Improving hydrograph routing of a semi- distributed conceptual hydrological model

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Comprehensive hydrological modelling tools have been developed to simulate hydrological response of the basin to the precipitation for predicting daily runoff. NAM (NedborAfstromnings Model) rainfall-runoff model is selected as core feature for hydrological model and it is enhanced to a semi-distributed model by including the Muskingum-Cunge flow routing method to simulate overland flow. The model was implemented technically using a combination of the automated basin delineation tool, hydrological modeling, flow routing, calibration, sensitivity and uncertainty analysis modules using Python programming language. Web based open source software is developed to prepare necessary input data, run the modules and for visualization of the results.

Study Area

The study area, located in the south part of Turkey, has 526 km² area and the elevation varies from 963 m to 3450 m. The median elevation is 1600 m. (Figure 1)

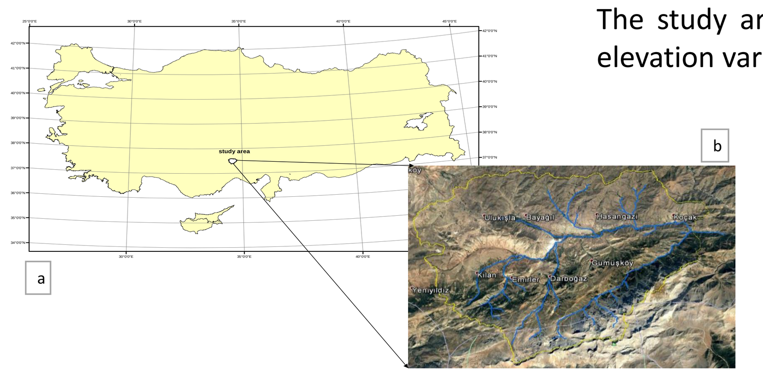

Figure 1. Location of study area (a), study area (b)

Figure 2. Views in different sesons from the area

The cherry trees along the river, agricultural areas and the natural vegetation composed of pasture and shrub are the main land cover in the basin (Figure 2).

Hydrometeorological Stations

3 stream and 3 meteorological gaging stations were installed in the study area. Discharge, electrical conductivity and water temperature are recorded with 15 min time interval in stream gaging stations. Wind speed, air temperature, pressure, radiation, snow depth and precipitation values are recorded in meteorological stations with 10 min time interval.

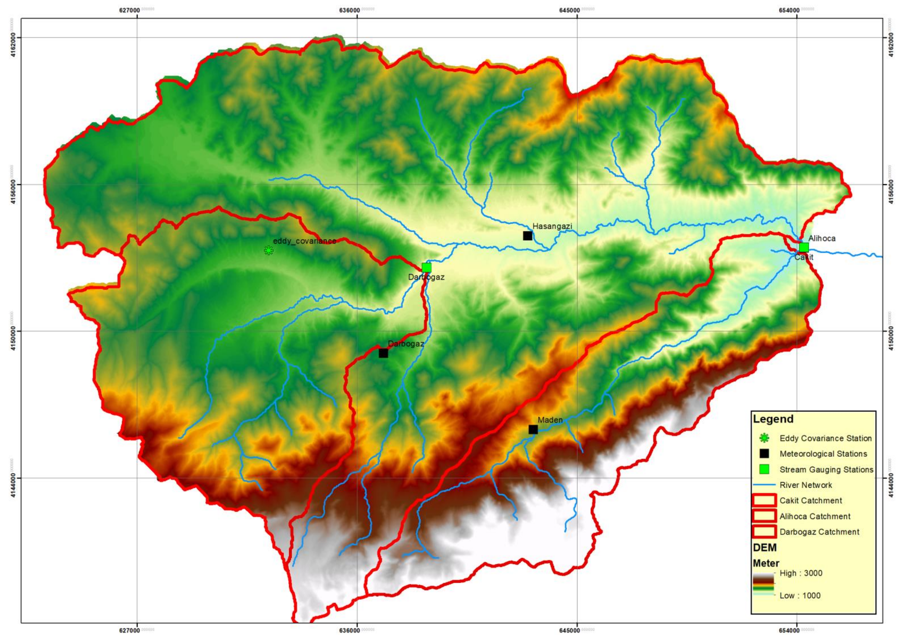

Figure 3. Location of gauge stations

3 sub-basins are delineated using GIS tools considering location of stream gage stations as the outlet. Meteorological stations located inside the sub-basins are assumed to be representative for the sub-basins. If needed, lapse rate (0.5°C/100m) is used to transfer the temperature values to the mean elevation of the sub-basins. Elevation of meteorological stations are given in Table 1. Area and mean elevation of sub-basins are shown in Table 2. In this study, Precipitation, temperature and discharge data from all stations are recorded for 2017 and 2018 water years.

