African Journal of Agricultural Research Vol. 6(25), pp. 5591-5599, 5 November, 2011
Available online at http://www.academicjournals.org/AJAR
ISSN 1991-637X ©2011 Academic Journals

Full Length Research Paper

Water balance of Gorganrood river basin East of Iran

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Accepted 9 August, 2011

Recent development of geographic information system (GIS) and remote sensing technology makes it possible to capture and manage a vast amount of spatially distributed hydrological parameters and variables. In this paper, a spatially distributed hydrologic model (WetSpa) is used to estimate daily river flow discharge and to analyze water balance of the Gorganrood river basin, Iran. The model combines topography, landuse and soil maps to predict discharge hydrographs and spatial distribution of hydrological parameters. For each grid cell the model holds water balance in the root zone by determination of soil moisture changes due to continues changes in infiltration of precipitation, runoff, initial absorption, evaporation transpiration, interflow, and percolation to the groundwater zone. The model gives all flow components at any cell, including surface flow, interflow and groundwater flow. The results show that the model is capable in reproducing water balance and its components. They also demonstrate the changes in the water balance during last two decades.

Key words: Water balance, distributed hydrological model, WetSpa, Gorganrood.

INTRODUCTION

Hydrological modelling provides a strong tool to investigate the impacts of climate and landuse changes on water balance and hydrological processes. Distributed hydrological models allow for detailed description of the hydrological and energy cycle and provide opportunities for dealing with forcing variables that fluctuate strongly in space and time, such as precipitation. Hydrologists increasingly implement these models as a means to apply the state of knowledge on basins of interest, and provide valuable information regarding hydrological state variables and potentially important distributed information on existing and future streamflow conditions. Geographic information system (GIS) provides representations of these spatial features of the earth, while hydrological modelling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment. With GIS-based distributed hydrological model one can simulate and determine the rate of different hydrological processes such as interception, depression storage, snow melt, runoff, infiltration, water balance, and flow and its components that is, surface flow, interflow and groundwater flow. The WetSpa model used in this study is a simple gridbased distributed runoff and water balance simulation model that runs on an hourly or daily time step. It predicts hourly/daily 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 (Kabir et al., 2011). The main inputs to the model are: precipitation, PET, discharge series and 90 m GIS grid maps of elevation, land use and soil. The model was originally developed by Wang et al. (1996) and adopted for flood prediction by De Smedt et al. (2000) and Liu and De Smedt (2004). It has been applied in tropical environments by Liu et al. (2005), for analyzing the effects of climate changes on stream flow by Gebremeskel et al. (2003, 2005) and for flow simulation in mountainous area of central Europe and simulation of reforestration impacts on flood by Bahremand et al. (2005, 2006, 2007), and for prediction of phosphorous transport by Liu 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. This paper presents the application of the WetSpa model which is a spatially distributed hydrological model to Gorganrood basin for a long daily simulation period and gives changes in water balance and its different

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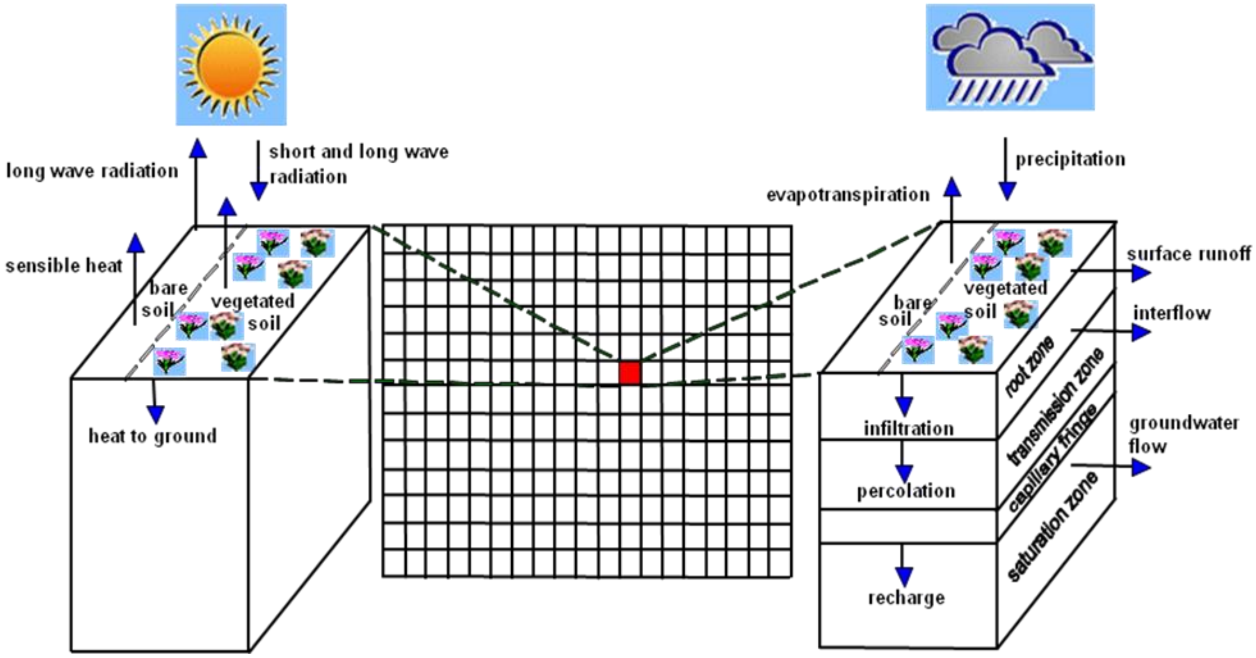

