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Rainfall–Runoff Simulation Using WetSpa Model in Golestan Dam Basin, Iran

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Abstract**—**Flood simulation and prediction is one of the most active research areas in surface water management. WetSpa is a distributed, continuous, and physical model with daily or hourly time step that explains precipitation, runoff, and evapotranspiration processes for both simple and complex contexts. This model uses a modified rational method for runoff calculation. In this model, runoff is routed along the flow path using Diffusion-Wave equation which depends on the slope, velocity, and flow route characteristics. Golestan Dam Basin is located in Golestan province in Iran and it is passing over coordinates 55° 16´ 50" to 56° 4´ 25" E and 37° 19´ 39" to 37° 49´ 28"N. The area of the catchment is about 224 km^2, and elevations in the catchment range from 414 to 2856 m at the outlet, with average slope of 29.78%. Results of the simulations show a good agreement between calculated and measured hydrographs at the outlet of the basin. Drawing upon Nash-Sutcliffe model efficiency coefficient for calibration periodic model estimated daily hydrographs and maximum flow rate with an accuracy up to 59% and 80.18%, respectively.

Keywords**—**Watershed simulation, WetSpa, stream flow, flood prediction.

I. Introduction

SIMULATION of river flow is of great importance as a prerequisite to solve some environmental and engineering issues. Rainfall-runoff models can simulate processes within watershed and serves as a tool to estimate runoff and study hydrological processes. Developing the technology of geographical information system has eased the possibility of widespread accessibility and management on parameters and spatial hydrologic variables [3]. Reference [6] ran WetSpa model with one hour time step in small watershed by an area 67.8 km^2 in Belgium. Statistical analysis of hydrographic derived from model and observed hydrograph showed that model can well predict its normal and flood currents. Reference [8] applied WetSpa hydrological model to predict runoff flow in Simiu, in the area of Lake Victoria in Tanzania. The results of the model showed that the model can route flow in river. Reference [3] in a research tilted as distributed hydrological modeling and sensitivity analysis in Slovakia Turisa basin found a good agreement between the observed and calculated hydrographs at the basin outlet. The model forecasted daily flow forecast with good accuracy 73% and it was based on Nash-Sutcliffe Model Efficiency Coefficient. The results showed that correction factor of actual evapotranspiration and kg (evaporation of groundwater) accounted for the highest and lowest relative sensitivity respectively. Reference [9] evaluated application of distributed hydrological WetSpa model for Distributed Model Integration Project in US. They used integration criteria that reflect the differences in shape, size, and volume of the observed and simulated hydrographs for model performance assessment. Reference [5] evaluated WetSpa distributed hydrological model in the Gorganrood basin with an area of 6717 km^2. The simulation results showed a good agreement between the calculated and observed hydrographs, and given Nash-Sutcliffe criteria, model predicted daily hydrograph model accuracy about 71 to 77%. Reference [10] dealt with WetSpa model validation and verification in rural basins (Wkra, Kamienna, Sidra) in Poland. The model was auto-calibrated using PEST, Nash-Sutcliffe proved reliable quality for modeling high flow in two basins, Sidra and Kamienna; however, low flow quality was not confirmed. Values for Wkra basin considered very good and good quality.

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II. Materials and Methods

Study area is a sub-basin of the Gorganroud Basin located in Golestan province. This basin has an area of 224 square kilometers and it has an average height of 1295 meters above sea level. This basin is located at 55° 16´ 50" to 56° 4´ 25" E and 37° 19´ 39" to 37° 49´ 28"N. Major land use of the study area is irrigated and rainfed agricultural lands, forests, and grassland. Output of the basin is at Golestan dam on the floor elevation 44 to 79 m above sea level [2]. Fig. 1 shows the study area location.

WetSpa is a distributed, continuous, and physical model with daily or hourly time step that explains processes of precipitation, runoff, and evapotranspiration for both simple and complex contexts. In this model for each cell grid, four layers are considered in vertical manner which includes following: canopy cover layer, root zone, transportation zone, and saturation zone. WetSpa model first calculates water balance in root zone because this is the most important area in water retention, and at the same time, it controls surface and subsurface runoff, evapotranspiration and underground water flow. Equation (1) illustrates water balance in root zone for each cellular grid:

