

Chapter 14

Application of the Hydrological Model SWAT in the Zayandeh Rud Catchment

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14.1 Introduction

Hydrological models are effective tools to provide framework to conceptualize and investigate the relationships between climate, human activities, and water resources (Doll et al. 2008; Bennett et al. 2013). Watershed models have been widely used in several areas including integrated watershed management, peak flow forecasting, test of the effectiveness of measures for the reduction of non-point source pollution, soil loss prediction, assessment of the effect of land use change, analysis of causes of nutrient loss, and climate change impact assessment (Tang et al. 2012). Among hydrological models, distributed models have important applications because they relate model parameters directly to physically observable land surface characteristics (Legesse et al. 2003). The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) is a process based model, used extensively for hydrologic simulation at different spatial scales to investigate management strategies on watershed hydrology and water quality response (e.g. Schoul et al. 2008; Faramarzi et al. 2009; Faramarzi et al. 2010; Tang et al. 2012; Qiu et al. 2012; Faramarzi et al. 2013). The reliability of such applications depends on the accuracy of hydrological models in representing the physical processes, correct input data, and proper model calibration

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(Faramarzi et al. 2015). As such, a key challenge is initially to set up an accurate hydrological model, which correctly represents the site's actual physical processes.

With an area of about 28,000 km², Zayandeh Rud basin is located in central part of Iran, where hydro-climatic and geospatial conditions vary considerably from the western highlands to the eastern lowland regions. Frequent and prolonged droughts, human factors such as population growth and economic development, as well as climate change present a significant concern for reconciling the limited water resources among all conflicting sectors (i.e. energy and food production, hydro-power generation, forestry, recreation and rural development) while ensuring a sustainable economy in the basin.

We used the SWAT model in combination with Sequential Uncertainty Fitting program (SUFI2) (Abbaspour 2011) to calibrate and validate a hydrological model of the Zayandeh Rud basin using the stream flow data of 17 hydrometric stations for the 1990–2009 period. Our goal was to simulate the natural historical and future stream flow data and use it in MIKE BASIN (MB) water allocation model for water resource management of the basin. The details of the MB model have been described in an earlier chapter of this volume. Our specific objectives in this study were (1) to construct a representative hydrological model of the Zayandeh Rud basin using the best available dataset and engaging stakeholders; (2) calibrate and validate the hydrologic model of the basin using the discharge data of 17 hydrometric stations; (3) to naturalize the stream flow data as input to the MB model.

14.2 Hydrological Model

SWAT is a computationally efficient simulator of hydrology and water quality at various scales. The model is physically based rather than incorporating regression equations to describe relationships between input and output variables. It is a mechanistic time-continuous model that can handle very large watersheds in a data efficient manner and is not designed to simulate detailed single-event flood routing (Neitsch et al. 2011). Overall, the model has been developed to quantify the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land uses, and management conditions over long periods of time. The main components of SWAT are hydrology, climate, nutrient cycling, soil temperature, sediment movement, crop growth, agricultural management, and pesticide dynamics (Neitsch et al. 2011).

SWAT model spatial parameterization is performed by dividing the watershed into sub-basins based on topography. These are further subdivided into a series of hydrologic response units (HRUs), based on unique elevation, soil, land use, and slope characteristics. The responses of each HRU in terms of water and nutrient transformations and losses are determined individually, aggregated at the sub-basin level and routed to the associated reach and catchment outlet through the channel network. SWAT represents the local water balance through four storage volumes: snow, soil profile (0–2 m), shallow aquifer (2–20 m) and deep aquifer (>20 m). The

soil water balance equation is the basis of hydrological modeling. The simulated processes include snow fall and snow melt, surface runoff, infiltration, evaporation, plant water uptake, lateral flow, and percolation to shallow and deep aquifers. Surface runoff is estimated by SCS curve number equation using daily precipitation data based on soil hydrologic group, land use/land cover characteristics and antecedent soil moisture. A more detailed description of the model is given by Neitsch et al. (2011). In this study, ArcSWAT 2009 was used, where ArcGIS (ver. 9.3) environment is used for project development.

14.3 Study Area

14.3.1 Climate

The Zayandeh Rud basin with an area of about 28,000 km² is located between 31 and 34 degrees north latitude and 49 and 53 degrees east longitude (Fig. 14.1). The Zayandeh Rud river originates from the Zagros Mountains, west of the city of Isfahan, and flows 350 kilometers eastward before ending in the Gavkhuni swamp, southeast of Isfahan city. The Zayandeh Rud river highly relies on annual snowfall in the Zagros Mountains, and therefore it is highly dependent on climate variability. The altitude varies from 1454 m to 3925 m, which has a pronounced influence on the diversity of the climate. With an average annual precipitation of 211 mm year⁻¹, the northern and high altitude areas found in the west receive about 300–1345 mm year⁻¹, while the central and eastern parts of the basin receive 75–230 mm year⁻¹. Long-term average winter temperatures of -0.4 °C in high altitudes and 11 °C in eastern low land regions, and summer temperatures of more than 7 and 24 °C in the western and eastern regions have been recorded, respectively (Fig. 14.2a–c). The temporal variations of these climate parameters are significant. Precipitation occurs mainly in winter months from December to April, and temperature reaches to 35 °C in July while it drops to -5 °C in January (Fig. 14.2d–f).