Figure 1. WetSpa model structure.

components yearly. The research is still continuing to find out any relationship between the climate change and the observed variation in water balance.

MATERIALS AND METHODS

The WetSpa model

WetSpa is a physically based and distributed hydrological model for predicting the Water and Energy Transfer between Soil, Plants and Atmosphere on regional or basin scale and daily time step developed in the Vrije University Brussel, Belgium (Wang et al., 1997; Batelaan et al., 1996). For each grid cell, four layers are considered in the vertical direction: a canopy layer, the root zone, a transmission zone and the groundwater reservoir. The hydrological processes considered in the model are precipitation, interception, depression storage, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow, and water balance in each layer. Figure 1 shows schematically the considered hydrological processes. 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. This allows accounting for the non-uniformity of the land use per cell, which is dependent on the resolution of the grid. For each grid cell, the root zone water balance is modeled continuously by equating inputs and outputs:

$$D\Delta\theta/\Delta t = P - I - V - E - R - F \qquad (1)$$

where D [L] is the root depth, Δθ [L^3L^{-3}] is the change in soil moisture, Δt [T] is the time interval, I [LT^{-1}] is the initial abstraction including interception and depression losses within time step Δt, V [LT^{-1}] is the rate of surface runoff or rainfall excess, E [LT^{-1}] is the actual evapotranspiration from the soil, R [LT^{-1}] is the percolation out of the root zone, and F [LT^{-1}] is the amount of interflow in depth over time. The rainfall excess is calculated using a moisture-related modified rational method with potential runoff coefficients depending on land cover, soil type, slope, the magnitude of rainfall, and the antecedent soil moisture. For the surface layer, actual evapotranspiration is computed as an area-weighted mean of the land use percentage. Also a portion is transpirated from the groundwater water as a function of the groundwater storage. Percolation and interflow are assumed to be gravity driven. The percolation out of the root zone is equated as the hydraulic conductivity as a function of the soil moisture. Interflow is assumed to occur in the root zone after percolation when the soil moisture is higher than field capacity. Darcy's law and a kinematic wave approximation are used to estimate 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 of the St. Venant equation:

$$\frac{\partial Q}{\partial t} = d\frac{\partial^2 Q}{\partial x^2} - c\frac{\partial Q}{\partial x} \qquad (2)$$

where Q [L^3T^{-1}] 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, which expresses the tendency of the disturbance to disperse longitudinally as it travels downstream. Assuming that 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 $d=(vH)/(2S_0)$, where v [L/T^{-1}] is the flow velocity calculated by the Manning equation, and H [L] is the hydraulic radius or average flow depth.

A linear approximate solution to the diffusive wave equation in the form of a first passage time distribution is applied, relating