Table 1. Elevation of meteorological stations

Meteorological Station	Elevation (m)
Darboğaz	1580
Maden	1790
Hasangaz	1246

Table 2. Sub-basin characteristics

Basin	Area (km²)	Basin mean elevation (m)
Darboğaz	121.2	1692
Alihoca	97.3	2147
Çakıt	421	1730

NAM conceptual rainfall-runoff model

Lumped, deterministic and conceptual NAM (NedborAfstromnings Model) rainfall-runoff model is selected to apply to study area. The model uses precipitation, potential evapotranspiration and temperature as driving forces in the simulation of snow accumulation and melting, interception, actual evapotranspiration, overland flow, interflow, groundwater recharge and baseflow (Figure 4) with using parameters given Table 3.

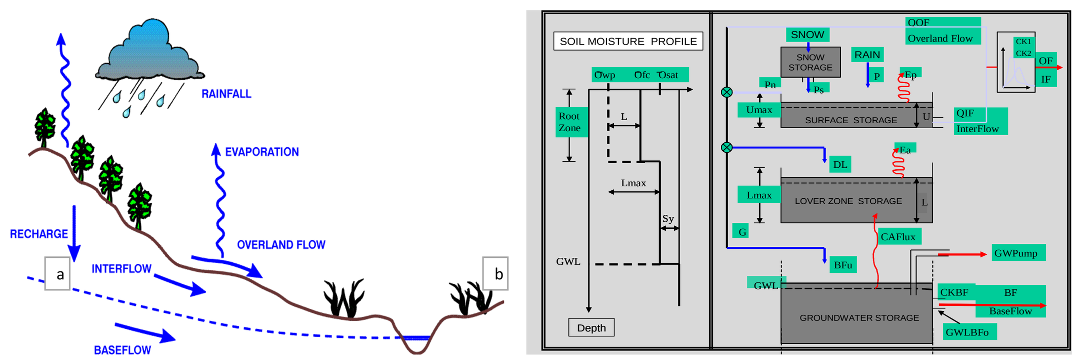

Figure 4. Structure of (a) Conceptual Rainfall-Runoff (b) NAM model

Mathematical algorithm of NAM model is programmed using Python language. Shuffled Complex Evolution (SCE) algorithm is also implemented to calibrate model parameters.

Daily protentional evapotranspiration are calculated using Penman-Monteith equation. Then, NAM Model is applied to Darboğaz, Çakıt and Alihoca sub-basins for 2017 and 2018 water years.

Table 3. NAM Model parameters

Parameter	Unit	Description	Range
U_{max}	mm	Max. water content in the surface storage	1 - 50
L_{max}	mm	Max water content in root zone storage	1-1000
CQOF	-	Overland flow runoff coefficient	0-1
CKIF	hours	Time Constant for Interflow	200-1000
CK_{12}	hours	Time constant for routing overland flow	10 - 50
TOF	-	Root zone threshold value for overland flow	0 - 0.99
TIF	-	Root zone threshold value for overland flow	0 - 0.99
TG	-	Root zone threshold value for groundwater recharge	0 - 0.99
CK_{BF}	hours	Time constant for routing base flow	500-5000
Csnow	°C	Degree day coefficient	2 - 4

Optimal calibration of the model parameters were obtained for three different model setups by using meteorological and discharge data. Comparison of calibrated model parameters with model setups are performed. Performance of the model is evaluated by statistical measures shown in Table 4.

