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Simulation of Water Balance Components Using a Distributed Hydrological Model in Taleghan Watershed

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Abstract

Information on water changes in the hydrological systems, in time and space, as an environmental issue is vital for managers and decision makers of the watersheds and river engineers. This information can be obtained using spatially distributed modeling. In this study, simulation of water balance components in Taleghan mountainous watershed is performed using the spatially distributed hydrological model, WetSpa. This area is located on south east of Alborz range in Iran with a mean annual precipitation of 591 mm, mean slope of 40.48%, and mean elevation of 2750 m. The model implementation is based on grids of 85 m pixel size and daily temporal resolution. Through application of the spatial parameters derived from three base digital maps and daily time series data as model inputs, peak discharges and flow hydrographs are predicted at any point of stream network and spatial distribution of water balance components and hydrologic characteristics are simulated. The simulated and observed hydrographs are compared using statistical and visual methods. The results revealed a very good agreement between simulated and observed data. Considering model outputs and accuracy of 83.5% based on the Nash-Sutcliffe efficiency criterion and the Aggregated Measure of 85.6%, performance of the model is assessed as very good, hence a good reproduction of stream flow and other hydrological processes. The model thus calibrated provides users with the ability of analyzing watershed hydrology response to land use/cover change.

***Keywords*:** Spatially distributed hydrologic model; WetSpa; Water balance components; Taleghan watershed

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1. Introduction

Simulation models can be helpful in qualitative understanding of hydrological processes, in guiding for management and decision-making as well as predicting/simulating (Letcher and Weidemann, 2004) under different input conditions, by extrapolating from current conditions to future conditions, short-term forecasting and so on. Difficulties in managing and efficiently using spatial information have prompted hydrologists either to abandon it in favor of lumped models or to develop more sophisticated technologies for managing geospatial data (Desconnets *et al.*, 1996). Various computer models have been developed to simulate processes such as flooding, soil erosion, evaporation, and desertification. Results of these models can provide important information for decision makers and planners, allowing better implementation of appropriate land management measures. For developing and choosing the model, it is very important to know the characteristics of the system which also dictates the required data density and frequency (van Waveren *et al.*, 1999). A distributed approach to modeling in the watershed consists of a grid representation of topography, precipitation, evapotranspiration, soils, and land use/cover that accounts for the variability of all these parameters. Lumping even at the sub-basin level may not be able to account for the change in slope and drainage network affecting the hydrologic response of the basin (Vieux, 2005). Large watersheds are characterized by a variety of topography, soil, land cover and geological factors and the variation of climate in time and space that will affect the rainfall-runoff processes. In such watersheds it is recommended to use a distributed hydrological model rather than a lumped model (Beven, 2000). A physically based distributed model has been developed for predicting the Water and Energy Transfer between Soil, Plants and Atmosphere, WetSpa at the basin scale (Wang *et al.*, 1997). This model is a simple grid-based distributed runoff and water balance simulation model. It predicts hourly or daily overland flow occurring at any point in a watershed, and provides spatially distributed hydrologic characteristics in the basin (Bahremand and De Smedt, 2010).

The aim of this study is simulation of water balance components in a certain period of time at watershed scale, and assessment of WetSpa model performance in the study area.

2. Materials and methods

2.1. WetSpa model description

WetSpa is a spatio-temporal distributed hydrologic and soil erosion model that predicts flooding, water balance components, and erosion and sediment transport. Not only the model is able to assess the effects of climate and land cover changes on hydrologic processes, but also can it be applied to the study of water quality and watershed management at the watershed, sub-watershed and grid cell scale on any time step e.g., hourly and daily. Rainfall is the fundamental driving force and main input behind most hydrological processes.