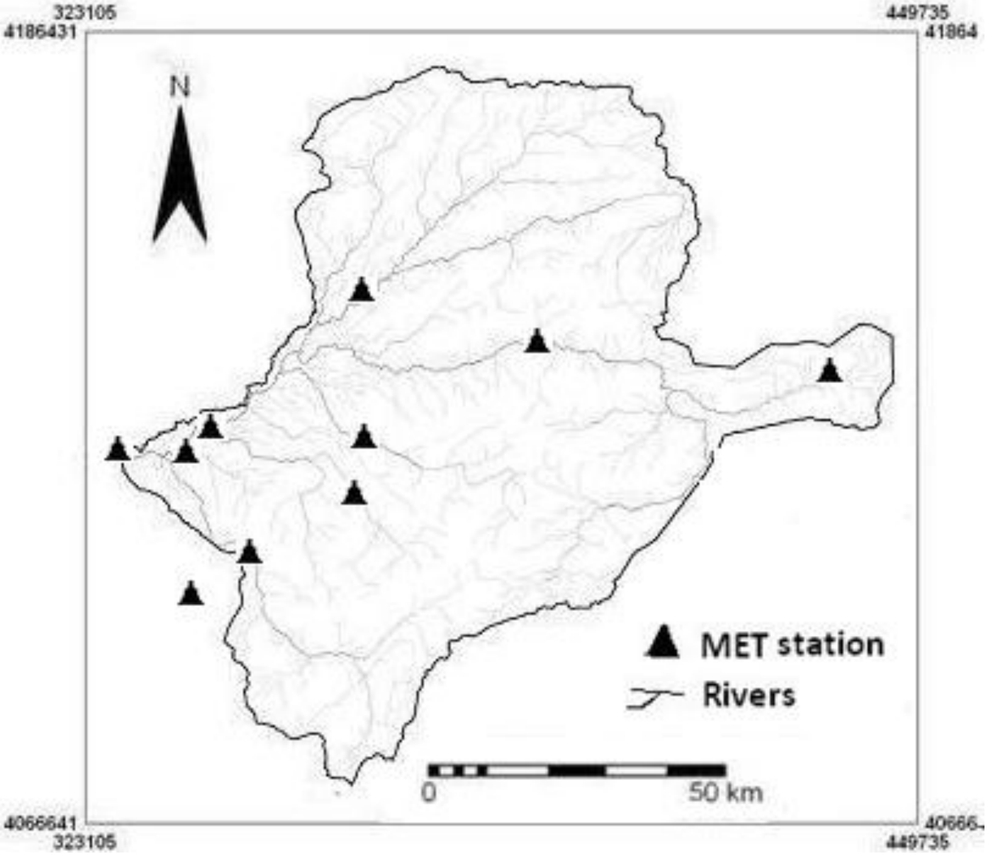

Figure 2. Gorganrood basin, with main rivers and location of stations.

the discharge at the end of a flow path to the available runoff at the start of the flow:

$$U(t) = \frac{1}{\sigma\sqrt{2\pi t^3 / t_0^3}} \exp\left[-\frac{(t-t_0)^2}{2\sigma^2 t / t_0}\right] \quad (3)$$

Where U(t) [T^{-1}] is the flow path unit response function, serving as an instantaneous unit hydrograph that makes it possible to route water surplus from any grid cell to the basin outlet or any downstream convergent point, and t_0 [T] and σ [T] are the mean and the standard deviation of the flow time. Parameters t_0 and σ are spatially distributed and can be obtained by integration along the topographic determined flow paths as a function of flow celerity and dispersion coefficient:

$$t_o = \int \frac{1}{c} dx \, , \quad \sigma = \sqrt{\int \frac{2d}{c^3} dx} \quad (4)$$

Because groundwater movement is much slower than the movement of surface water, groundwater flow is simplified as a lumped linear reservoir for each 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. Since, a large part of the annual precipitation is in the form of snow, the conceptual temperature index or degree-day method is used to simulate snow melt.

Model application

The rivers that flow to the Caspian Sea through the Iranian coast have a drainage basin of 135,000 km^2, most of which is located on the northern flank of the Alborz Mountain chain. Around 130 rivers flow into the Caspian Sea through the northern, southern and western coasts. Gorganrood on the East coast is a river that cut through Alborz and drains the Copet-Daq mountain range and ends at the Caspian sea. The watershed has an area of 6717 km^2 upstream the Voshmgir dam. The Gorganrood basin is a large catchment, with elevation ranging from 21 to 2837 m. The mean elevation of the catchment is 922 m; the mean slope of the catchment is about 18.23%. The digital maps of topography, land use and soil type are the 3 base maps used in the model. The DEM for the river basin was 90 m grid size DEM, from which the drainage system and area were determined. All GIS data is raster based with a 90 m grid size. Figure 2 shows the Gorganrood basin; topography, flow stations and Figures 3, 4a and b shows the topographic elevation map of the Gorganrood catchment, the spatial distribution of the different land uses, and the soil texture. The basic meteorological data requirements are rainfall and evaporation (PET).For this study, the daily precipitation, temperature, PET and discharge data are obtained from the relevant authorities. The sets include daily precipitation for 10 stations, temperature for 3 stations and PET for 5 stations, and discharge data at outlet from 1983 to 1995. The precipitation in a given raster cell is obtained from the precipitation