14.3.2 Hydrology

Overall, the hydrological, climatic and management conditions vary considerably in the basin. Accordingly we considered a total of seven major regions in this study to model the hydrological processes (Fig. 14.3). The main characteristics of these regions are as follows:

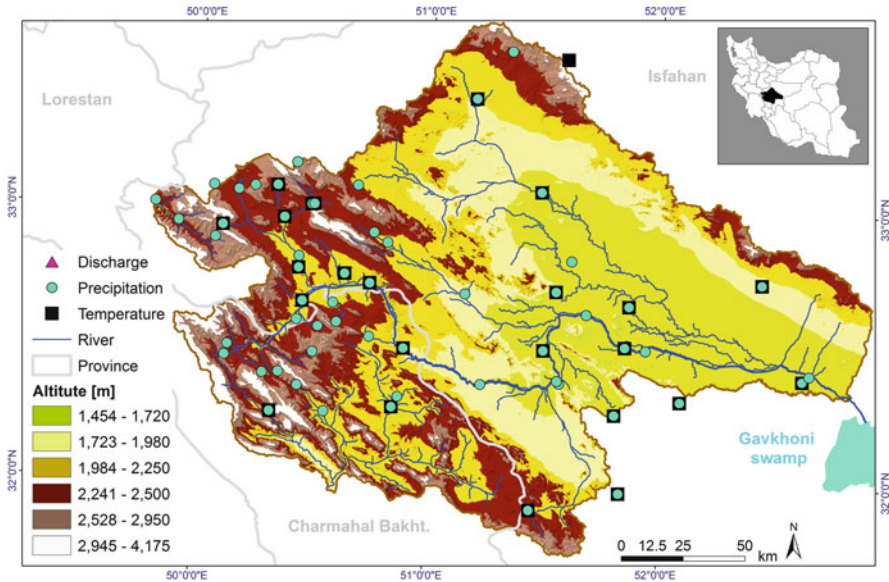


Fig. 14.1 Geographic location of the Zayandeh Rud river basin, the SRTM 90 m DEM map of the study area, and the spatial distribution of the model used precipitation, temperature, and hydro-metric gauges

14.3.2.1 Upstream Zayandeh Rud Dam

A high altitude and snow fall and accumulation in fall and winter seasons and snow melt in spring time make this region different in climatic and hydrological conditions from the other regions of the study area. The precipitation is about 1400 mm in high altitude areas. With a total drainage area of about 4100 km², this region is the main source of water supply in the Zayandeh Rud basin. Water yield and flow regime in this region is altered mainly by water transferred from Karoon and Dez basins. The Cheshmeh Langan water transfer tunnel is being excavated for transferring water from Sardab river, Sibak river, and Cheshmelangan spring to Zayandeh Rud basin. Its yield is around 12 MCM to the basin. Koohrang Tunnels (Tunnel 1 and Tunnel 2, construction completed in 1950) redirect some of the Koohrang's water toward the Zayandeh Rud river. The annual yield of these water transfer projects are 250–300 MCM. The Sadtanzimi station is located past the Chadegan dam where the water is regulated and released for downstream users (Fig. 14.3).

14.3.2.2 Downstream Zayandeh Rud Dam

In this region the flow regime is highly regulated by the Chadegan dam, Sadtanzimi station, and later influenced by various water diversion schemes including modern and traditional irrigation networks, diversion dams along the river, and water

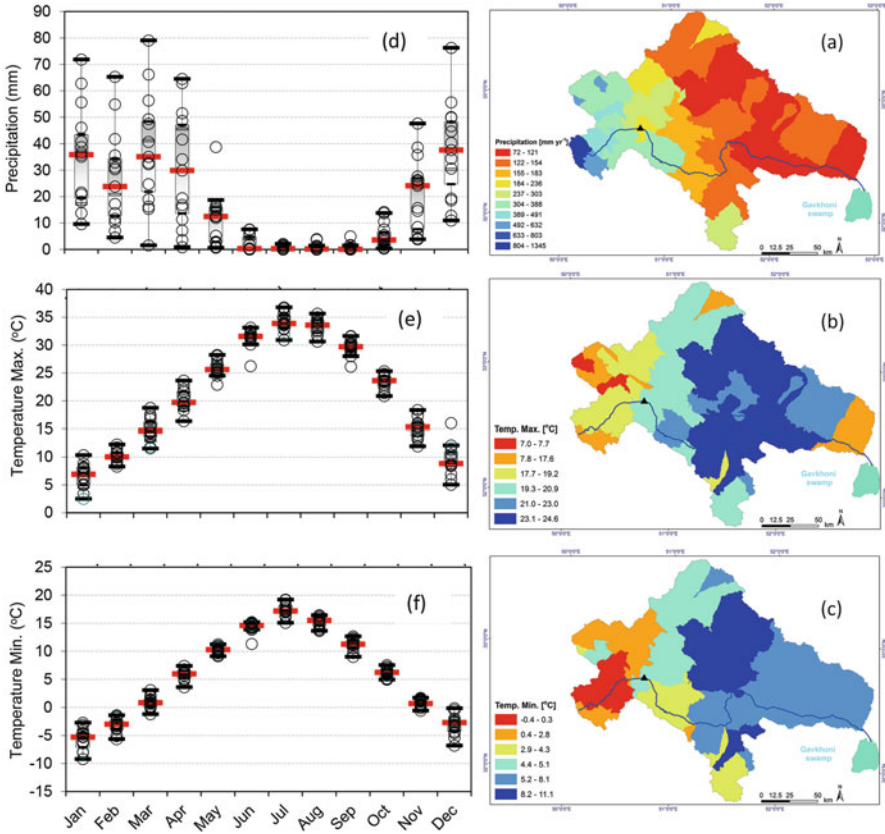


Fig. 14.2 Long-term (1990–2009) average annual (a–c) and monthly (d–f) precipitation, maximum temperature, and minimum temperature of Zayandeh Rud river basin. Circles show year to year variation of the climate variables at different months of the study period (1990–2009). Box-plots show minimum, 25th percentile, median (shown with red dashes), 75th percentile, and maximum values

extraction wells distributed on river bank (e.g. Felman wells). The natural climatic conditions vary from 300 mm year⁻¹ near Chadegan dam to below 75 mm year⁻¹ near Gavkhuni swamp.

14.3.2.3 Shoor River and Mobarakeh Tributary

This river originates in the southern highlands, and flows northward to end at the Zayandeh Rud right before the Dizicheh hydrometric station. The total drainage area of this river is approximately 1,653 km². In general the Shoor river has almost no contribution to Zayandeh Rud river. Most of the water which is generated at upstream Shoor is consumed in agricultural lands and villages in that part of the region. Therefore, the river is almost dry before it reaches to the main Zayandeh Rud river.