The simulated hydrological system consists of four control items: plant canopy cover, the soil surface, the root zone, and the saturated groundwater aquifer. Incident precipitation first encounters the plant canopy, which intercepts all or part until the interception storage capacity is fully reached. Excess rainfall, which reaches the soil surface, can be retained on the soil surface, infiltrate the soil zone, or is diverted as surface runoff (Liu and De Smedt, 2004; Zeinivand and De Smedt, 2009a). Different topography, land cover and soil properties in different grid cells of a watershed results in different amounts of excess runoff when subjected to the same amount of rainfall. The routing of runoff from different cells to the watershed outlet depends upon flow velocity and wave damping coefficient using the diffusive wave approximation method. The spatial variability of land covers, soil and topographic properties in a watershed are considered in the WetSpa model. The groundwater response is modeled on s0mall sub-watershed scale for the convenience of model parameterization and model simulation. Figure 1 gives schematic diagram of the WetSpa model on the cell scale.

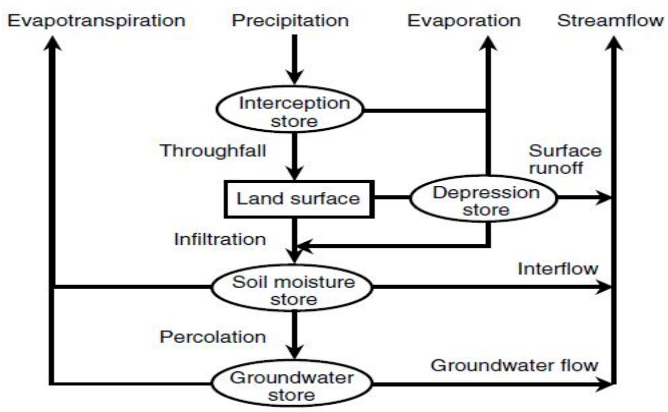

Figure 1. Schematic diagram of the WetSpa model on the cell scale (Liu *et al*., 2006)

Soil characteristics, canopy cover, and ground cover are isotropic and homogeneous, as well as precipitation for a single grid cell. WetSpa model runs with a continuous input data series. The greater the variability over the cell, the greater will be the error induced through the use of an average value. Thus, the grid size of the input maps should be well defined. The model employs some default parameters, which are interpolated from the literature and used over the entire watershed. The total water balance for each raster cell is composed of a separate water balance for the vegetated, bare soil, open water, and impervious part of each cell. For each grid cell, the root zone water balance is modeled continuously by equating inputs and outputs (Bahremand *et al.*, 2007):

$$D \Delta\theta / \Delta t = P - I - S - E - PE - IR \quad (1)$$

where D [mm] is the root depth, $\Delta\theta$ [m³/m³] is the change in soil moisture, Δt [d] is the time interval, P [mm/d] is the precipitation, I [mm/d] is the initial abstraction including interception and depression losses within time step Δt, S [mm/d] is the surface runoff or rainfall excess, E [mm/d] is the actual evapotranspiration from the soil, PE [mm/d] is the percolation out of the root zone, and IR [mm/d] is the amount of interflow in depth over time.

A modified coefficient method for estimating surface runoff and infiltration processes is used for runoff and infiltration with topography, soil type, land use, soil moisture, and rainfall intensity. The equations can be expressed as (Liu, 2004; Zeinivand and De Smedt, 2009b):

$$S = C(P - I + M)\left(\frac{\theta}{\theta_s}\right)^{\alpha} \quad (2)$$

$$F = P - I - S \quad (3)$$

where S [mm] is the surface runoff, C [-] is the potential runoff coefficient, I [mm] is the initial loss due to interception and depression storage including accumulation of snow, M [mm] is the rate of snowmelt, θ is the cell soil moisture content [m³/m³], and θ_s [m³/m³] is the soil porosity. There is a lookup table for values of C, linking values to slope, soil type, and land use classes. The exponent α [-] in the formula is a parameter reflecting the effect of rainfall intensity on the surface runoff. In equation 3, F is the infiltration [mm].

