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Runoff Simulation using WetSpa Distributed Hydrological Model in Ziarat Watershed of Golestan Province, Iran

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ABSTRACT

Aims Modeling precipitation-runoff processes and forecasting river flow are an essential step in floods management and controlling, designing water structures in watersheds and droughts management.

Materials & Methods In the present research, WetSpa distributed hydrological model was applied to simulate river flow in Ziarat watershed of Golestan Province. This basin has an area of 95 km^2 and it has an average height of 1760 m above sea level. As a distributed, continuous, and physical model, WetSpa is characterized with daily or hourly time series which accounts for processes of precipitation, runoff, and evapotranspiration contexts. The model parameters include distributive and global parameters. To run model, daily data on flow, precipitation, temperature, and evaporation for years 2008–2016 were considered for calibration and validation.

Findings The results of simulation showed a relatively good compatibility between calculated and measured hydrograph at the basin outlet. According to Nash-Sutcliffe model for calibration periodic model, efficiency coefficient estimated daily hydrographs and maximum flow rate by 57.32% and 84.11% accuracy, respectively. However, given Nash–Sutcliffe coefficient which was equaled to −385.39 and −209.06 for low and high flow, respectively, validation results are not acceptable which it can be attributed to water withdrawal and diversion dam for water harvesting before gauging stations in outlet.

Conclusion Given the calibration results, WetSpa model has great efficiency under high flow circumstances compared to low flow mainly due to model weakness in low flow estimation but as a whole model simulated total flow with acceptable accuracy.

Keywords Flow Simulation; Precipitation-runoff Models; Calibration and Validation; Ziarat Basin

CITATION LINKS

[1] Climate change impact on river flows and catchment hydrology: a comparison of two spatially distributed models [2] Flood modeling for complex terrain using GIS and remote sensed information. Water Resour Manag [3] Optimal utilization of the chahnimeh water reservoirs in Sistan region of Iran using goal programming method [4] Simulation of snowmelt runoff using SRM model and comparison with neural networks ANN and ANFIS (case study: Kardeh dam basin) [5] A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa) [6] Hydrological modeling on a catchment scale using GIS and remote sensed land use information [7] A diffusive transport approach for flow routing in GIS-based flood modeling [8] WetSpa model application in the distributed model intercomparison project (DMIP2) [9] Predictive analysis and simulation uncertainty of a distributed hydrological model [10] Evaluation and verification of the WetSpa model based on selected rural catchments in Poland [11] Distributed simulation of Runoff in space and time using WetSpa model in Taleghan watershed [12] A report of water resources status in Golestan Province [13] Wetspa extension a gis-based hydrologic model for flood prediction and watershed management documentation and user manual [14] Stream flow simulation by WetSpa model in Hornad river basin, Slovakia [15] Prediction of runoff and discharge in the Simiyu river (tributary of Lake Victoria, Tanzania) using the WetSpa model [16] Automated calibration applied to a GIS-based flood simulation model using PEST

Introduction

Optimal utilization and consumption of water resources and its optimal management require a better understanding of the hydrological model. Precipitation and subsequently surface runoff are important phases of the hydrological cycle.[1]

Given the present situation in most of the country's watersheds in terms of missing statistics and high complexity and impossibility of fully understanding hydrological ecosystem, is essential.[2]

Hydrological models can simulate processes within watershed and study hydrological processes.[2] Prediction of floods is an integral part of water resource management.[3]

Hydrological models are applied for various purposes. For example, Akbari *et al.*[4] applied snowmelt runoff (SRM) hydrological model to predict SRM from Karde dam watershed so that SRM model could model daily flow changes with acceptable accuracy.

WetSpa model first was developed by Wang *et al.*[5] and was implemented in Terkelp- *Molenbeek* watershed in Belgium and subsequently was extended by De Smedt *et al.*[6] and Liu *et al.*[7] Safari *et al.*[8] evaluated the application of distributed hydrological WetSpa model for Distributed Model Intercomparison Project in the US. The results for the calibration of five river basins, except for Blue River, were excellent to very good and for the entire validation period suggesting that model can accurately simulate hydrological processes.