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

where D is the root depth (m), $\Delta\theta$ denotes the soil moisture variation (m^3/m^3), Δt is the time step (h/day), P is the precipitation (m/h/d), $I = I_a + D_a$ is the initial loss including stem flow (Ia) and depression storage (Da) in time step m/h/d, V is the surface runoff or surplus precipitation, E is the evapotranspiration (m/h/d), R is percolation on root zone (m/h/d), and F is the subsurface flow in time (m/h/d). Model applies modified rational method to calculate runoff and applies GDD to estimate snow melt runoff. Subsurface is calculated based on Darcy's law and kinematic wave equations. Groundwater flow is determined using linear reservoir method. Runoff is routed along the flow path using diffusion wave approximations equation, which is dependent on slope, velocity, and flow path parameters. Stream flow and surface flow were routed along river by Saint-Venant diffusion wave approximations equation and it is calculated using the following relation:

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

where Q is the discharge (m^2/s), t is the time (days), X is the distance in flow direction (m), C denotes the kinematic wave velocity in pixel and is calculated from (4). V is the flow velocity (m/s), and d is the diffusion factor in pixel derived from (4) where R is the hydraulic radius or average depth, and S_0 is the stream bed slope and it is constant. These two parameters depend on velocity and depth [5]. To calculate flow rate at the end of the flow path, (6) is used as a Saint-Venant linear response function [3].

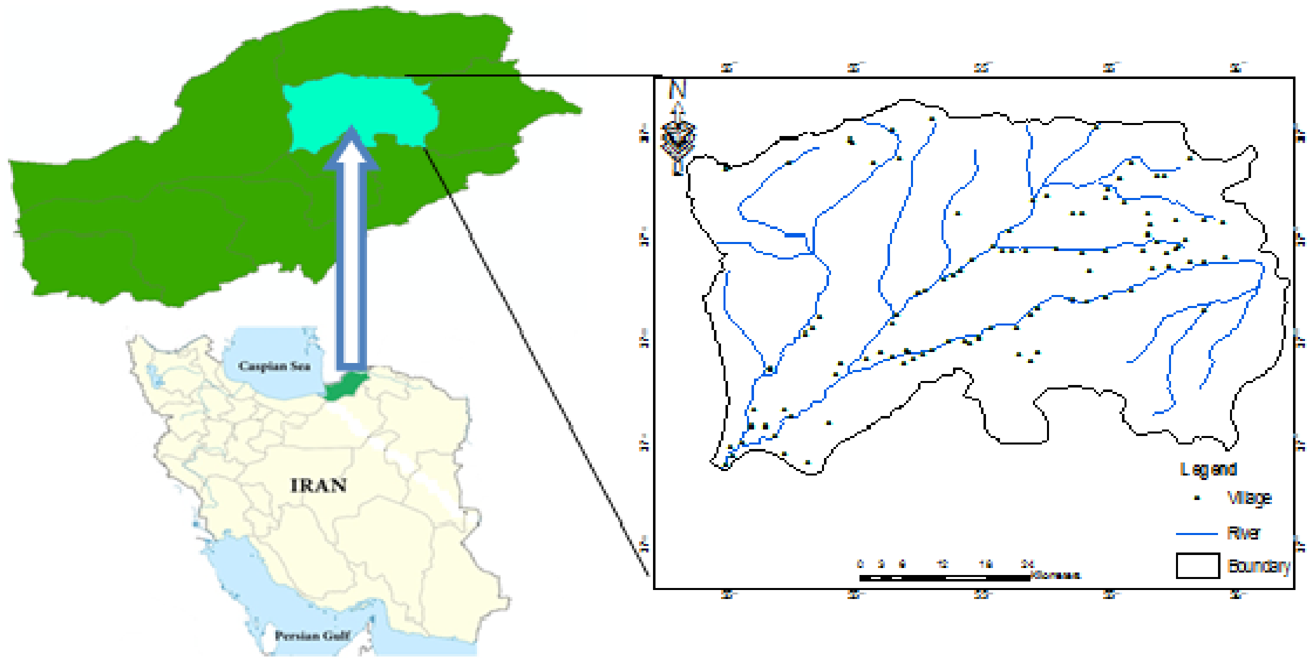

Fig. 1 Location of the study area

$$C = (5/3) \times v \tag{3}$$

$$d = \left(\frac{VR}{2S_0}\right) \tag{4}$$

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

Considering a limited system between upstream and downstream cross-section, solution for (2) in pixel outlet can be expressed using a Gaussian probability density function as in (6):

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

where U(t) is flow response function which is used to determine instantaneous unit hydrograph and allows routing flow path to basin outlet. t_0 is the flow travel time (T), σ is the flow time standard deviation, and finally, flow hydrographs in outlet which combined in downstream are calculated from (7):

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

where $Q(t)$ represents the discharge, U is the flow path response function, τ is the lag time, and V is the output runoff volume.