In the model, the snowmelt volume adds to the net precipitation that will reach the soil surface. The total snowmelt is calculated using a degree-day method. Evapotranspiration from soil and vegetation is calculated based on the relationship developed by Thornthwaite and Mather (1955) as a function of potential evapotranspiration, vegetation type, stage of growth and soil moisture content. The percolation out of the root zone is equated as the hydraulic conductivity corresponding to the moisture content which itself is a function of the soil pore size distribution index (Eagleson, 1978). Darcy's law and a kinematic wave approximation are used to estimate the amount of interflow generated from each cell, based on hydraulic conductivity function, the moisture content, slope angle, and the root depth. At the end of each sub-watershed the groundwater flow is added to the simulated runoff. The routing of overland flow and channel flow is implemented by the diffusive wave approximation equation of the St. Venant (Bahremand *et al*., 2007).

2.1.1. Model parameters

There are two types of parameters in WetSpa, i.e., spatially varying model parameters and globally fixed model parameters (Safari *et al*., 2009). The spatially varying model parameters also include two types: directly derived parameters of the three base maps and combination-induced parameters of three base maps. Global model parameters cannot be directly appraised and need to be adjusted using available observed discharge to parameters optimization and model goodness of fit. Table 1 shows global parameters of WetSpa model.

Table 1. Global parameters of WetSpa model

No	Symbol	Parameter and unit
1	K_i	Interflow scaling factor [-]
2	K_g	Groundwater recession coefficient [d^{-1}]
3	K_{ss}	Initial soil moisture [mm]
4	K_{ep}	Correction factor for PET [-]
5	G_0	Initial active groundwater storage [mm]
6	G_{max}	Maximum active groundwater storage [mm]
7	K_{run}	Moisture or surface runoff exponent [-]
8	P_{max}	Maximum rainfall intensity [m]
9	T_0	Threshold melt temperature [^oc]
10	K_{snow}	Melt-rate factor [m d^{-1} $^oc^{-1}$]
11	K_{rain}	Rainfall melt-rate factor [$^oc^{-1}d^{-1}$]

2.2. Case study

In order to simulate water balance components, runoff and river hydrograph using a more accurate and efficient approach, the distributed hydrological WetSpa model was applied in the Taleghan watershed. This approximately 809 km^2 watershed is one of the important sub-basins of Sefid-Rud river basin located on the south east of Alborz range in Iran with mean annual precipitation and temperature 591 mm and 4.48 ^{oC}, respectively. The study area is a mountainous watershed with a mean slope of 40.5% and mean elevation of 2750 m above sea level. The main river (Taleghan-Rud) length is 53 km and the drainage network ends at Galinak station. Figure 2 gives the location of the Taleghan watershed, gauging stations and stream networks and the digital elevation model of the area.

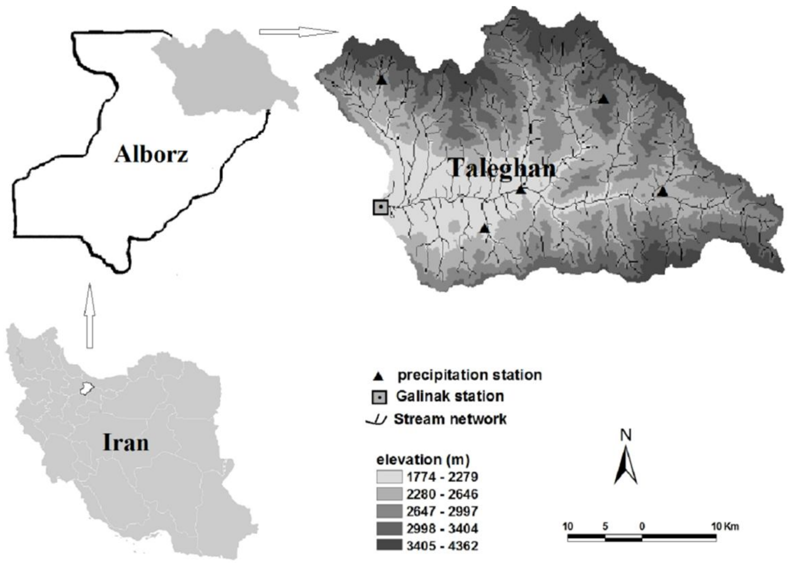

Figure 2. The location of Taleghan watershed, gauging stations and stream networks