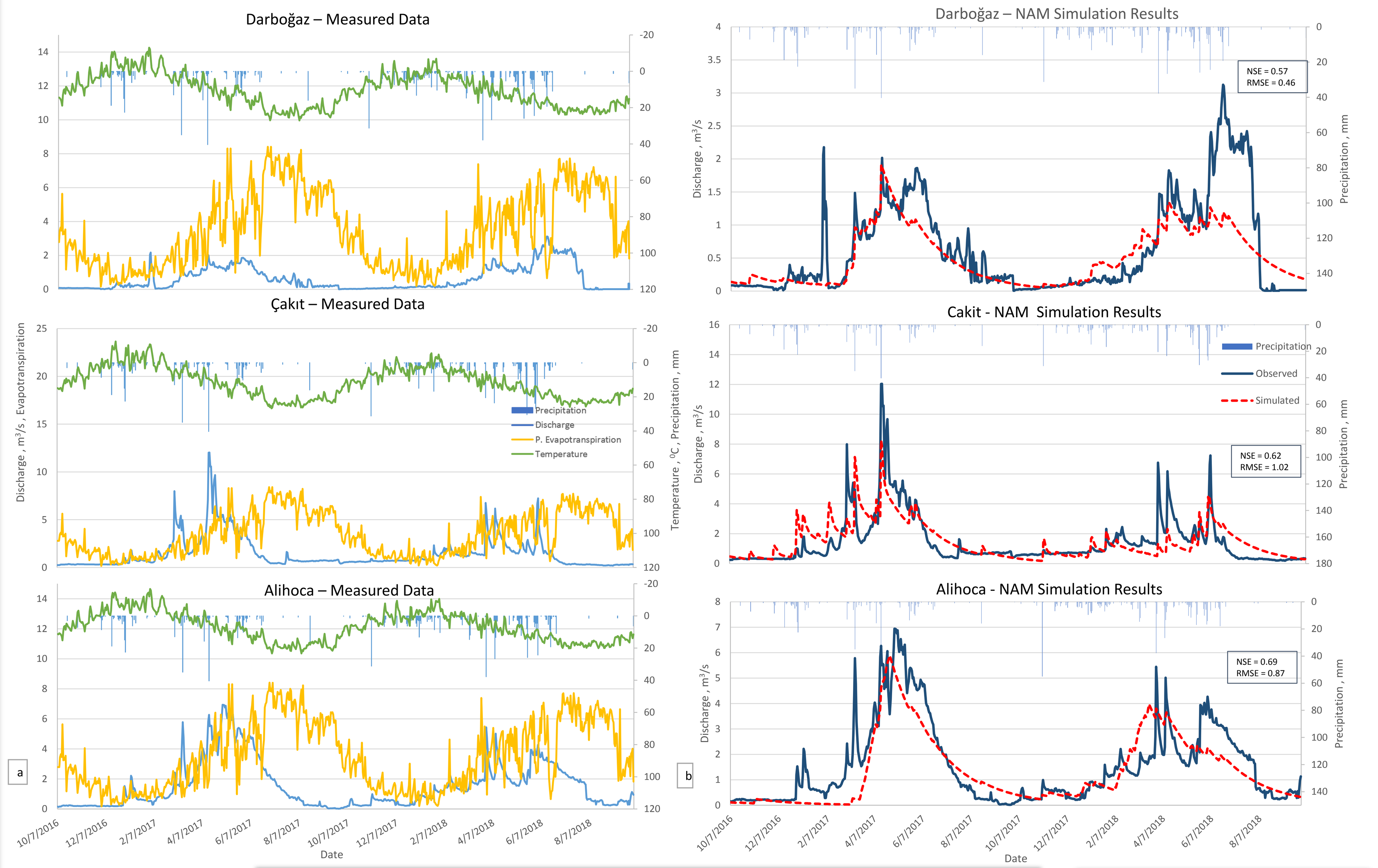

Figure 5. Model input data (a) , comparison of observed and simulated daily runoff (b) for 3 sub- basins

Temperature, precipitation, potential evapotranspiration and discharge as model input data for 3 different sub-basins are given in Figure 5 (a). Comparison of observed and simulated daily runoff is shown in Figure 5(b).

All calibrated parameters are given in Fig 6 and Table 5 according to the statistical measures used in the modelling.