Bahremand and De Smedt[9] investigated uncertainty of the WetSpa model parameters and its effect on significant uncertainty in model prediction using PEST model in Slovakia's Torsion basin. The results showed that correction factor for relative evapotranspiration has the highest relative sensitivity. Model uncertainty analysis provided insight into the proper parameter sets and proved that model parameter uncertainty does not have significant effects on uncertainty prediction.

Porretta *et al.*[10] dealt with WetSpa model validation and verification in rural basins (Wkra, Kamienna, Sidra) in Poland. PEST was applied to model autocalibration, and at the same time, Nash–Sutcliffe demonstrated reliable quality to model high flow in two basins Sidra and Kamienna, but its potential as for low flow quality was not proved. Values for Wkra basin confirmed very good and good quality.

Moradipour *et al.*[11] simulated river's flow using WetSpa distributed hydrological model in Taleghan Watershed. Simulated results reveal that there is a good agreement between observations and simulations. The Nash–Sutcliffe criteria, 83.3% and accuracy of the simulation show the high performance of the model in this watershed.

In general, enormous studies in different countries such as Luxembourg, Belgium, Slovakia, Hungary, Tanzania, Thailand, Poland, and Iran suggest that WetSpa model in different areas with various geography and climate and diverse topographies as well as in small to very big basins is well able to simulate flow ranging from flood or daily flow of rivers. In such a way that allowed researchers to calculate the impact of various affecting factors, such as climate change and land use change, on outlet flow as well as the different components of the water balance and hydrological phenomena in distributed manner.

Given that the WetSpa model has been developed for the climatic and geographical conditions of Belgium, and on the other hand, different regions of the country have different climatic and topographic conditions, and as WetSpa model can be run with simple and accessible inputs and it offers acceptable results, it is necessary to evaluate this model in different climate conditions and topographies of Iran. The present research is aimed to study the evaluation of the efficiency of the WetSpa model in Ziarat watershed with its different topography and vast area.

Materials & Methods

The study area

Ziarat watershed with an 95 km^2 area is located in Golestan Province in Iran with coordinates

53° 23´ 54”–54° 31´ 11” E and 36° 36´ 51”–36° 43´ 59”N. Its minimum and maximum sea above elevation is 491 and 3027 m, respectively. The average annual precipitation is 750 mm and annual temperature is 17°C.[12] The average annual evaporation is 1950 mm in Ziarat watershed.[12] Figure 1 shows the study area location.

WetSpa model

As a distributed, continuous, and physical model with daily or hourly time step, WetSpa is found to explain some processes including precipitation, runoff, and evapotranspiration for both simple and complicated conditions. To install and run WetSpa model, Windows operating system XP/2000/ME/98 or Windows NT 4 are required. The main required programs are version Arc view 3.2 Geographic Information Systems (GIS) and extension spatial analyst v2. The main advantages and strengths of WetSpa model include using GIS to generate distributional maps required for modeling, need for low inputs for running (land use, digital elevation model, and soil type), the existence of an auxiliary algorithm called PEST to calibrate, and sensitivity analysis of model parameters which are less common in similar models, and the most hydrological models require too many and complex inputs and their parameters are calibrated manually.[13] As for each cell grid in the present model, the numbers of four layers are taken into account in vertical manner which includes following: Canopy cover layer, rhizosphere, transmission zone, and saturation zone. At first, WetSpa model estimates water balance in rhizosphere as this is the most substantial area playing a role in water retention, and hence, it controls surface and subsurface runoff, evapotranspiration, and groundwater flow.[10] Equation 1 calculates water balance in rhizosphere for each cell grid:

$$D\frac{\Delta\theta}{\Delta t} = P - I - V - E - R - F \quad (1)$$

Where D is root depth (m), represents oil moisture changes ($m^3\ m^{-3}$), is time step ($h\ day^{-1}$), P is precipitation ($m\ h\ d^{-1}$), $I = I_a + D_a$ is initial loss including stem flow (I_a) and depression storage (D_a) in time step m/h/d, V is surface runoff or surplus precipitation, E denotes evapotranspiration ($m\ hd^{-1}$), R is percolation on rhizosphere ($m\ h\ d^{-1}$), and F is subsurface flow over time ($m\ h\ d^{-1}$). The model uses modified rational method to calculate runoff is and to estimate snow melt runoff, growth it applies day- degrees coefficient method. Base flow is calculated by Darcy’s law and kinematic wave equations. Linear reservoir method is used to determine groundwater flow. Diffusion wave approximation equation is used to routing runoff along the flow path, in turn,