2.3. Model inputs

2.3.1. Digital data

The watershed digital elevation model and land cover maps (derived from 1:20000 and 1:40000 remotely-sensed satellite images of Landsat TM and ETM^+ in 1987 and 2001) were obtained from SCWMRI of Iran. The watershed's six-category land cover map was prepared in raster format with 85 m pixel size and comprised water body (0.014%), deciduous broad leaf forest (0.41%), natural vegetation (1.6%), cropland (1.7%), open shrubland (88.54%) and urban and built-up (7.74%). Soil type map was prepared considering soil texture test reports performed in Taleghan watershed in GIS. The dominant soil type is sandy loam (50.1%), and loam and clay loam cover about 18.2% and 12.7% of the watershed area, respectively. Figures 3 and 4 depict land cover-use and soil type maps of Taleghan watershed.

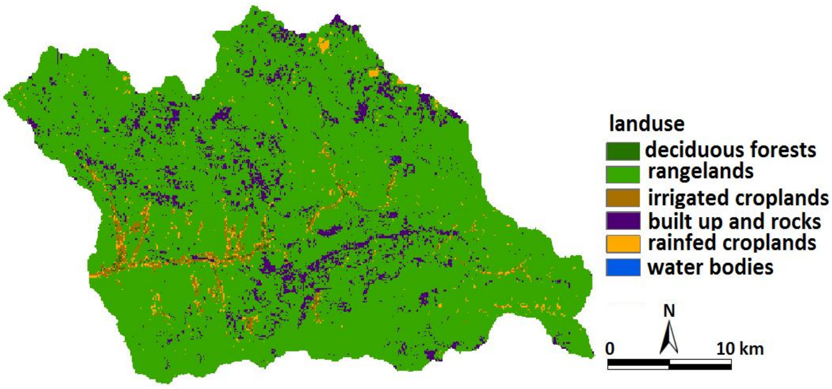

Figure 3. Land cover-use map of Taleghan watershed

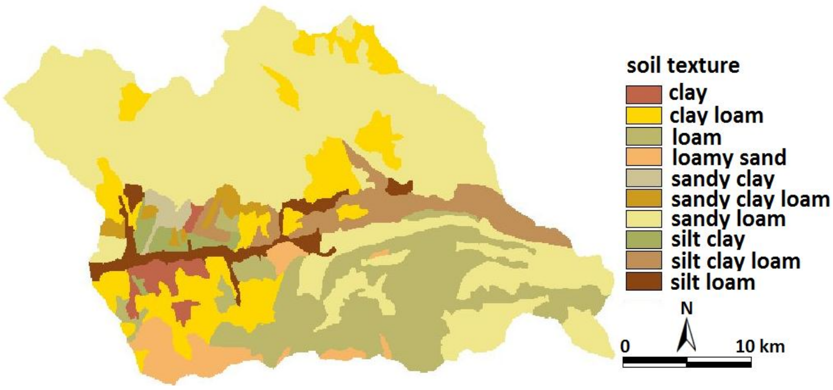

Figure 3. Soil type map of Taleghan watershed

2.3.2. Hydro-meteorological data

The basic necessary meteorological data are rainfall and PET. Temperature data is optional and used for simulation of snowmelt. The areal rainfall, evaporation and temperature during model simulation are interpolated using the Thiessen polygon method. Hydro-meteorological data, as the main model inputs obtained from the Iran Water Resources Research, included 8 years (1996-2003) of daily precipitation in 9 stations, evaporation and air temperature in 3 stations, and daily discharge data at watershed outlet, namely Galinak station.