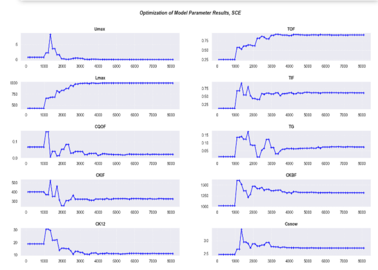

Figure 6. Calibration of model parameters

Table 5. Calibrated model parameters

	Darboğaz	Çakıt	Alihoca
U_{max}	0.00	2.20	0.00
L_{max}	192.18	1000.00	1000.00
CQOF	0.43	0.11	0.26
CKIF	992.82	927.88	919.75
CK12	27.01	43.12	20.24
TOF	0.75	0.00	0.97
TIF	0.52	0.84	0.66
TG	0.00	0.10	0.07
CKBF	1250.62	1125.04	1325.27
C_{snow}	0.66	0.85	2.72

Table 4. Statistical measures

$$NSE = 1 - \frac{\sum_{t=1}^{n_t}\left(Q_t^{Observed} - Q_t^{Simulated}\right)}{\sum_{t=1}^{n_t}\left(Q_t^{Observed} - \bar{Q}_t^{Observed}\right)}$$

$$RMSE = \sqrt{\frac{1}{n_t}\sum_{t=1}^{n_t}\left(Q_t^{Observed} - Q_t^{Simulated}\right)^2}$$

$$P.BIAS = 100 * \frac{\sum_{t=1}^{n_t}\left(Q_t^{Observed} - Q_t^{Simulated}\right)}{\sum_{t=1}^{n_t}\left(Q_t^{Observed}\right)}$$

$$R^2 = 1 - \frac{\sum_{t=1}^{n_t}\left(Q_t^{Observed} - Q_t^{Simulated}\right)^2}{\sum_{t=1}^{n_t}\left(Q_t^{Observed} - \bar{Q}_t^{simulated}\right)^2}$$

Sensitivity Analysis and Results

Sensitivity analysis on 10 model parameters is also performed. Nash-Sutcliffe efficiency (NSE) , Root Mean Square Error (RMSE), Percent BIAS and Coefficient of Determination (R²) values are used as statistical measures (Figure 7).

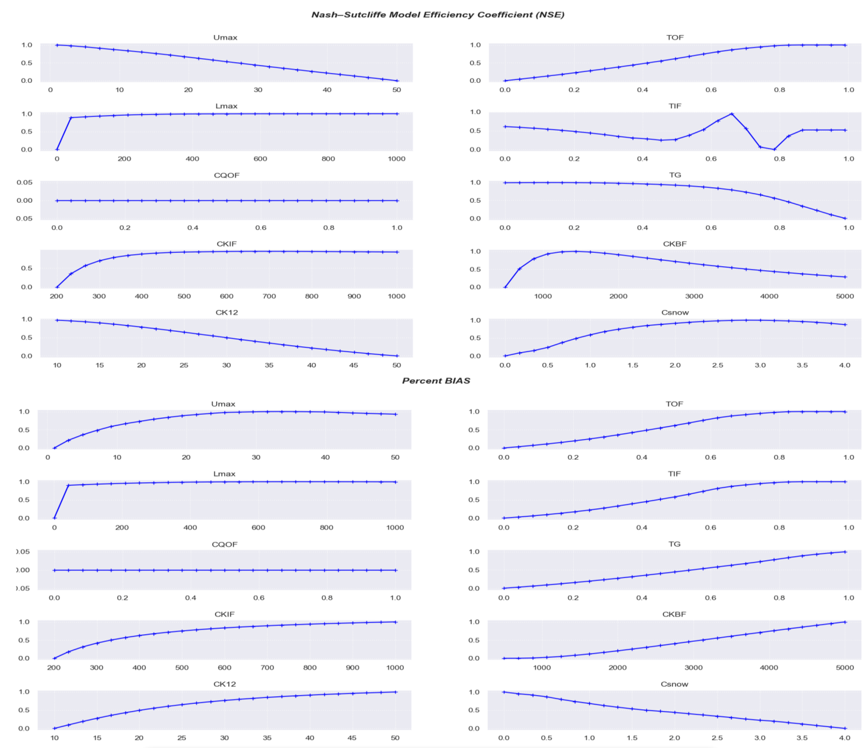

Figure 7. Sensitivity analysis results for Alihoca basin

- NAM Model is successful in predicting runoff.
- However, it is seen that simulated runoff when snow melting process is dominant underestimated in Darboğaz and Alihoca sub-basins.
- Calibrated model parameters also varies significantly for each sub-basin due to different hydrological characteristics.
- Most sensitive model parameters are found as U_{max} and L_{max} based on statistical measures. Moreover, CQOF parameter is the least sensitive one for all basin.
- Due to high basin mean elevation, snow accumulation and melting processes are dominant. Therefore, contribution of CQOF parameter to runoff is relatively small.