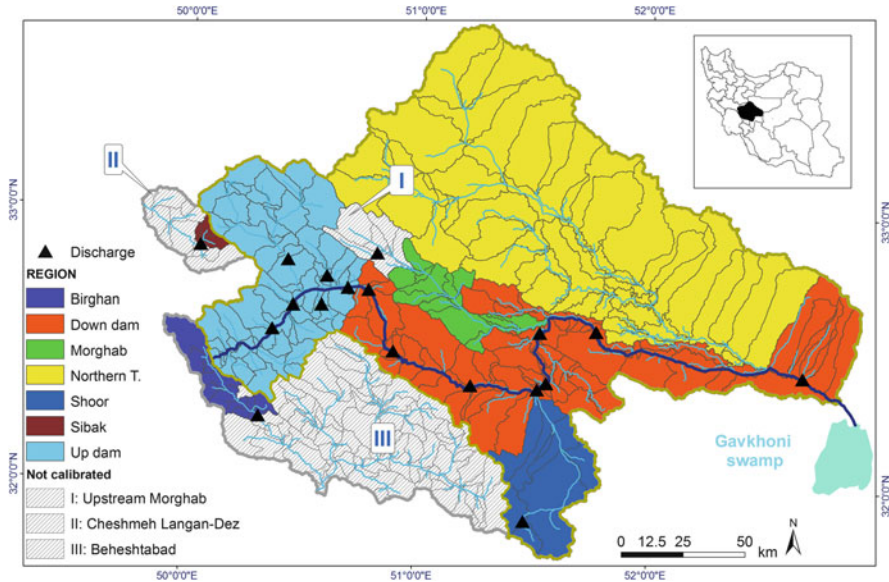


Fig. 14.3 The main hydrological regions of Zayandeh Rud basin. I: the management data are not available; II, and III: calibration of these regions is beyond the scope of our study

Similar hydrological and management conditions are to be found in Mobarakeh tributary (located west of Shoor river). The contribution of this tributary to the Zayandeh Rud is negligible.

14.3.2.4 Northern Tributaries (Dastkan River)

With a drainage area of about 12,520 km², the stream flow generated in this river is not reaching the Zayandeh Rud where (traditional or modern) irrigation networks are located. Similar to Shoor river basin, the discharge from tributaries in this region is fully used before it reaches to the main river or to the main irrigated networks. Water harvesting is practiced in most of the upstream tributaries during the wet seasons and water is artificially discharged into groundwater for later uses during the dry seasons. The potential water users of this region are agriculture, industries, and drinking water in rural and urban areas (Fig. 14.3).

14.3.2.5 Morghab River

Morghab river originates from streams and springs located at the northern side of Chadegan dam. Hydrological and management conditions are different in its upstream and downstream areas. Upstream, Morghab is fed mainly by the Cheshmeh-Morghab spring before the Ghalenazer hydrometric station. The

Khamiran dam is constructed in this river section after a confluence of the Cheshmeh Morghanb river and Kordolia tributary. The dam is supplied by the water yield of these two upstream tributaries and through the Karvan water transfer project. It is the source of water for downstream users e.g. Karvan irrigation networks. The total drainage area of Morghab river, from its originating tributaries to the mouth of the river where it joins the Zayandeh Rud, is about 1,463 km². Similar to Shoor and Dastkan rivers, stream flow generated in this river basin does not reach to Zayandeh Rud as it is used partly outside of irrigation networks.

14.3.2.6 Behestabad-Birghan River Basin

We included in this study the Beheshtabad river basin where the two main water transfer projects (Koohrang Tunnels 1 and 2) have existed for years. This river basin is not part of the Zayandeh Rud basin but is the potential source for future water development plans and belongs to the upstream catchments of the Karoon-Dez river system in western Iran. In this study, however, we opted to calibrate upstream Dezakabad hydrometric station with a drainage area of about 614 km². The Birghan river (upstream tributaries of Beheshtabad) flows in this basin and Koohrang dams are located on this river.

14.3.2.7 Cheshmeh Langan Spring-Sibak Basin

The Cheshmeh Langan spring is located in the upstream part of Dez river basin. A tunnel was constructed to transfer its water into Cheshmeh Langan dam located at the confluence of Sardab and Sibak rivers upstream of the Zayandeh Rud basin. The only hydrometric station measuring stream flow in this region is Charkhfalak station downstream of Sibak river. While we incorporated the upstream Dez basin in this study, we calibrated only the Sibak river, with an area of about 95 km².

14.3.3 Management

The water management and regulation of the Zayandeh Rud basin has changed over time. Before the 1960s, the distribution of water in the Zayandeh Rud watershed followed the 'Tomar', a document based on which the Zayandeh Rud stream flow was divided into 33 parts which were then specifically allotted to the eight major districts within the region. At the district level the water flow was divided either on a time basis, or by the use of variable weirs, so that the proportion could be maintained regardless of the height of the flow. After 1960, population growth, economic development within the basin, and rising standards of living particularly within the city, caused an increasing pressure on water resources so that the division of water according to Tomar was no longer feasible. Development of modern

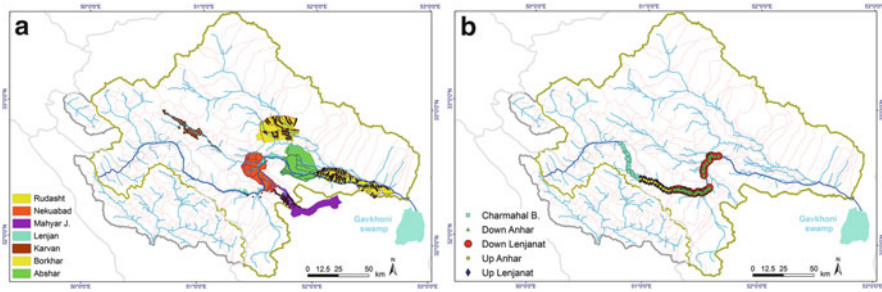


Fig. 14.4 Modern (a) and traditional (b) networks of water supply in the Zayandeh Rud river basin

irrigation networks (Fig. 14.4a) instead of traditional diversion through pumping from the shallow and deep wells (Fig. 14.4b), the creation of large steel works, Zobahan-e-Isfahan, Foolad Mobarekeh steel companies, Isfahan's petrochemical, refinery and power plants, and other new industries demanded more water than the past.

Agriculture is reported to be the largest water user accounting for about 80% of total water consumption in the basin. Three different sources of water supply the agricultural sector. These are surface water (mainly from Zayandeh Rud river), groundwater (mainly in the plains located far from the main river to access surface water), and waste water (WW). Among them the portion of surface water is the largest compared to WW which accounts for a sparse supply.