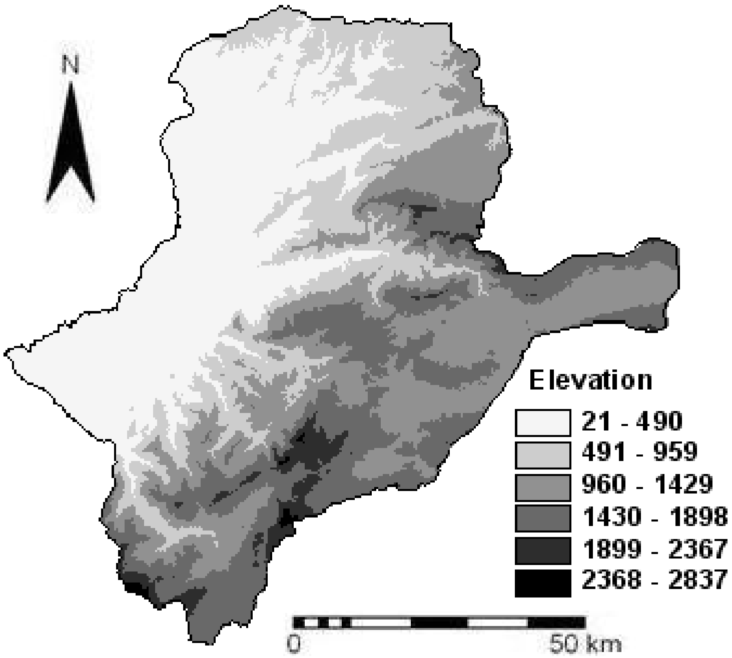

Figure 3. Topographical map of the Gorganrood basin and meteorological (MET) stations.

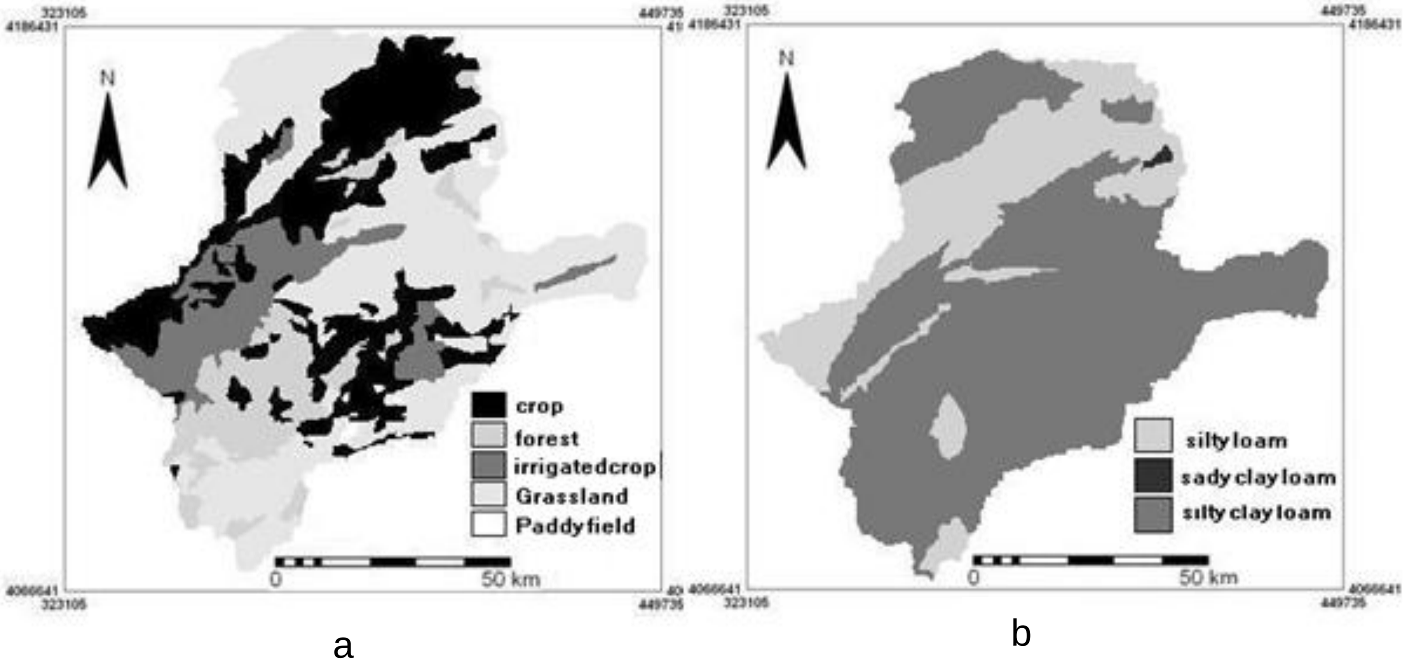

Figure 4. (a) Land use map of the Gorganrood basin, (b) soil texture map of the Gorganrood basin.