Flow Routing

- Muskingum-Cunge flow routing method is used for the flow routing.
- The results of Muskingum-Cunge method is checked with the results of HEC-RAS hydraulic model with simplyfied hydrograph and rectangular river cross section (Figure 8 – 9).
- Results indicate that Muskingum-Cunge method gives good approximation of the routed flow. (Figure 8).
- Hydrograph as a result a hydrological model is routed to the outlet of the basin for each sub-basin considering river cross section is rectangular with average top width, slope and manning's value obtained from elevation map as well as satellite images (Figure 10).

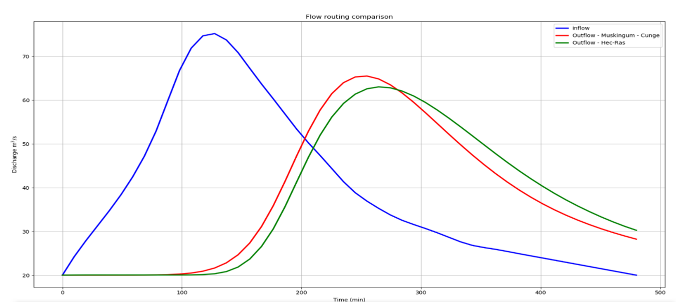

Figure 8. Comparison of Muskingum-Cunge routing with Hec-Ras hydraulic model

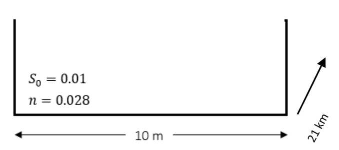

Figure 9. Representative river cross section

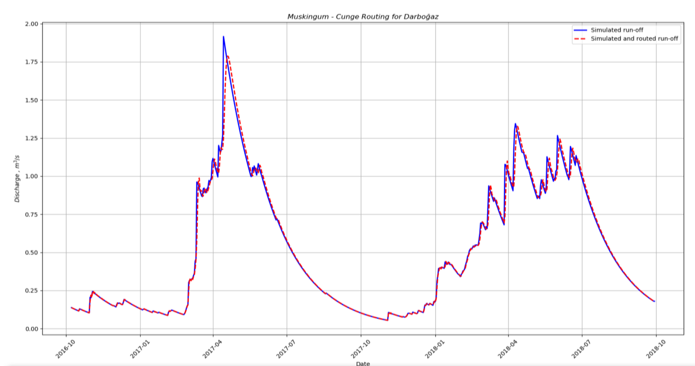

Figure 10. Simulated and routed flow for Darboğaz basin

Software Development

An open source computer software is designed to simulate the hydrologic processes of dendritic watershed systems. The software includes modules developed for automated basin delineation, hydrological model, flow routing, calibration, sensitivity analysis and uncertainty analysis (Figure 11).

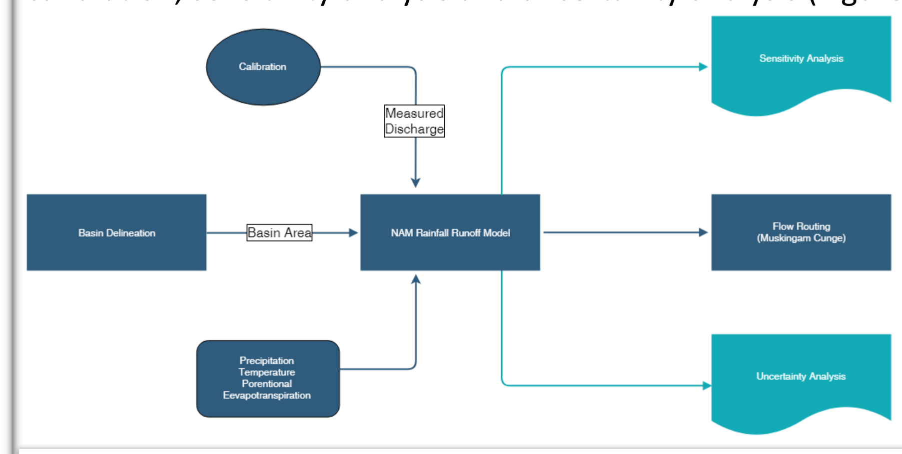

Figure 11. Flow chart of computer software

- Model is served as a web service (At the front end OpenLayers5, JavaScript, HTML and CSS, at the back end Node.js and Python modules are used)
- User friendly web interface is designed to input data (DEM, measured data in several file formats such as csv, xlsx, txt.
- Based on DEM data and basin outlet point introduced by user, flow direction with D8 algorithm , flow accumulation layers are calculated and basin boundaries as well as river network are obtained automatically. (Figure 12)