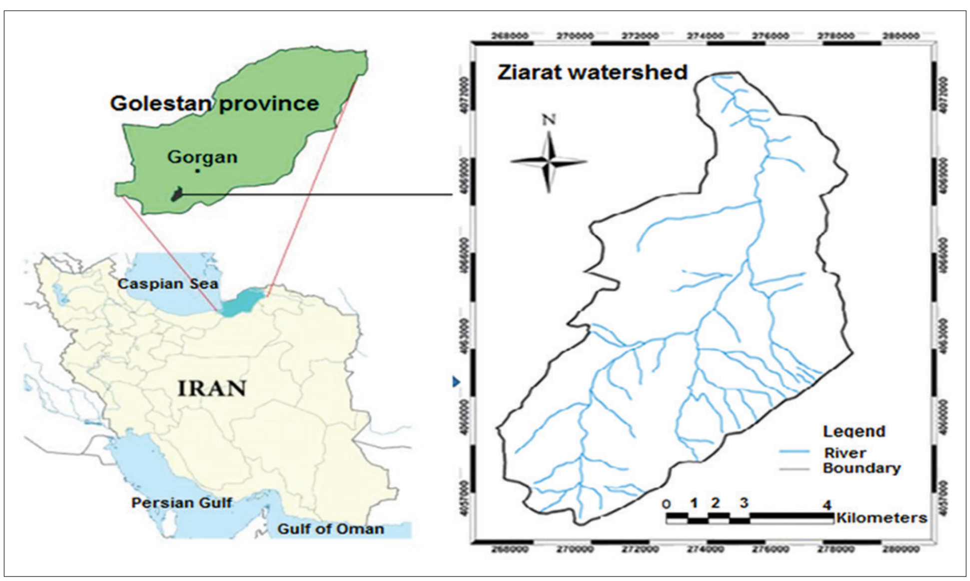

Figure 1: A general view of Ziarat watershed, Iran

it depends on slope, velocity, and flow path parameters. Streamflow and surface flow were routed along the river by Saint–Venant diffusion wave approximation equation and are obtained using following relation:

$$\frac{\partial Q}{\partial t}+c\frac{\partial Q}{\partial x}-d\frac{\partial^2 Q}{\partial t^2}=0 \quad (2)$$

Here, Q represents discharge (m^3s^{-1}), t denotes time (days), X is the distance in flow direction (m), and C denotes kinematic wave velocity in terms of pixel and is calculated from equation 3. v is flow velocity ($m\ s^{-1}$) and d is diffusion factor in pixel which is deduced from equation 4, and R is hydraulic radius or average depth (m) and S_0 is stream bed slope and is constant. These two parameters vary on velocity and depth.[14] Equation 5 is applied as a Saint– Venant linear response function to obtain flow rate at the end of the flow path, equation.[6]

$$C=(5/3)\times v \quad (3)$$

$$d=(\frac{VR}{2S_0}) \quad (4)$$

$$\sigma=\sqrt{\int\frac{2d}{c^3}dx} \quad (5)$$

Given a limited system between upstream and downstream cross-section, solution for equation 2 in pixel outlet can be calculated by a Gaussian probability density function as it can be seen in equation 6.

$$U(t)=\frac{1}{\sigma\sqrt{\frac{2\pi t^3}{t_0{}^3}}}exp\left[\frac{\frac{(t-t_0)^2}{2\sigma^2 t}}{t_0}\right] \quad (6)$$