of the representative weather station and is corrected for the altitude of that cell within its Thiessen polygon with the use of elevation data from the DEM. The same procedures are applied for the temperature and PET for each raster cell. Model simulation starts with the derivation of the spatially distributed model parameters from DEM, landuse and soil map. The input parameters adjusted were scaling factor for interflow computation (Ki), groundwater recession coefficient (Kg), initial groundwater storage (G_0), temperature degree-day coefficient (K_snow), rainfall degree-day coefficient (K_rain), surface runoff exponent for a near

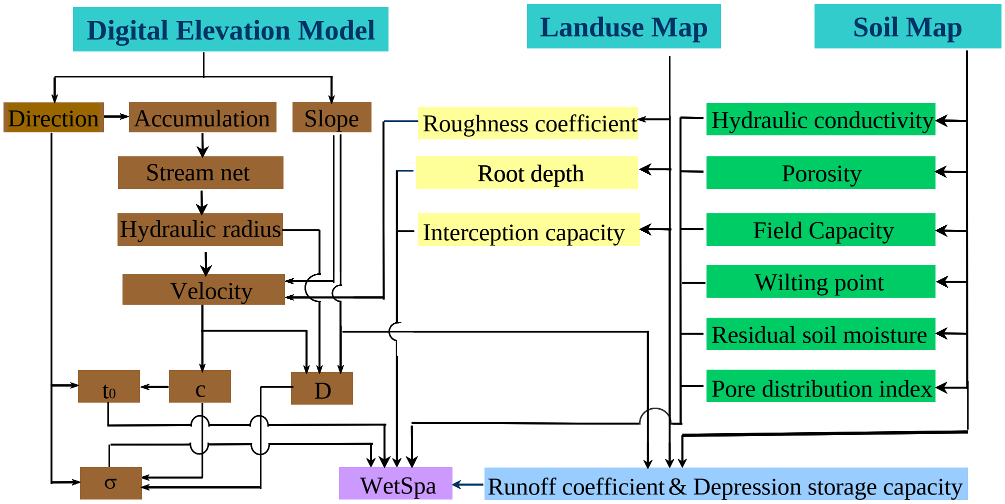

Figure 5. Model parameter derivation.

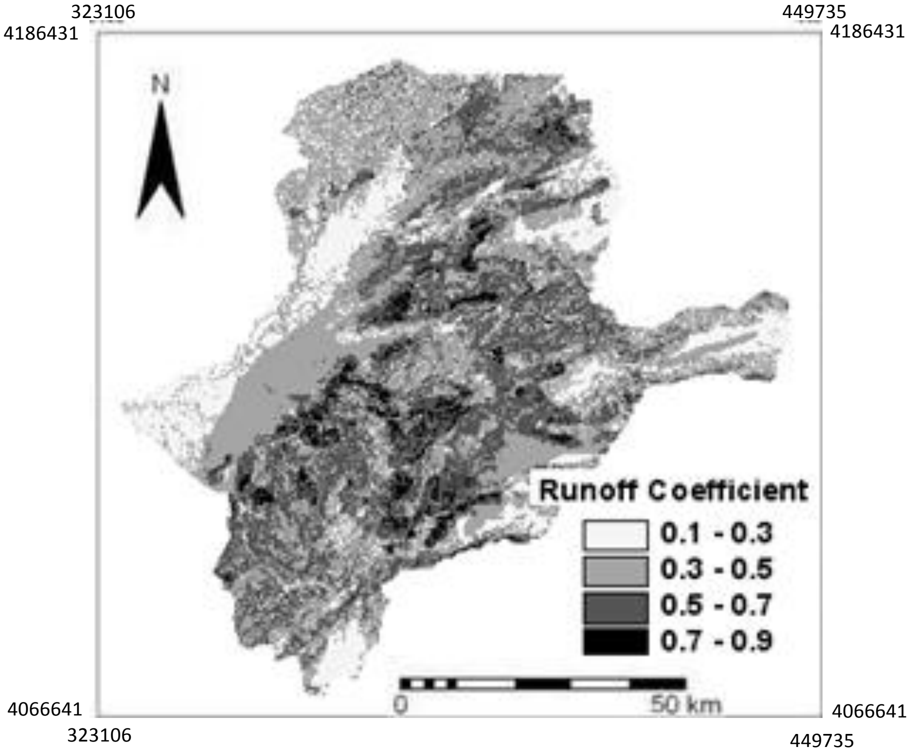

Figure 6. Potential runoff coefficient map of the Gorganrood basin.

zero rainfall intensity (K_run), rainfall intensity corresponding to a surface runoff exponent of 1 (P_max), correction factor for potential evapotranspiration (K_ep). After the adjustment of the input global model parameters and running the model, the post-processing capabilities of WetSpa (listings, plots, statistics, etc.) were used extensively to evaluate the calibration/verification effort. More than 20 parameters are spatially determined and stored as ASCII files to be used later by the model FORTRAN code. Figure 5 shows model parameter derivation. Figures 6 and 7 shows two derived parameter maps, which are important for model simulation, that is, potential runoff coefficient and flow travel time maps.