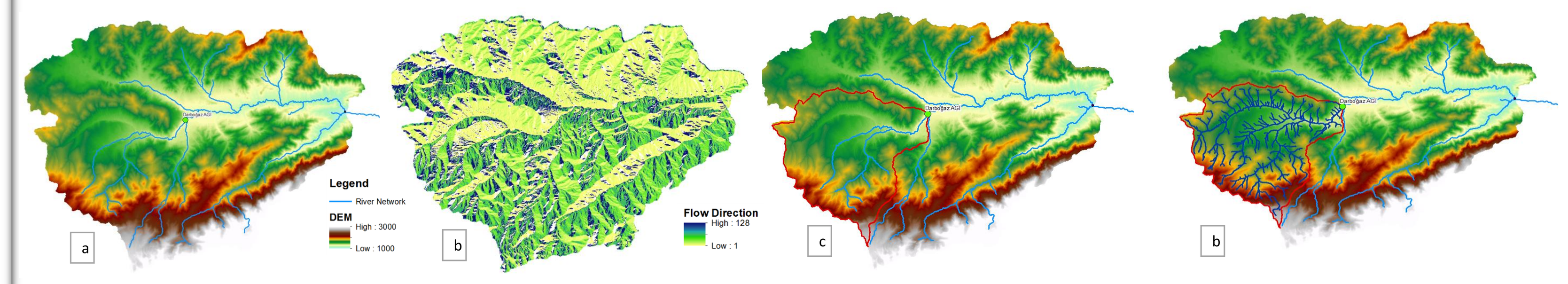

Figure 12. (a) Digital Elevation Model of study area, (b) flow direction map, (c) delineated basin boundaries, (d) delineated river network in Darboğaz Basin

- Web interface includes layers tool, basin delineation tool switch, input data viewer and model setup view. (Figure 13)
- Desired modules (NAM, routing, sensitivity etc.) can be selected to run by user.
- Model outputs are served in several file formats such as csv, xlsx, txt .