In the aforementioned equation, U (t) is found to be a flow response function which is applied to specify unit hydrograph and allows routing flow path to basin outlet. t_0 is flow passing time (T), σ is flow time standard deviation, and finally flow hydrographs in outlet which are calculated from equation 7:

$$Q(t)=\int A\int_0^{\tau}V(\tau)U(T-\tau)d\tau dA \quad (7)$$

Here, Q(t) is discharge, U denotes flow path response function, τ is lag time, and V represents outlet runoff volume. Digital elevation data, soil type, land use, and time series of precipitation and evaporation are model inputs so that all hydrological processes can be simulated in GIS. To model running, a digital elevation map (DEM) with a pixel size of 50*50 m was prepared from a topographic map with a scale 1:50000 in Ziart watershed. Figure 2 shows DEM of Ziarat watershed. The hydrological processes of the model which are simulated in the GIS include rainfall, snow, interception storage, depression storage, surface runoff, infiltration, evapotranspiration, percolation, subsurface flow, groundwater flow, and water balance.

The parameters used in the model are divided into two groups of default distributive parameters and global parameters. The default distributive parameters define the soil texture classes, the land use classes, and the potential runoff coefficient and depression storage. Global parameters include potential evapotranspiration factor and subsurface flow coefficient, groundwater drop coefficient, soil initial moisture content, initial groundwater storage, maximum groundwater storage, base temperature for snowmelt, temperature and temperature degree-days coefficient and precipitation degree-days coefficient, the surface runoff power, and the maximum rainfall intensity.

In the present research, daily data on flow, rainfall, temperature, and evaporation in Cheshme ziarat and Naharkhoran hydrometric stations for years 2008-2009–2013-2014 were used for calibration and 2014-2015–2015-2016 were used for model validation. We used 75 and 25% of data for model calibration and validation periods, respectively. The simulation results were compared graphically and statistically with observational data. To quantitative comparison of model efficiency in two calibration and validation stages, following criteria were used.

Model evaluation criteria

The main purpose of modeling is to generate simulation data that are similar to observational data. Therefore, the

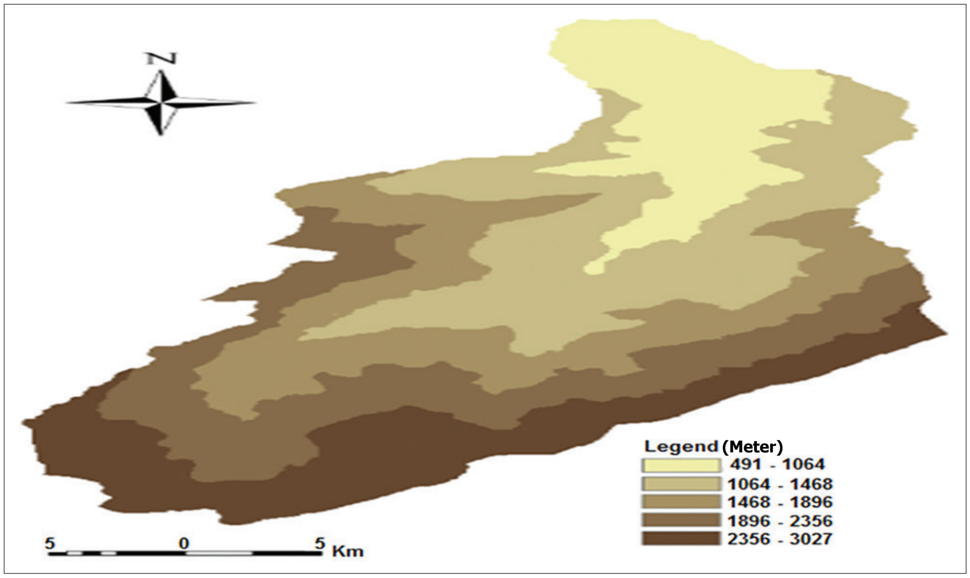

Figure 2: Digital elevation map of Ziarat watershed

model's evaluation criteria are based on the comparison of simulation values and observations and the similarity or differences between them. The evaluation criteria used in this study are presented in Table 1 and are also explained in following.