Model inputs include digital elevation data, soil type, land use, time series of precipitation and evaporation so that all hydrological processes are simulated in GIS.

In the present research, daily data on flow, rainfall, temperature, and evaporation in Tamar hydrometric stations for years 2014-2015 to 2015-2016 were used for calibration.

III. Model Validation and Efficiency Metrics

A. Model Bias

Model bias can be simulated as relative mean difference between the observed and predicted flows in a great simulation and this criterion is expressed as follows:

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

where MB is the model bias, Qsi and Qoi represents the simulated and observed flows in i^{th} time step (m^3/s), and N is the number of time steps during simulation. MB low values indicate a better fitting, and the value zero represents perfect simulation of observed flow.

B. RMSE

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

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

C. Nash–Sutcliffe Coefficient

Nash-Sutcliffe criterion indicates how accurate flow rates simulated by the model are, the equation is as follows.

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

where NS is the Nash–Sutcliffe efficiency index which is used to evaluate potential to simulate flow channel, ranging from a negative value to 1, and 1 represents the full compliance between the observed and simulated hydrographs.

D. Nash–Sutcliffe Low

Logarithmic Nash-Sutcliffe in (11) emphasizes on evaluation of low-flow simulation.

$$NS = 1 - \frac{\sum_{i=1}^{N}[\ln(Qs_i) - \ln(Qo_i)]^2}{\sum_{i=1}^{N}[\ln(Qo_i) - \overline{\ln(Qo_i)}]^2} \tag{11}$$

log Nash-Sutcliffe efficiency coefficient NSL is used to assess low flow rates. In a complete simulation, NSL is equal to 1.

E. Nash–Sutcliffe High

Nash – Sutcliffe criterion is provided in (12) which is used to evaluate potential to simulate high flow.

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

IV. Results

Once WetSpa model runs, given daily data on flow, rainfall, temperature, evaporation and land use, soil and digital elevation maps, the first model was calibrated for a two-year period (2014-2015 to 2015-2016). Results are presented in Table I. As it can be seen in Table I, results of the assessment criteria indicated that, in calibration period, model was chastised with necessary efficiency.

TABLE I
Values for Model Efficiency Crireria during Calibration Period

Efficiency criterion	calibration
model bias to flow volume balance	-0. 76
RMSE	58.81
Total Nash–Sutcliffe coefficient (%)	59.03
Nash–Sutcliffe high (%)	80.18
Nash–Sutcliffe low (%)	30.19

Comparison of the observed and simulated hydrographs shown in Fig. 2 demonstrates that the model can well simulate high flow (peak flow) to runoff estimation, but it has low accuracy in prediction of low flow, which can be presumably attributed to simplification of groundwater in model or lack of accurate evapotranspiration of groundwater estimation during dry periods. At the same time, using base flow in the summer for agriculture and farming can be considered as determinant factor.

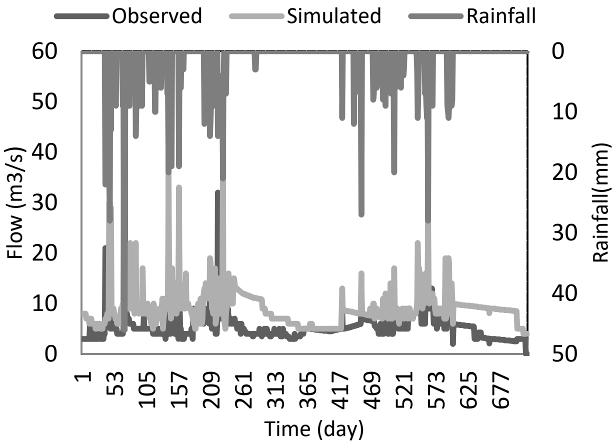

Fig. 2 Model calibration during two statistical years (2014-2015 to 2015-2016)

V. Discussion and Conclusion

Until now, WetSpa model has been applied and studied by enormous researchers including Barbic basin in Belgium [4], Alzette River Basin in Luxembourg [7], Karst river basin Somui in Vietnam [6], Hornad watershed in Slovakia [3]. Literature review indicated that model can well handle a variety of hydrological processes under diverse topography, soils, land-use, and areas and has great potential in this field. In this study, model was validated in Golestan Dam Basin with 2-years data on daily rainfall, temperature, evaporation rate. As calibration results implied, model is more efficient under high flow compared to high flow, which could be attributed to model weakness in low flow estimation. In this case, small Nash-Sutcliffe coefficient for low flows can be found in other literatures [9], [1], [8]. However, validation results are unacceptable, and this may be due to the model structure or and data and basin conditions.

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