2.4. Model simulation

After processing data for application in the WetSpa modeling platform, the model program was set up to extract spatial model parameters. Terrain features at each grid cell including elevation, flow direction, flow accumulation, stream network, stream link, stream order, slope, and hydraulic radius were extracted from the DEM. The stream network was extracted from the raster DEM using a threshold cell value of 10, which ensures that a channel is detected when the drainage area is greater than 7.2 ha. The threshold value for determining sub-watersheds was set at 500, by which 116 sub-watersheds were identified. When deriving the grid of surface slope, a threshold value of minimum slope 0.01% was considered; if the calculated slope is less than the threshold value, the slope was set at 0.01% to avoid stagnant water or extreme low velocities. The grid of hydraulic radius was generated with an exceeding frequency of 2-year return period, for which the network constant and the geometry scaling exponent were set at 0.05 and 0.48, resulting in an average hydraulic radius of 0.005 m for the upland cells and 1.24 m at the outlet of the main channel. The grids of root depth, interception storage capacity, and Manning's roughness coefficient n, were reclassified from the land use grid (Liu and De Smedt, 2004). Similarly, the grids of soil hydraulic conductivity, porosity, field capacity, residual moisture, pore size distribution index, and plant wilting point were reclassified based on the soil texture grid by means of an attribute lookup table. The grids of potential runoff coefficient and depression storage capacity were obtained by means of attribute tables combining the grids of elevation, soil and land use (Bahremand and De Smedt, 2008). Finally, the grids of routing parameters, flow velocity, travel time to the basin and sub-basin outlet, as well as the standard deviation were generated which enabled us to calculate the IUH from each grid cell to the basin outlet. The calculated mean potential runoff coefficient is 0.68 for the entire catchment. The calculated flow time for the most remote area was around 24 hours.

3. Results and discussion

Calibration procedure is necessary to make model behavior as close to the system behavior as possible, thus upgrading the model performance. In order to determine whether or not a manually calibrated model is 'good', it must be validated (van Waveren *et al*., 1999). Some of the model parameters as scalar values in the WetSpa model included global model parameters. 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). These parameters are calibrated using manual and automated procedures during model calibration. In this research, manual calibration of the model was carried out considering stream flow observations for the period September 1996 to September 2000 and validation for the period October 2000 to October 2003.

Usually, continuous simulation models require a long warm-up period to neutralize the effect of initial conditions in the catchment. However, in the WetSpa there are two global model parameters, i.e., initial soil moisture distribution factor and initial groundwater storage that enable estimation of the initial conditions at the beginning of the simulation period. Hence, there are two options to run the model: (1) use a warm-up period and default values for these two parameters, or (2) no warm-up period but calibrate these parameters. The second option was selected to have longer time series for model calibration and validation (Zeinivand and De Smedt, 2009b). More details of the procedure on calibration of the WetSpa global parameters can be found in Liu and De Smedt (2004), Liu *et al.* (2006), Bahremand *et al*. (2007), Zeinivand and De Smedt (2009a) and Safari *et al.* (2009).

Evaluation of model performances for calibration and validation were carried out through visual and comparisons of statistics and the scatter plot for daily stream flow observations versus those acquired through simulations.

Figures 5 and 6 give a graphical comparison between observed and simulated daily flows at Galinak guaging station, the watershed outlet, for the calibration and validation period respectively. The mentioned comparisons reveal that the model is capable of simulating stream flows very well.

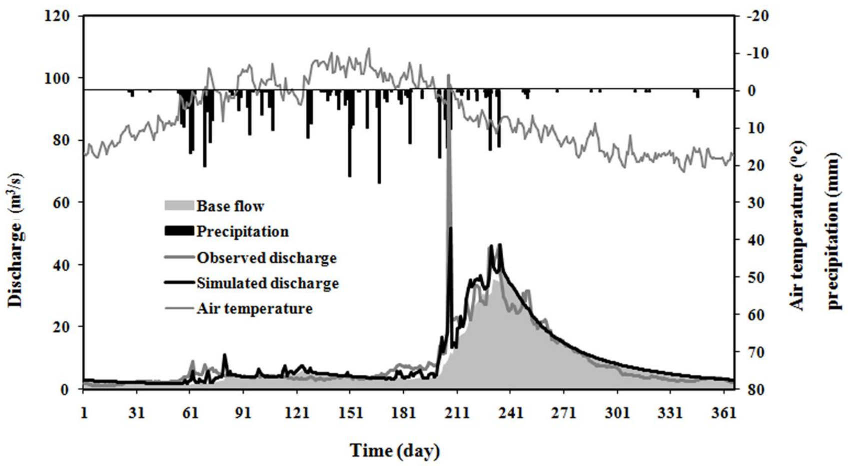

Figure 5. Graphical comparison between observed and calculated daily flow at Galinak for September 1999 to September 2000