Model bias (MB)

MB might be simulated as relative average difference between the observed and predicted flow in a simulation, and such criterion is expressed as follows:

$$MB = \left[\frac{\sum_{i=1}^{N} (QS_i - Qo_i)}{\sum_{i=1}^{N} (Qo_i)} \right] \quad (8)$$

In this equation, MB is MB, Qsi–Qo_i are simulated and observed flow in i^{th} time step (m^3 s^{-1}), respectively, and N is the number of time steps in simulation period. MB low values show a good fitting and zero represents perfect simulation of observed flow.

Root mean square error

Root mean squared error represents a difference of predicted and observed value in model and as follows:

$$RMSE = \sqrt{\frac{\sum (XO - XS)^2}{N}} \quad (9)$$

XO and XS are observed and simulated discharge, and N represents a number of time steps during simulation. The lower this value, the better simulation model has, and it has not a given range.

Nash–Sutcliffe coefficient

Nash–Sutcliffe measure indicates that to what extent flow rates simulated by the model are correct, and here, the equation is as follows.

$$NS = 1 - \frac{\sum_{i=1}^{N} \left(Q_{si} - Q_{oi}\right)^2}{\sum_{i=1}^{N} \left(Q_{oi} - \overline{Q_o}\right)^2} \quad (10)$$

In this equation, NS is Nash–Sutcliffe efficiency index that measures potential to flow channel simulation, ranging from a negative value to 1, and 1 represents full consistency between observed and simulated hydrograph.

Nash–Sutcliffe low (NSL)

Logarithmic Nash–Sutcliffe equation 11 focuses on low-flow simulation evaluation.

$$NSL = 1 - \frac{\sum_{i=1}^{N} \left[\ln(Qs_i) - \ln(Qo_i)\right]^2}{\sum_{i=1}^{N} \left[\ln(Qo_i) - \overline{\ln(Qo_i)}\right]^2} \quad (11)$$

To assess low flow rates, in a complete simulation log Nash–Sutcliffe efficiency coefficient, NSL is applied, and NSL equals to one.

Nash–Sutcliffe high (NSH)

Nash–Sutcliffe measure is presented in equation (12) applied to assess potential to simulate high flow. For the full compliance of simulated and observed value, NSH equals to 1.

$$NSH = 1 - \frac{\sum_{i=1}^{N}(Qo_i + \overline{Qo})(Qs_i - Qo_i)^2}{\sum_{i=1}^{N}(Qo_i + \overline{Qo})(Qo_i - \overline{Qo_i})^2} \quad (12)$$

Findings

When WetSpa model running was completed, considering daily data as for flow, rainfall, temperature, evaporation and land use, soil, and DEMs, initially model was calibrated for 6 years' period (2008-2009–2013-2014), and subsequently, it was validated for 2 years (2014-2015–2015-2016). Table 2 presents the results. As Table 2 shows, assessment criteria results suggest that in calibration period model was characterized with necessary efficiency; however, in validation period, results cannot be accepted.

By comparing gall observed and simulated hydrographs which are presented in Figures 3 and 4, it was found that model can simulate high flow (peak flow) to runoff estimation in well manner, but it has low accuracy in forecasting low flow which is due it simplification of groundwater in model or no precise estimation on evapotranspiration of groundwater during drought periods simultaneously, and hence, base flow can be considered as determinant factor in the summer to agriculture and farming.

By keeping constant factors derived from automatic calibration, the model was run for years 2014–2015 and 2015–2016. The results of the simulation in the validation period compared with observed discharge data are shown in Figure 5. As it can be seen from Figure 5, WetSpa model has not well-simulated runoff in the validation period, particularly in areas characterized with circle.