RESULTS

Model calibration for the study catchment was performed for the time period from 1983 to 1989, while the period

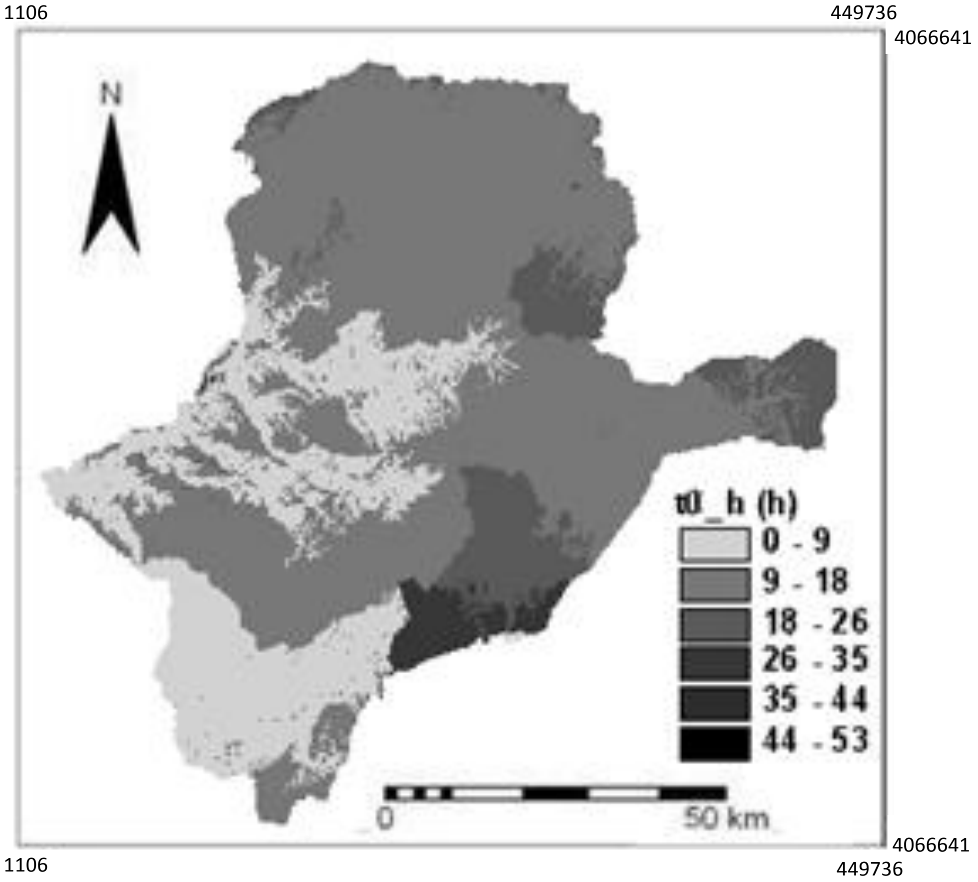

Figure 7. Flow travel time of the Gorganrood basin.

from 1990 to 1995 was used for model validation. Both the visual and statistical comparisons for the observed and simulated flow hydrographs at Gorganrood station were done for the calibration and validation periods. Calibration of the WetSpa extension was a cyclical process of making parameter changes, running the model, producing the comparisons of simulated and observed values, and interpreting the results. The calibration process was performed mainly for the global parameters including interflow scaling factor, baseflow recession coefficient, evapotranspiration coefficient, initial soil moisture and groundwater storage, as well as the surface runoff exponent as listed in the input file of the model. Other spatially distributed model parameters were assumed to be reasonable and remained as they are. Figure 8 give a graphical comparison between observed and calculated daily flow at Gorganrood for the years 1988 of calibration period and Figure 9 shows the year 1995 of validation period. It can be found that the calculated hydrograph is generally in a good agreement compared with the observed hydrograph for both calibration and validation periods. Simulation results are obtained for other hydrological years and the model performance is found to be satisfactory. Model bias to reproduce water balance for the simulation period is within the range of -0.07 to 0.035. The flow efficiency coefficient is within the range of 71 to 76% based on Nash-Sutcliffe criterion and the correlation coefficient is about 0.86. These evaluation results indicate that the model has a high confidence and can give a fair representation of flow hydrographs for the study catchment. The model outputs also show that 6.22% of the precipitation is intercepted by the plant canopy, 90.19% infiltrates to the soil, 84.41% evapotranspirates to the atmosphere, 12.43% recharges to the groundwater reservoir, and 15.83% becomes runoff, of which surface flow, interflow, and groundwater flow contribute 2.71, 1.15 and 11.97% respectively. Moreover, these values are reasonable in view of the catchment hydrological characteristics.

