted and together with rainfall led to discharge of 40 to 80 $m^3 s^{-1}$. The simulation results of the model and prediction of runoff are quite accurate. It is sufficient to note that for the 8 years simulation period the Nash-Sutcliffe efficiency is 0.795, and the modified Nash-Sutcliffe efficiency is 0.841 and 0.726 respectively for high and low flows. This indicates that the model is able to consider precipitation, antecedent moisture and runoff-generating processes in a spatially realistic manner based on topography, land use and soil type, resulting in a fair accuracy for both high and low flows, and the general hydrological trends being well captured by the model. The model outputs also show that 8.03% of the precipitation is intercepted by the plant canopy, 82.21% infiltrates to the soil, 67.90% evapotranspirates to the atmosphere, 23.59% recharges to the groundwater reservoir, and 29.53% becomes runoff, of which direct flow, interflow, and groundwater flow contribute 16.9%, 8.29% and 74.80% respectively. These values are reasonable in view of the catchment hydrological characteristics.

4. SUMMARY AND CONCLUSION

In this paper a method for estimating flood runoff due to rainfall and snowmelt is presented using detailed basin characteristics together with meteorological data as an input. Discharge is attained as the sum of surface runoff, interflow and groundwater drainage. The surface runoff is calculated using a moisture-related modified rational method with a potential runoff coefficient depending on land cover, soil type, slope, the magnitude of rainfall, and antecedent soil moisture. Because a large part of the annual precipitation is in the form of snow, an energy balance approach is used to simulate snowmelt which involves mass and energy balance as well as heat and mass transport. Flows are routed through the basin along flow paths determined by the topography using a diffusive wave transfer model, while interflow and groundwater recharge are simulated using Darcy's law and the kinematic approximation. The model performance was tested by simulating runoff due to rainfall and snowmelt as well as snow accumulation and melt in the 4262 km^2 Hornad watershed, upstream of Zdana station, in the east part of the Tatras Mountains, Slovakia. The model is applied and calibrated with 8 years (1993 - 2000) of observed rainfall, air temperature, potential evaporation, and windspeed. Daily discharge data at Zdana gauging station was used for model calibration. The model calibration is performed manually for global parameters of the model only, whereas spatial model parameters (DEM, soil and land-use maps, and characteristics derived thereof) are fixed by default. The model efficiency turns out to be 74% (Nash-Sutcliffe efficiency). In order to show the performance of the model an interesting period with runoff resulted from rainfall and snowmelt as well snow accumulation was discussed in detail. Peak discharges and flood waves are well predicted by the model as compared to the observed hydrographs.

We conclude that the present model is useful to simulate runoff but can be improved provided more comprehensive datasets become available.

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