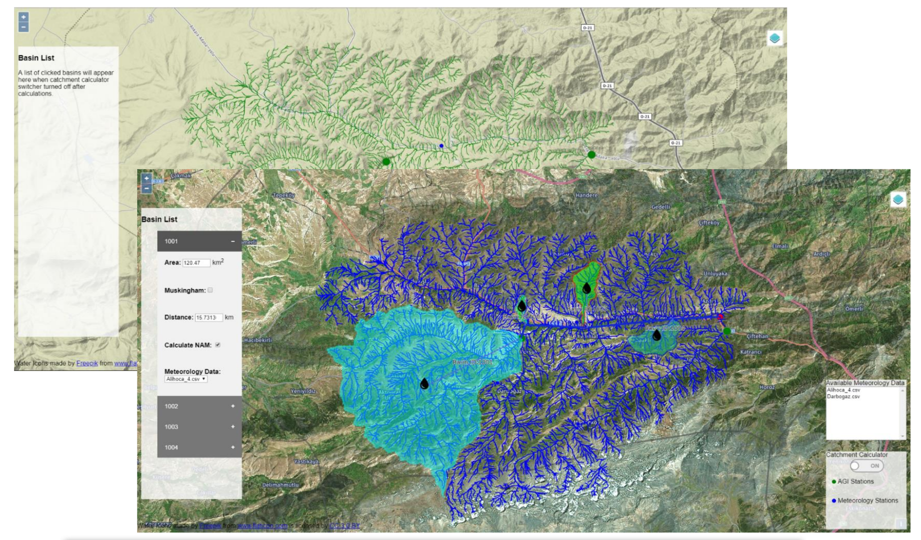

Figure 13. Web interface of computer software

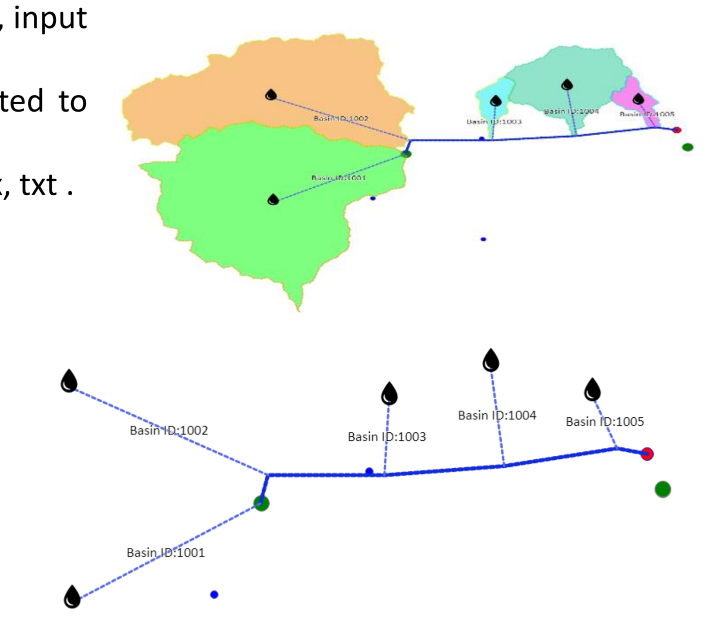

Figure 14. Digitized basin boundaries and model scheme

It is also available to specify more than one basin and each sub-basin is digitized and connected by using a simple scheme. List of basins are created and corresponding input data are supplied (Figure 14).

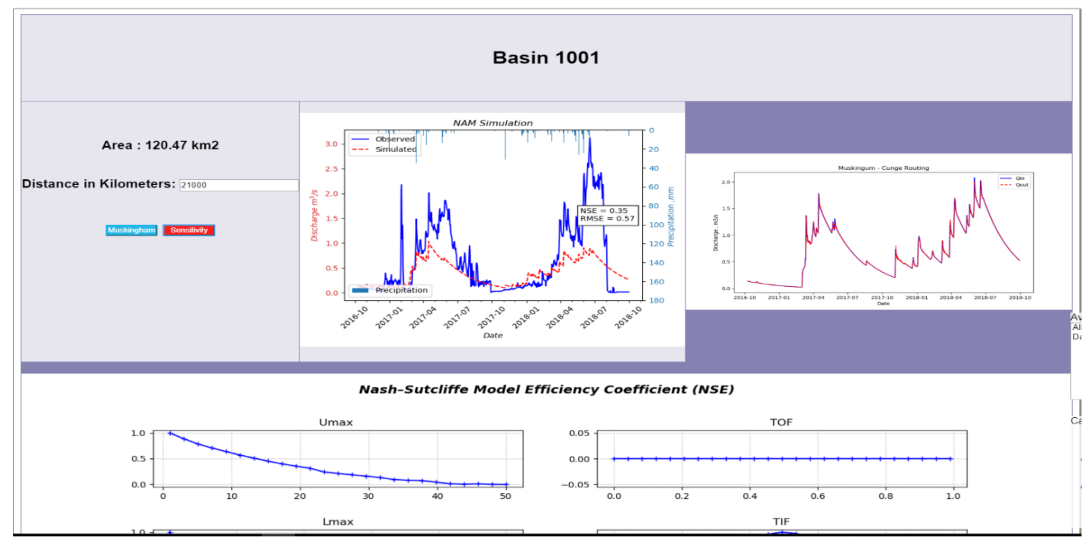

Figure 15. Visualization of results

A popup window is created for each sub-basin with a unique id number. Data input, selection of desired analysis and model parameters can be initialized.

Results can be visualized by clicking desired sub-basin. Results of sensitivity analysis of the model parameters are presented (Figure 15)

Remarks and Future Work

- Uncertainty analysis on input and model parameters module will be added to web interface.
- Multi-objective calibration of parameters will be integrated to the optimization module.
- Optimization would be also based on soil – moisture data available in study area.
- Calculation of protentional evapotranspiration by Penman-Monteith equation module will be developed.
- Computer software is considered to be publicly available.

Acknowledgement

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