Discussion

In this study, model was validated in Ziarat watershed with 4-year data on daily rainfall, temperature, and evaporation rate. As it can be seen from the calibration results, the model in estimation of high flow is more efficient with Nash–Sutcliffe coefficient about 85.13% than low flow, which this can be attributed to weakness of the model structure in the low flow estimation, but in general, model has accurately simulated total flow with Nash–Sutcliff coefficient about 52.09%. In this case, small Nash–Sutcliffe coefficient for low flows can be found in other literatures, Liu and De Smedt,[2] Bahremand *et al.*,[14] and Rwetabula *et al.*[15] However, validation results are unacceptable that this may be due to the model structure or/and data and basin conditions.

As it can be seen from Figure 5, in terms of model structure, model response to rainfall in basin is reasonable, except for certain areas which are illustrated by circle. Failure

Table 1: The indices, model evaluation criteria, and their range

Abbreviation	Name	Range	Good if
MB	Model bias	−∞, +∞	0
RMSE	Root mean square error	0, +∞	Small
NSE	Nash–Sutcliffe efficiency	−∞, 1	1
NSH	Nash–Sutcliffe high	−∞, 1	1
NSL	Nash–Sutcliffe low	−∞, 1	1

Table 2: Values for model efficiency criteria during calibration and validation period

Statistical evaluation criteria	Calibration	Validation
Model bias to flow volume (Balance)	−0.08	115.49
RMSE	53.89	174.31
Total Nash–Sutcliffe coefficient (%)	57.32	−632.20
NSH (%)	84.11	−385.39
NSL (%)	20.29	−209.06

RMSE: Root mean square error, NSH: Nash–Sutcliffe high, NSL: Nash–Sutcliffe low

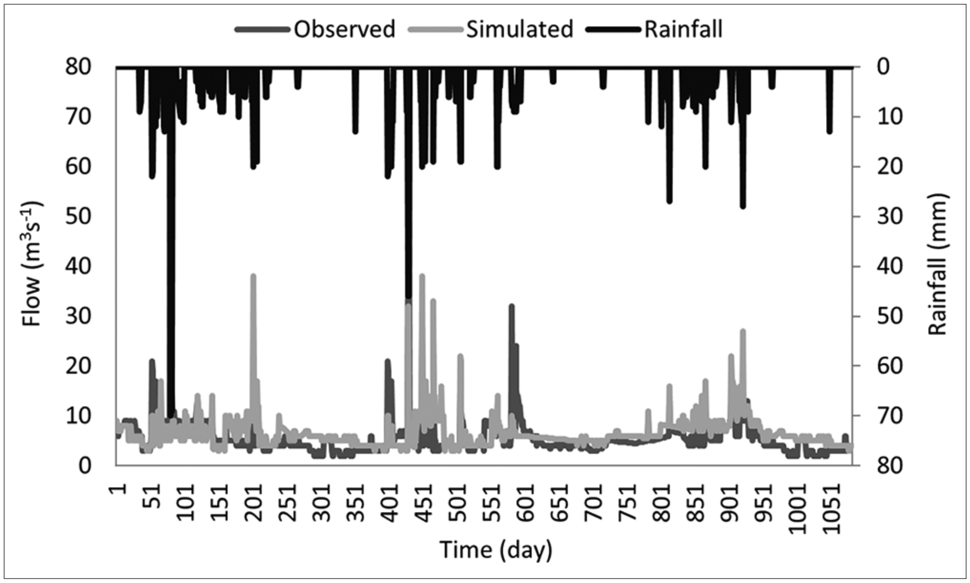

Figure 3: Model calibration during three statistical years (2008-2009–2010-2011)