Due to snowfall in autumn and winter 1999, at the begining of hydrograph when there is no high measured peak flows, the model simulated no high runoff generation. In other words, the model was able to simulate snow accumulation very well according to below zero temperatures. In March and April, snowmelt and rainfall occurred and resulted in generation of more surface runoff and streamflow. Indeed, flow volume shows an increase due to snowmelting, antecedant soil moisture, and reduction of canopy cover at this time. The figures also present the model's prediction of baseflow. It can be seen that the main part of the flow volume come from baseflow.

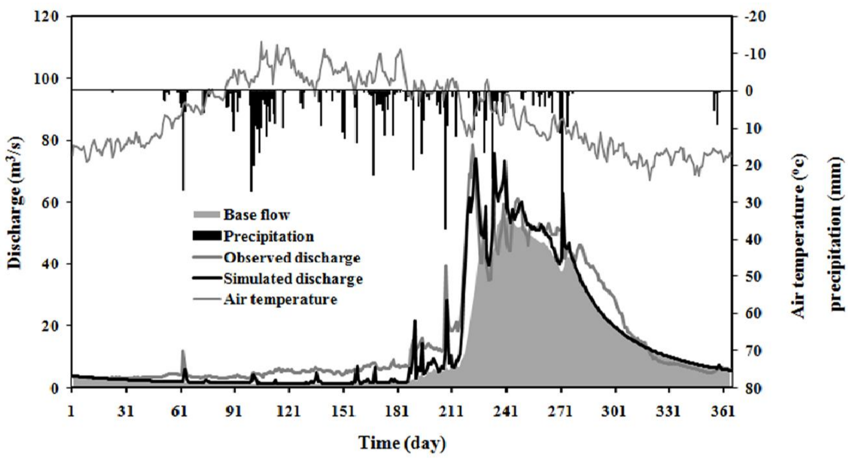

Figure 6. Graphical comparison between observed and calculated daily flow at Galinak from September 2002 to September 2003

Figures 7a and 7b show the scatter plots of observed and simulated discharges for both calibration and validation periods within 95% confidence limits.

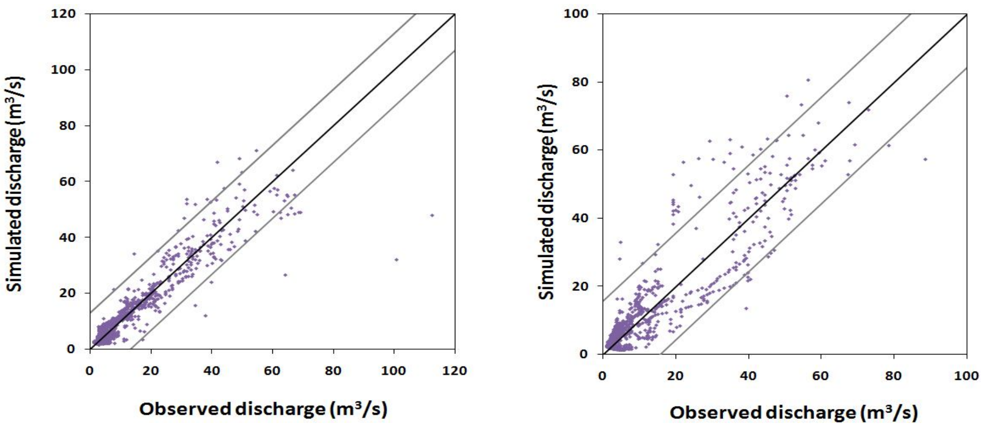

Figure 7. Scatter plots of the observed *vs.* simulated discharges within 95% confidence limits for calibration (a) and validation (b) periods