In response to increasing water demand, three main inter-basin water transfer projects were developed to convey water from the head water tributaries of Karoon-Dez river basin in south west Iran into the western upstream tributaries of Zayandeh Rud basin. These are Koohrang Tunnel 1 (Chelgerd WT project), Koohrang Tunnel 2 (Darreh Dor WT project), and Cheshmeh Langan or Vahdatabad WT project. Large hydraulic structures such as tunnels, channels, pipes, dams, and pumping stations were constructed to implement water transfer projects.

In addition to the inter basin water transfer projects, a multipurpose storage reservoir with an average annual outflow of $47.5 \text{ m}^3 \text{ s}^{-1}$ was constructed in 1972 to regulate and to allocate water during drought and dry spells. With a storage capacity of 1500 MCM, the reservoir captures most of the spring floodwater and releases it gradually throughout the summer. This has enabled the expansion of summer cropping lands (rice and maize), hydropower generation of 55.2 MW, utilization to meet the industrial and urban water demands, as well as flood control in spring time.

In this study we have considered the operation of major water management projects in the hydrological model of the basin as these anthropogenic changes can alter the downstream hydrological system. It is worth mentioning that our goal is to simulate both the Zayandeh Rud river basin and the upstream catchments of the Karoon-Dez watersheds which are considered as the major source of water supply for the Zayandeh Rud basin, through current and future water development and

Table 14.1 Input data used to build hydrological model of the study area

Data type	Data name	Time span	Resolution/ time step	Nr. of stations	Source
Climate	Precipitation (Rain gauge)	1990–2009	Daily	32	Isfahan Regional Water Board
	Precipitation (Evaporation gauge)	1990–2009	Daily	13	Isfahan Regional Water Board
	Precipitation (Climatology)	1990–2009	Daily	8	Iranian Meteorological organization
	Precipitation (Synoptic)	1990–2009	Daily	5	Iranian Meteorological organization
	Maximum and minimum temperature (Evaporation gauge)	1990–2009	Daily	11	Isfahan Regional Water Board
	Maximum and minimum temperature (Climatology)	1990–2009	Daily	9	Iranian Meteorological organization
	Maximum and minimum temperature (Synoptic)	1990–2009	Daily	5	Iranian Meteorological organization
Digital maps	DEM SRTM	2008	90 m × 90 m	–	Jarvis et al. (2008)
	Land use/Land cover	2005	1:250,000	–	Iranian Forest, Rangeland and Watershed Management Organization (IFRWMO)
	Soil map (map of land unites and map of land components)	2009	152 soil types	–	Jahad-e-Agriculture
	Soil properties	2000	maximum of 6 soil layers	353 soil profile	Isfahan Agricultural Research Institute
Management	Reservoir/dam	1990–2009	Daily	1	Iranian Ministry of energy; Isfahan Regional Water Board
	Inter-basin water transfer (Inflow to the basin: Koohrang 1-2, and Cheshmeh Langan)	1990–2009	Daily	3	Iranian Ministry of energy; Isfahan Regional water Board

(continued)

Table 14.1 (continued)

Data type	Data name	Time span	Resolution/ time step	Nr. of stations	Source
	Consumptive water use: Modern Irrigation Networks	1990–2009	Monthly/ seasonal	7	Isfahan Regional Water Board
	Consumptive water use: Traditional Irrigation Networks	1990–2009	Monthly/ seasonal	Water wells of five regions along the river	Isfahan Regional Water Board
	Consumptive water use: Industry	1990–2009	Monthly/ seasonal	major industries	Isfahan Regional Water Board
	Consumptive water use: Municipal	1990–2009	Monthly/ seasonal	Isfahan city and others	Isfahan Regional Water Board
	Water transfer to other basins (Yazd and Kashan WT projects)	1990–2009	Monthly/ seasonal	2	Isfahan Regional Water Board
Hydrometric	Stream flow	1990–2009	Daily/ monthly	17	Iranian Ministry of energy; Isfahan Regional Water Board

transfer projects. Therefore, our modelled area is larger than the Zayandeh Rud basin (Figs. 14.1 and 14.3).

14.4 Input Data and Model Setup

Table 14.1 summarizes input data used to develop the SWAT hydrological model of the study area. A digital elevation model (DEM) was used for stream network and sub-basin delineation.

Figure 14.1 shows different elevation bands classified using the ESRI 90m DEM for the study area. The land use/land cover map was obtained from the Iranian Forest Rangeland and Watershed Management Organization (IFRWMO). The map has a spatial resolution of 1:250,000 and it is created using Landsat images of the year 2005 (Fig. 14.5a). With this resolution, 27 land use classes were identified in the study area. We further used SWAT database to initially characterize each land use class for the study area. A total of 41 land use parameters were assigned for each land use class illustrated in Fig. 14.5a. A soil map of basin coverage was not available. We used different components available from different organizations to build a soil map of the study area. The soil properties were acquired from Isfahan

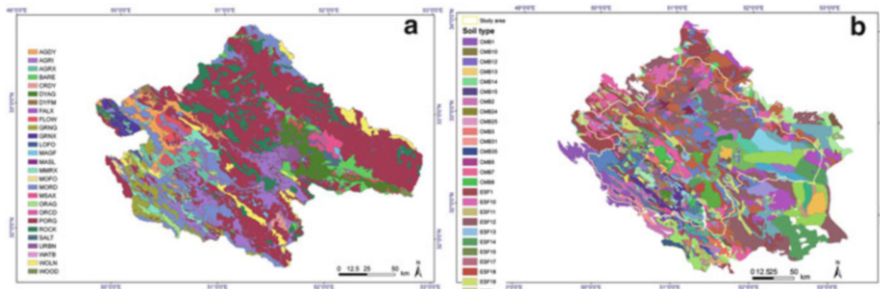


Fig. 14.5 Land use (a) and soil (b) maps of the study area. Example land use classes and soil types are shown in the legends

Agricultural Research Institute (IARI). Soil properties of approximately 353 soil profiles were studied by IARI, and data including sand, silt, and clay contents, rock fragment content, organic carbon content, soil electrical conductivity, water content, porosity, bulk density, saturated hydraulic conductivity, and soil hydrologic groups were available for each soil profile (Fig. 14.5b).