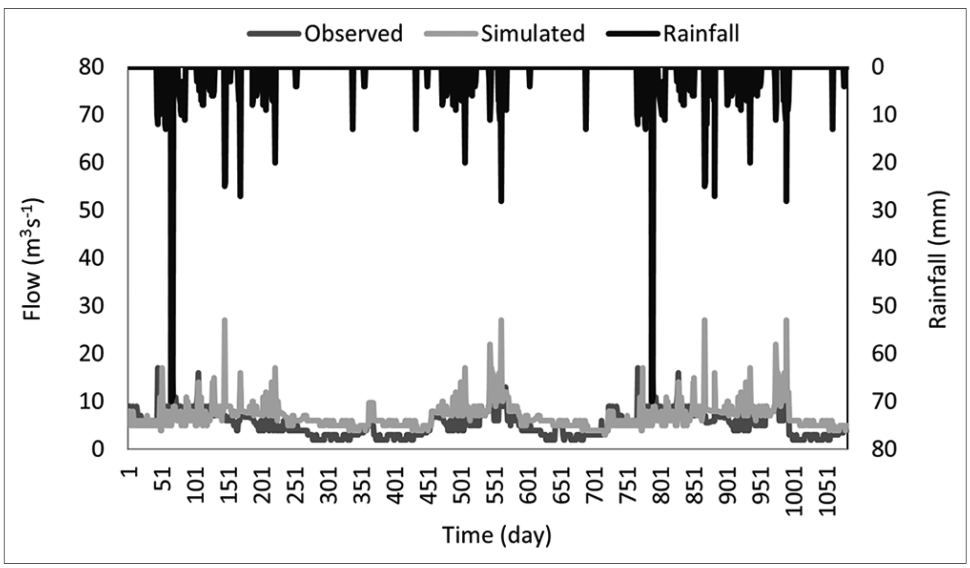

Figure 4: Model calibrations during three statistical years (2011-2012–2013-2014)

of simulation in these regions can be caused by several factors such as the presence of the reservoir or dam or water withdrawal in the basin, lack of accurate precipitation recording, and drawbacks in taking flow data. It was found that before hydrometric stations in outlet, a diversion dam was constructed to extract water, and as shown in Figure 4, simulated flow rate is much more than observed one that can be attributed to above-mentioned diversion dam. Evaluation of outlet hydrometric stations showed that section profile over the years has not changed and stage-discharge rating curve and collected data have been accurate. For 2 years' validation period, precipitation rate experienced 47% increase compared to calibration period, but evaporation has remained constant, while runoff experienced 25% decrease and this confirms water withdrawal, suggesting that unacceptable results stem from lack of model efficiency.

To the best of our knowledge, WetSpa model has been adopted and studied by enormous studies including Barbic basin in Belgium,[6] Alzette River Basin in Luxembourg,[7]

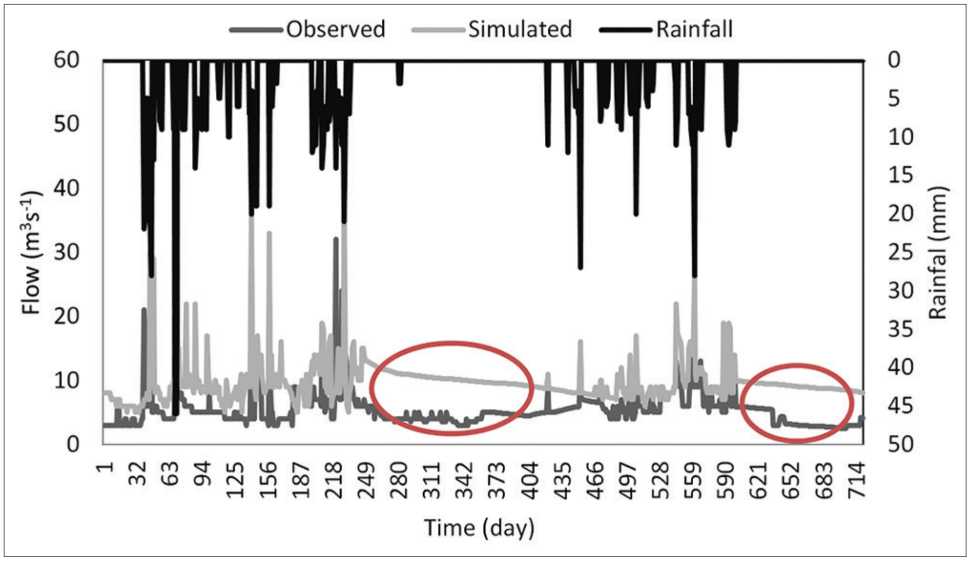

Figure 5: Model validation during two statistical years (2014-2015–2015-2016)

Somuikarst river basin in Vietnam,[16] and Hornad watershed in Slovakia.[14] As per literature, it was found that model can well account form any hydrological processes under various topography, soils, and land-use conditions, has great potential, and is promising in this field.