Table 1 gives the detailed yearly variations of water balance and its components in millimeter. The flow (R) consists of surface runoff (RS), interflow (RI) and groundwater flow (RG) all presented in mm. Figure 10 shows the different components of the calculated flow in comparison with rainfall.

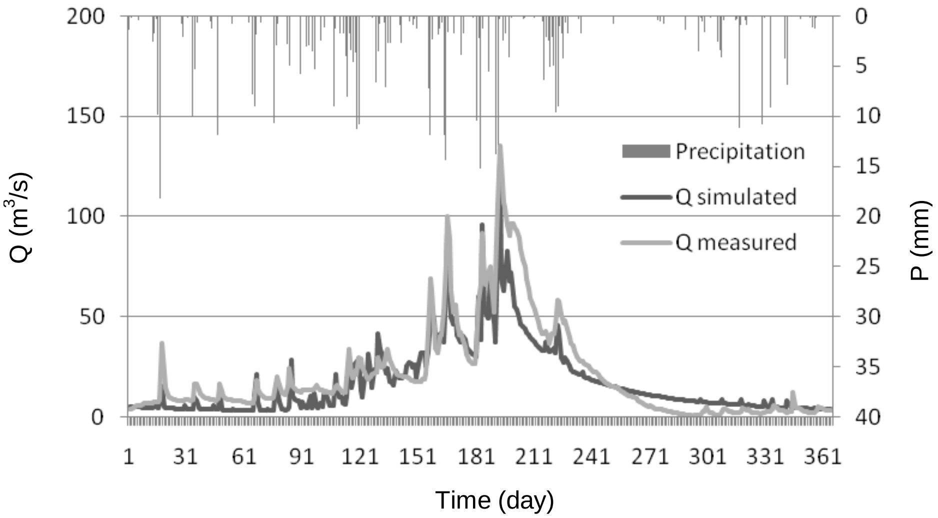

Figure 8. Graphical comparison between observed and calculated daily flow at Gorganrood for the year 1988 of Calibration period.

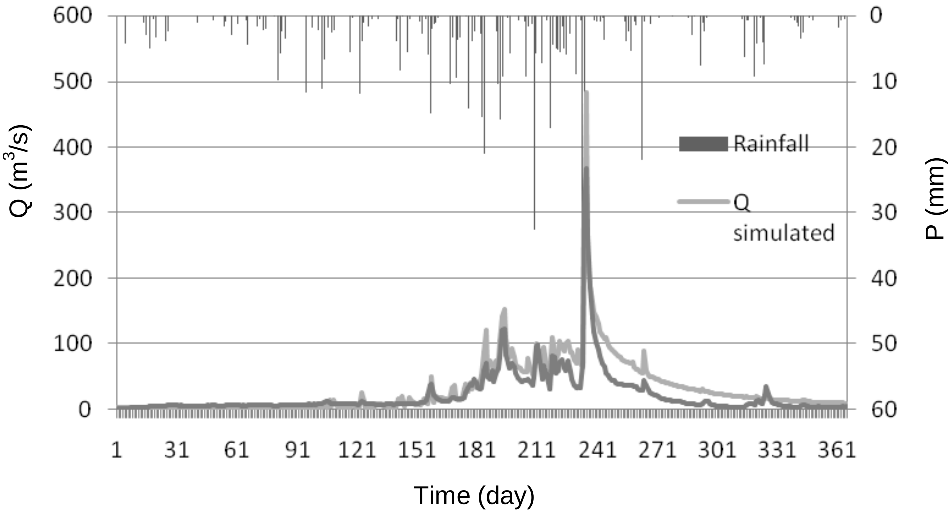

Figure 9. Graphical comparison between observed and calculated daily flow at Gorganrood for the year 1995 of Validation period.

The model can give the daily changes of soil moisture content in root depth. It is also possible for model to calculate and illustrate a map showing the spatial variation of soil moisture at a certain time step.