Climate data, including daily total precipitation (mm), maximum and minimum temperature ($^{\circ}\text{C}$), and snow fall ($\text{mm.H}_2\text{O}$) were obtained from various sources in the study area (see Table 14.1). Other than snow fall data, the rest is required as input data for the SWAT model. Snow fall data was used for model verification in terms of partitioning the total precipitation to rain and snow. A preliminary analysis of climate data resulted in the selection of older stations which provided longer time series and contained less missing values. The availability of climate data was the main criterion to decide the study period. Figure 14.1 shows the distribution of the climate stations used in this study. Likewise, only 17 hydrometric stations were selected for the calibration and validation of the SWAT simulation results (Figs. 14.1 and 14.3).

We used the digital maps (i.e., DEM, land use, and soil) to delineate and characterize spatial units and river network for the study area. Providing a 20 km^2 as the minimum threshold area and eliminating unnecessary outlets created by the model, we delineated a total of 370 sub-basins for the study area. We considered dominant land use, dominant soil, and dominant slope for each sub-basin to balance data resolution and model complexity.

As the management control structures and water diversion plans can disrupt natural processes, we incorporated the operation of various management options in our hydrological model. These included diversion of surface water for consumptive use by various sectors, upstream flow regulation by reservoir/dam, and inter-basin water transfer projects. The consumptive water use included monthly water diversion through traditional and modern irrigation networks, and water needs of industries, and domestic sectors as well as those transferred to Yazd and Kashan provinces. A detailed analysis of water use data indicating monthly and seasonal

fluctuations was conducted by the project team and was fed into the SWAT hydrological model.

A preliminary analysis of the available data for the inter-basin water transfer plans revealed that in Koohrang Tunnel 1, Koohrang Tunnel 2, and Cheshmeh Langan projects the daily data was not consistent and subject to some missing data for the earlier periods. We estimated the missing data at stakeholder meetings and using other available information. Further we calculated the monthly data and fed them into the SWAT model for the period 1990–2009 (Calibration-validation period).

We used the daily outflow of the Sadtanzimi and allowed the model to simulate the Zayandeh Rud dam's operation through modelling upstream water inflow to the reservoir and the water inflow-outflow processes in the reservoir behind the dam. It is important to mention that although the measured outflow data of dam was provided as input to the model, a proper simulation of the dam outflow in the model relies on the accuracy of the stream flow simulation in the upstream catchments. An improper stream flow simulation at the upstream tributaries of the dam can result in incorrect inflow to the reservoir which then results in emptying or overflowing of the dams (Faramarzi et al. 2015).

In this study, surface runoff was simulated using the SCS curve number method. Potential evapotranspiration (PET) was simulated using the Hargreaves method (Hargreaves and Samani 1985). Actual evapotranspiration (AET) was predicted based on the methodology developed by Ritchie (1972). The daily value of the leaf area index (LAI) was used to partition the PET into potential soil evaporation and potential plant transpiration. LAI and root development were simulated using the “crop growth” component of SWAT. This component represents the interrelation between vegetation and hydrologic balance. The calibration and validation time period was from 1990 to 1998 and 1998 to 2009, respectively, where the first three years were used as the model warm-up period.

14.5 The Calibration Program SUFI-2 and Calibration Setup

We used the SUFI-2 program to calibrate and validate the model using the observed monthly river discharge data of 17 stations for the years 1990–1998 and 1998–2009, respectively. Using this program the prediction uncertainties associated with input data (e.g., rainfall), conceptual model (e.g., process simplification), and model parameters (non-uniqueness) are aggregated and mapped into the parameter ranges. The parameter uncertainty leads to uncertainty in the output which is quantified by the 95% prediction uncertainty (95PPU) calculated at the 2.5% (L95PPU) and the 97.5% (U95PPU) levels of the cumulative distribution obtained through Latin hypercube sampling. Starting with large but physically meaningful parameter ranges that bracket ‘most’ of the measured data within the

95PPU, the SUFI2 decreases the parameter uncertainties through a semi-automated calibration procedure iteratively. In this procedure the best parameter set obtained through previous iteration is considered as the base to narrow the uncertainty band in the next iteration. In this iterative simulation technique where predicted output is presented by a prediction uncertainty band instead of a signal, two different indices are used to control the prediction performance (Abbaspour 2011).

Sensitivity, calibration, validation, and uncertainty analysis were performed for the hydrology using monthly river discharge data. As the SWAT model involves a large number of parameters, sensitivity analysis was essential to identify the key parameters across different regions of the study area. For the sensitivity analysis, 22 parameters integrally related to stream flow were initially selected (Table 14.2). In a second step, these parameters were further differentiated by main hydrological regions (Fig. 14.3) in order to account for regional and spatial variation in climate and management conditions. This resulted in 102 spatially scaled parameters. For this study, to better account for the regional diversity, each hydrological region was parameterized and calibrated separately.

14.6 Precipitation, Temperature, and Snow Simulation

The simulation results showed an average annual precipitation of 257 mm year⁻¹ for the study area. We found that the high altitude areas found in the west received about 300–1345 mm year⁻¹, while the central and eastern parts of the basin received 75–230 mm year⁻¹. Long-term average winter temperatures of -0.4 °C in high altitudes and 11 °C in eastern low land regions, and summer temperatures of more than 7 and 24 °C in the western and eastern regions were found, respectively. The temporal variations of these climate parameters were significant. The precipitation occurred mainly in winter months from December to April, and temperature reached to over 35 °C in July while it dropped to below -5 °C in January. We also verified the simulated precipitation data with those of reported by Water and Sustainable Development Reports (WSDR). For the purpose of comparison, the weighted averages of precipitation at sub-basin level were computed and aggregated to account for the average annual (1990–2009) precipitation for every WSDR sub-catchments (Fig. 14.6). The results showed that in most of the sub-catchments simulated precipitation agrees well with those of reported by WSDR.

To check the accuracy of the model in partitioning total precipitation as snow and rain, the simulated snow fall values were compared with that of observed in highland stations (Fig. 14.7). This is important because as compare to the rain, snow fall has significant but not direct contribution to the stream flow. As shown our simulation results agreed well with the measured data.