Conclusion

According to the results of WetSpa model calibration and validation, this model outperforms in simulation of higher flows. However, in general, it simulates total flow with acceptable accuracy and it has sufficient potential. Given that there are insufficient data and parameters required to running WetSpa model and easily are available in each basin, and on the other hand, simulation results are acceptable, therefore, the WetSpa model, as a hydrologic model which can simulate flow with small data, can be easily applied in watersheds.

Given that, Ziarat watershed is prone to flood and huge runoff which causes significant great damages to region each year, and it is recommended to apply WetSpa model to simulate and predict the runoff from the rainfall with different return periods. This will help to manage and control flood in the area and prevent flood damage and finally optimizes the use of water resources in the area. Finally, given that WetSpa model has been developed for the climate and geographic conditions of Belgium, it is recommended that this model be evaluated in other watersheds of the country to evaluate the accuracy of this model in these watersheds.

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شبیه‌سازی رواناب با استفاده از مدل هیدرولوژیکی-توزیعی WetSpa در حوزه آبخیز زیارت استان گلستان، ایران

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چکیده

اهداف: شبیه‌سازی جریان رودخانه به عنوان پیش‌نیاز برخی از مسایل زیست‌محیطی و مهندسی، دارای اهمیت فراوانی است. مدل‌های هیدرولوژیکی برای شبیه‌سازی و پیش‌بینی جریان‌ها در حوزه‌های آبخیز به‌کار می‌روند.

مواد و روش‌ها: در این پژوهش از مدل هیدرولوژیکی- توزیعی WetSpa جهت شبیه‌سازی جریان رودخانه در حوزه آبخیز زیارت واقع در استان گلستان استفاده شده است. مساحت حوزه آبخیز زیارت ۹۵ کیلومتر مربع و میانگین ارتفاع آن ۱۸۲۰ متر از سطح دریا است. WetSpa یک مدل توزیعی، پیوسته و فیزیکی با گام زمانی روزانه یا ساعتی است که فرآیندهای بارش، رواناب و تبخیر و تعرق را بیان می‌کند. پارامترهای مدل شامل پارامترهای توزیعی و پارامترهای کلی هستند. برای اجرای مدل از داده‌های روزانه دبی، بارش، دما و تبخیر سال‌های ۱۳۹۱ تا ۱۳۹۵ برای کالیبراسیون و اعتبار سنجی مدل استفاده شد.

یافته‌ها: نتایج شبیه‌سازی تطابق نسبتاً خوبی بین هیدروگراف‌های محاسبه‌شده و اندازه‌گیری‌شده در خروجی حوزه نشان داد. مدل برای دوره واسنجی براساس معیار ناش- ساتکلیف، هیدروگراف‌های روزانه را با دقتی بیش از ۵۹% و دبی‌های حداکثر را با دقت ۸۵/۱۳% برآورد نمود. اما نتایج اعتبارسنجی با توجه به ضریب ناش- ساتکلیف ۳۸۵/۳۹- برای جریان‌های کم و ۲۰۹/۰۶- برای جریان‌های بالا، قابل قبول نیست که ناشی از برداشت آب و وجود بند انحرافی جهت استحصال آب قبل از ایستگاه هیدرومتری خروجی حوزه بود.

نتیجه‌گیری: مدل WetSpa در برآورد جریان بالا کاراتر از جریان‌های کم است که این امر می‌تواند ناشی از ضعف ساختار مدل در برآورد جریان کم باشد ولی در مجموع، مدل جریان کل را با دقت قابل قبولی شبیه‌سازی کرده است.

کلیدواژه‌ها
شبیه‌سازی جریان؛
مدل‌های بارش- رواناب؛
واسنجی و اعتبارسنجی؛
حوزه زیارت

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