In general, trade-offs exist between different criteria used for calibration. For instance, one may find a set of parameters that provide a very good simulation of peak flows but a poor simulation of low flows, and vice versa. Hence, in order to obtain a successful calibration, it is necessary to formulate performance measures in a multi-objective framework (Shafii and De Smedt, 2009). Simulation results for calibration period from 1996 to 2000 show the flow volume is under-estimated by 1.4%. The Nash-Sutcliffe criterion (Nash and Sutcliffe, 1970) is 83.5% and the modified Nash-Sutcliffe efficiency for low and high flows (Hoffmann *et al*., 2004) is 79.2%, 81.3% respectively. The results of the selected simulation period from September 2000 to September 2003 for model validation are remarkable as the calibration results. The flow volume is over-estimated by 5.7%, the Nash-Sutcliffe criterion is 77% and modified Nash-Sutcliffe efficiency for low and high flows is 63.8%, 84.1% respectively. To evaluate the goodness of the model performance during calibration and validation periods, the following Aggregated Measure (AM) was adopted from Anderson *et al*. (2002); Henriksen *et al*. (2003); and Safari *et al*. (2009) that measures different aspects of the simulated hydrograph such as shape, size and volume. A value of 1 for AM represents a perfect fit. The Aggregated Measure for both calibration and validation periods is respectively 0.856 and 0.834. Based on this measure, the model performance is judged to be very good.

Water balance at the watershed scale is used to keep track of water changes in the hydrological system and as a measure of model performance by comparing the simulation results with observations. The model outputs during the five years simulation period shows that 5.33% of the precipitation is intercepted by the plant canopy, 34.78% evapotranspirates, and 73.55% becomes runoff, of which 7.27%, 6.63% and 59.65% contributes to direct flow, interflow, and groundwater flow, respectively. Other hydrologic components such as infiltration and percolation are given in Table 2. The table shows calculated water balance components during the simulation period (1996-2000).

Table 2. Calculated water balance during the simulation period (1996-2000)

Water balance component*(mm)	P	I	SD	F	E	PERC	SR	IR	GR	R	GD
Sum	2100.8	112	-87.1	1816.6	730.6	1179.6	152.7	139.2	1253.1	1545	-87.7
% of P	--	5.33	-4.15	86.48	34.78	56.15	7.27	6.63	59.65	73.55	-4.18
Mean	1.44	0.07	154.02	1.24	0.49	0.80	0.10	0.09	0.86	1.06	129.2
Max	35.91	1.84	217.10	24.30	2.28	11.95	4.11	1.60	4.29	7.09	295.92

*P: total precipitation; I: total interception; SD: soil moisture difference; F: total infiltration; E: total evapotranspiration; PERC: total percolation; SR: total surface runoff; IR: total interflow; GR: total groundwater flow; R: total runoff; GD: groundwater storage difference.

These values are reasonable in view of the watershed hydrological characteristics. Estimation of 73.5% runoff compared to 74.9% observed runoff indicates model efficiency and capability of simulation of watershed runoff and the other water balance components.

4. Conclusion

In this study, an application of a spatially distributed approach was presented to calculate surface runoff, interflow, ground water recharge and the other water balance variables. The model was applied and tested on Taleghan mountainous watershed in Iran. For evaluating model performance we referred to two criteria, Nash-Sutcliffe coefficient and Aggregated Measure. The Nash-Sutcliffe criterion as the objective function for the five year calibration period and for low and high flows pointed out the efficiency of model simulation. The classified performance according to the Aggregated Measure was found to be very good. Also, the validation results were very good. Estimation of runoff volume compared with observed runoff indicates model efficiency and capability of simulation of watershed runoff and the other water balance components. WetSpa requires few parameters for calibration that is an advantage particularly for manual calibration. Regarding the results and possibility of taking spatial and temporal variability of terrain characteristics, and hydrological processes into account, model potential is proven for investigating the effects of land cover and soil cover changes on the hydrological response of river basin. This study exemplifies the high performance of spatially distributed hydrologic WetSpa model, to simulate runoff at watershed outlet and the other water balance variables.

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