Table 14.2 Initially selected input parameters in the calibration process

Parameter name ^a	Definition	t-value ^b	p-value ^c
v__SURLAG.bsn	Surface runoff lag time (days)	2.988	0.0003
v__SMTMP.bsn	Snow melt base temperature (°C)	7.002	1.25×10^{-9}
v__SFTMP.bsn	Snowfall temperature (°C)	5.1235	7.22×10^{-8}
v__SMFMN.bsn	Minimum melt rate for snow during the year (mm/°C-day)	3.21	0.0041
v__TIMP.bsn	Snow pack temperature lag factor	3.121	0.019
v__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	2.812	0.021
r__CN2.mgt	SCS runoff curve number for moisture condition II	19.232	1×10^{-15}
v__ALPHA_BF.gw	Base flow alpha factor (days)	3.051	0.0513
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)	2.187	0.0125
v__GW_DELAY.gw	Groundwater delay time (days)	3.988	0.00021
v__GW_REVAP.gw	Groundwater revap coefficient	3.102	0.00221
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	2.015	0.00621
v__RCHRG_DP.gw	Deep aquifer percolation fraction	6.184	2.71×10^{-6}
v__ESCO.hru	Soil evaporation compensation factor	6.238	1.02×10^{-9}
r__SOL_AWC.sol	Soil available water storage capacity (mm H ₂ O/mm soil)	9.041	3×10^{-15}
r__SOL_K.sol	Soil conductivity (mm/hr)	3.018	0.0129
r__SOL_BD.sol	Soil bulk density (g/cm ³)	8.005	2.01×10^{-13}
v__SMFMX.bsn	Maximum melt rate for snow during the year (mm/°C-day)	0.059	0.821
v__EPCO.hru	Plant uptake compensation factor	2.001	0.362
r__OV_N.hrul	Manning's n value for overland flow	0.002	0.722
r__SOL_ALB.sol	Moist soil albedo	0.302	0.933
v__CH_N2.rte	Manning's n value for main channel	0.901	0.299
v__CH_N1.sub	Manning's n value for tributary channel	1.120	0.29
v__CH_K2.rte	Effective hydraulic conductivity in the main channel (mm/hr)	1.528	0.41

^av__: The parameter value is replaced by given value or absolute change; r__: parameter value is multiplied by (1+ a given value) or relative change (See Faramarzi et al. 2009 for more detail)

^bt-value indicates parameter sensitivity. The large the t-value, the more sensitive the parameter
^cp-value indicates the significance of the t-value. The smaller the p-values, the less chance of a parameter being accidentally assigned as sensitive

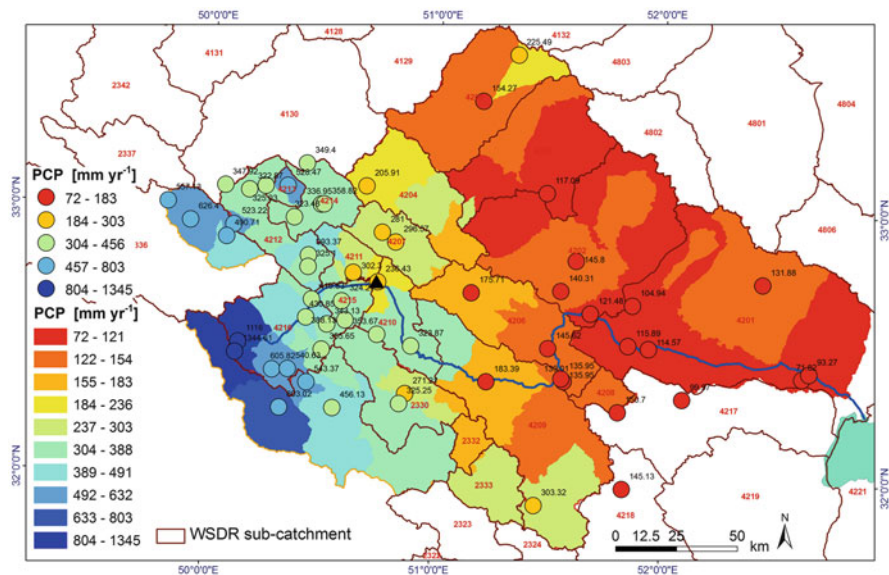


Fig. 14.6 Long-term (1990–2009) average annual precipitation. The background colors represent SWAT simulation results in each sub-basin; and the observed values are shown in circles for different rain gauges

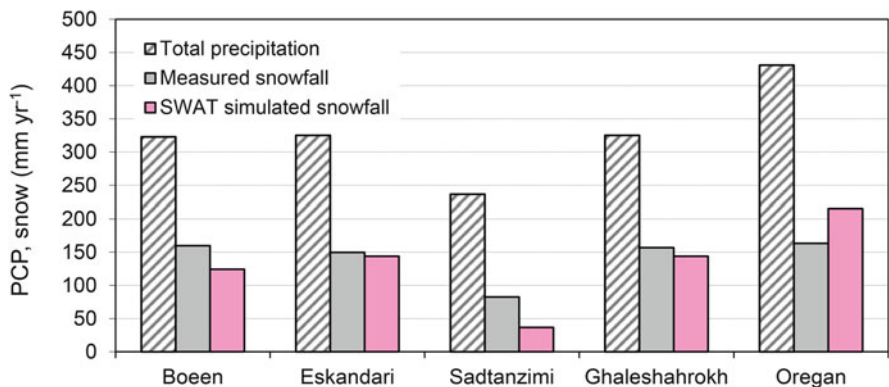


Fig. 14.7 Comparison of measured and simulated snow fall (mm) at selected high-altitude gauges

14.7 Stream Flow Simulation and Calibration-Validation Results

To calibrate and validate the hydrological model, we started with one first run to get an indication of the model performance and observed discharge stations to be used for the calibration. The results showed that many stations are highly influenced by:

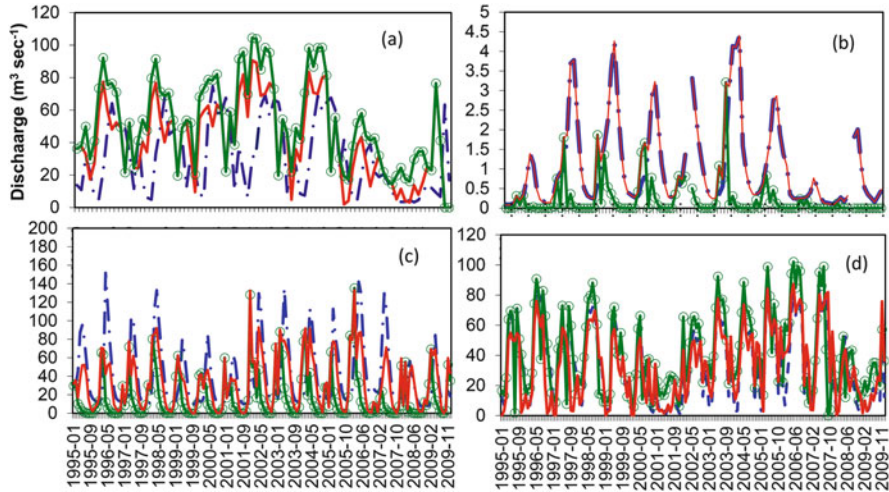


Fig. 14.8 Example of stations located at downstream of various natural and anthropogenic objects: Diziche station downstream of few check dams (a), Ghalezazer station downstream of Morghab spring (b), Ghaleshahrokh station downstream of Koohrang water transfer tunnels (c), and Polekale downstream of SadTanzimi dam (d). The red solid line and the green circled line show the swat simulated stream flow with and without simulating the effects of management or natural objects, respectively. The blue dash line shows measured stream flow data

(1) water diversion channels including traditional and modern irrigation networks, (2) reservoirs, dams (e.g., Zayandeh Rud dam), (3) springs, (4) extraction wells located at river bank, (5) inter-basin water transfers, and (7) geographic coordinates of some stations which were not properly reported and were located on a wrong tributary (Fig. 14.8).

A first run of the SWAT hydrological model, prior to calibration, revealed a considerable stream flow contribution from Shoor, Dastkan (Northern Tributaries), and Morghab rivers (see Fig. 14.3) into Zayandeh Rud main river (Fig. 14.9). This does not correspond to the actual condition. In actual condition, the Zayandeh Rud river does not receive water from these tributaries. This over estimation was mainly due to the water use data which was not available and therefore was not considered in the model. To increase model accuracy in representing the actual processes we ran several stakeholder meetings to understand the water management options and allocation scheme in these tributary catchments. Therefore, we considered water allocation to various uses within these sub catchments in the model and also adjusted physical parameters to represent actual processes related to the rain water harvesting projects in the northern tributaries to allow the surface water to be infiltrated and recharged into the ground water (Fig. 14.10).

After identifying and properly accounting for management and all other natural and anthropogenic changes (Figs. 14.8 and 14.9), we calibrated hydrological model of the basin using the discharge data of 17 hydrometric stations with the regional approach as described in the previous section (Fig 14.10). It is important to mention

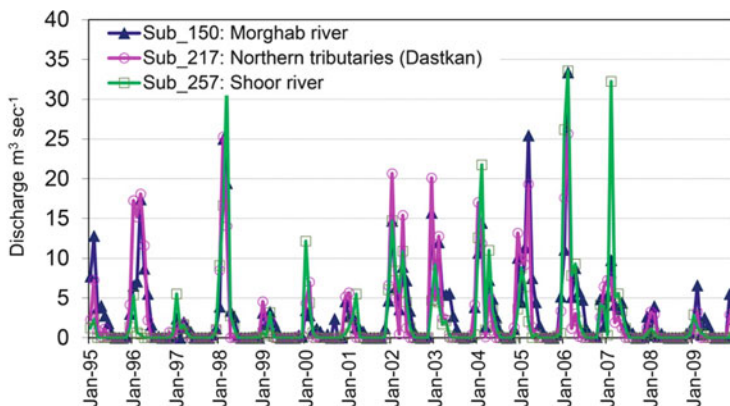


Fig. 14.9 Simulated stream flow contribution of the three main tributaries into Zayandeh Rud river prior to incorporating the water use and other management options in the model

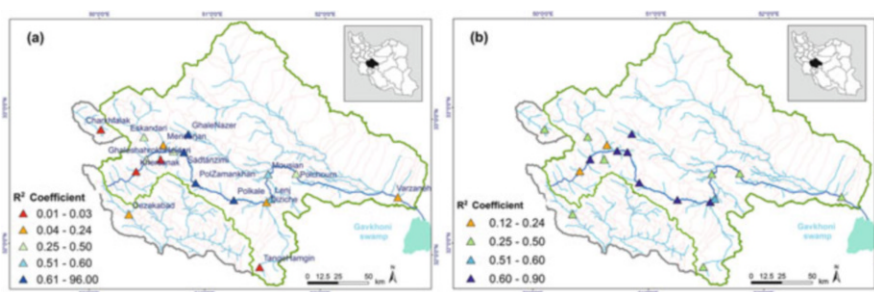


Fig. 14.10 Comparison of observed and simulated discharges using coefficient of determination (R^2) for 17 hydrometric stations: pre-calibration (a), post-calibration (b)

that an appropriate model setup incorporating the most important processes prevents over calibration of the physical models and increases model reliability in future scenario analysis (Faramarzi et al. 2015). Engagement of the stakeholders in various steps of the model development prevents this over calibration problem as it helps understanding the actual processes and increases our ability to setup a more representative model prior to calibration. Table 14.3 and Fig. 14.10 show our model performance for pre- and post-calibration steps. Overall, the basin wide bR^2 was improved from the average of 0.34 to about 0.45. However, performance gain was not identical for all stations and all sub catchments. In upstream region (see Fig. 14.3), the average bR^2 improved from 0.27 to about 0.44 while it improved from 0.39 to about 0.46 in downstream catchment. In upstream highland areas where snow is dominant in the winter season, snow hydrology and related processes were reasonably simulated with the best available data (see Fig. 14.7). However, the simulation results were not consistent for all stations in upstream catchment.