Conclusion

Distributed models have proven to be useful in assessing the impact of climate and landuse change on hydrologic functioning as well as scenario analyses because of their ability to predict the effect of spatially changing variables, like landuse change. This paper at first defines a method for estimating flood runoff in the Gorganrood basin by using detailed basin characteristics together with meteorological data as an input to the WetSpa spatially distributed model. To avoid the complexity inherent in estimating surface runoff, a simple but effective approach is presented where the whole basin is divided into grid cells, giving the possibility to simulate the hydrologic processes at reasonably small scale. The generation of runoff depends upon rainfall intensity and soil moisture and is calculated as the net precipitation times a runoff coefficient, which depends upon slope, land use and soil type and is further continued by antecedent soil moisture. Overland flow is routed through the basin along flow paths determined by the topography using a diffusive wave transfer model, while interflow and groundwater

Table 1. Water balance components calculated for each year.

Year	Rainfall (mm)	Interception (mm)	soil moisture (mm)	Infiltration (mm)	Evapotranspiration (mm)	Percolation (mm)	RS (mm)	RI (mm)	RG (mm)	R (mm)
1983	278	25.75	250	256	304	12.9	5.2	1.45	26.94	34
1984	301	21.31	245	367	358	31.8	10	3.73	30.43	44
1985	256	25.96	248	291	285	33.1	7	2.77	31.48	41
1986	301	26.1	252	384	372	37.5	9.1	3.38	32.17	45
1987	355	32.67	257	434	385	81.3	17	7.92	67.74	92
1988	336	29.53	257	440	400	61.9	14	6.18	62.75	83
1989	257	22.11	250	355	319	43.7	8.4	3.84	41.86	54
1990	296	25.34	248	321	327	38	8.3	3.39	36.82	49
1991	325	23.28	247	389	360	50.5	11	4.45	45.01	60
1992	377	34.32	258	566	461	131	24	12.7	110.9	147
1993	310	26.28	250	419	389	53.2	13	5.14	54.14	72
1994	287	27.1	256	397	350	57.3	11	4.76	57.02	73
1995	267	28.2	249	329	347	29.5	7.6	2.34	33.3	43

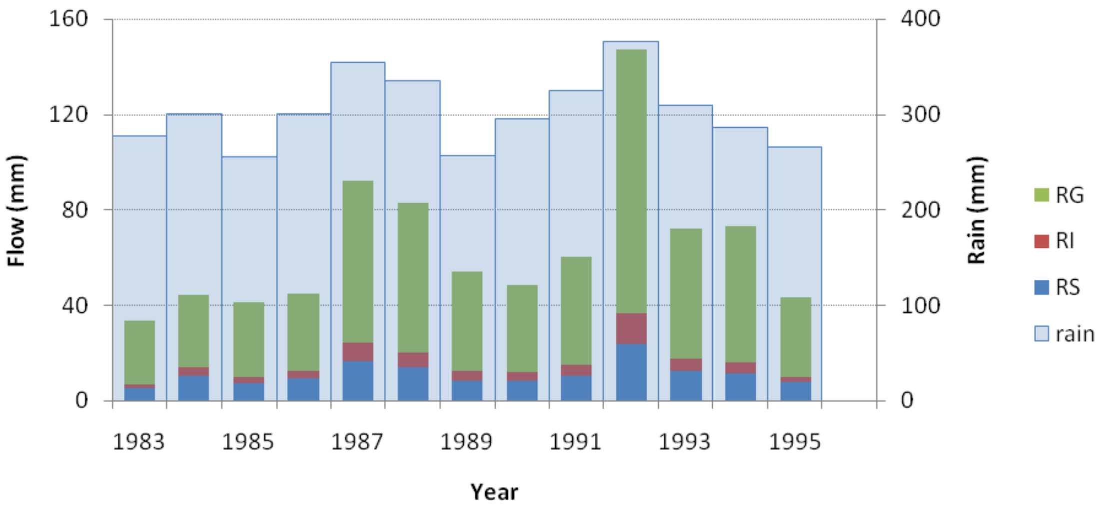

Figure 10. Comparison between different calculated flow components and rain amount.

recharge are simulated using Darcy's law and the kinematic approximation. Model parameters based on surface slope, land use, soil type and their combinations are collected from literature, which can be prepared easily using standard GIS techniques. The model is tested on the Gorganrood mountainous catchment, located in the northern Iran, Caspian coast, with 13 years of observed daily rainfall and evaporation data. Good agreement with the measured hydrograph is achieved. The paper presents the model ability to give the detailed information about water balance and different hydrological processes. Since the spatial distribution of hydrologic characteristics can be obtained from the model outputs at each time step, the model is especially useful to analyze the effects of topography, soil type, and landuse on the hydrologic behavior of a river basin.

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