Table 14.3 Model performance of the study area during the pre- and post-calibration steps

Sub-catchments	Station name	Pre-calibration			Post-calibration		
		R ²	NS	bR ²	R ²	NS	bR ²
Upstream dam	Eskandari	0.22	-1.63	0.18	0.44	0.39	0.23
	Ghaleshahrokh	0.49	0.44	0.29	0.85	0.83	0.80
	Heidari	0.11	-42.00	0.09	0.29	-12.00	0.20
	Khersanak	0.13	-0.21	0.08	0.20	0.02	0.11
	Menderjan	0.22	-28.83	0.08	0.12	-4.35	0.09
	Sadtanzimi	0.87	0.85	0.84	0.87	0.83	0.86
	Zayand. Dam inflow	0.44	0.24	0.32	0.86	0.84	0.82
	Average	0.35	-10.16	0.27	0.52	-1.92	0.44
Downstream dam	Dizicheh	0.62	0.55	0.49	0.81	0.76	0.68
	Lenj	0.48	0.03	0.42	0.60	0.27	0.44
	Mousian	0.44	-0.08	0.40	0.49	0.14	0.48
	Polechoum	0.26	-1.61	0.25	0.30	-0.60	0.15
	Polekale	0.71	0.68	0.59	0.75	0.70	0.60
	Polezamankhan	0.82	0.76	0.76	0.82	0.76	0.76
	Tangehangin	0.23	0.17	0.15	0.36	0.26	0.25
	Varzaneh	0.09	-89.70	0.03	0.33	0.29	0.31
Average	0.46	-11.15	0.39	0.56	0.32	0.46	
Karoon-Dez	Charkhfalak	0.32	0.31	0.19	0.47	0.39	0.23
	Dezakabad	0.29	0.19	0.18	0.42	0.39	0.23
	Ghalenazer	0.78	0.52	0.69	0.90	0.66	0.86

Inadequate availability of the temperature data in Ghaleshahrokh sub-catchment (southern tributary in upstream dam) caused poorer performance (e.g. Khersanak station, Fig. 14.11a) than northern tributaries (e.g. Eskandari station, Fig. 14.11b) where more climate data were employed in the model from the nearest stations. The quantity of temperature data for upstream dam, especially in Ghaleshahrokh basin is poor and simulation of snow fall and snow melt for all modeled sub-basins located at Ghaleshahrokh basin is based on the single temperature station in Ghaleshahrokh region. In downstream stations the calibration performance was highly depended on the quality and quantity of water use and water diversion data. As shown in Fig. 14.11c, d the calibration results after Polekale station are not as desirable as those in upstream stations (see Table 14.3).

14.8 Water Balance

To further verify the model results we plotted Fig. 14.12. We aggregated our sub-basin based and monthly predictions to Zayandeh Rud basin only and compared water balance components with the results of the study conducted by Water

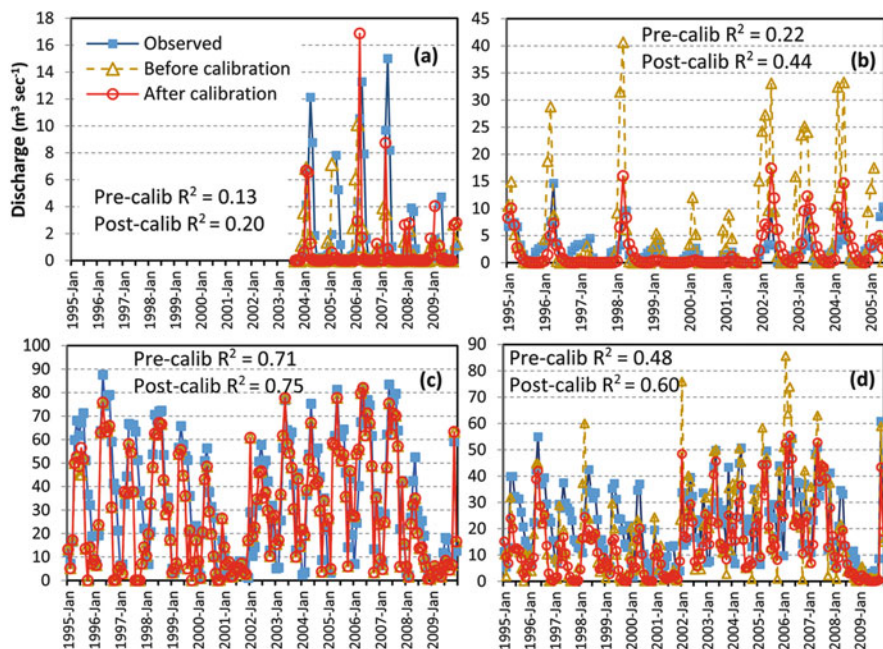


Fig. 14.11 Comparison of the observed (*blue squared blue line*) and simulated (*red circled line* for post calibration and *triangle yellow line* for pre-calibration steps) river discharges for the 1995–2009 period for selected stations: Khersanak (a), Eskandar (b), Polekeh (c), and Dizicheh (d) stations

and Sustainable Development (WSD) in Iran for the last 30 years. As shown in Fig. 14.12a, our results are comparable with the study by (WSD) in Isfahan.

Upstream dam is the major source of water supply for the downstream region. To verify our results in upstream dam we plotted Fig. 14.12b–d to account for the volume of water entered into the Chadegan Reservoir (Zayandeh Rud Dam). As shown there is a good match between observed and simulated stream flow (Fig. 14.12b); and the monthly and yearly variation of water entering into the reservoir (Fig. 14.12c, d) were reasonably simulated. Overall, our simulation resulted in 1300 ± 20 MCM of water inflow to the reservoir over 1995–2009 whereas the observed data produced 1349 MCM of water entering into Zayandeh Rud Dam over this period of time.

To meet the ultimate goal of this project, the naturalized stream flow daily data was required from SWAT to feed the MIKE Basin (MB) model for the management and allocation purposes. To generate the natural stream flow using SWAT, we used our calibrated and validated hydrologic model of the basin and excluded all management measures (i.e. water transfers, water diversion for agricultures, industries, drinking and municipalities, and dam operation) from the SWAT model and ran it on daily basis to simulate daily natural stream flow (DNS) for each SWAT sub-basin. The simulated DNS data in each SWAT sub-basin was spatially

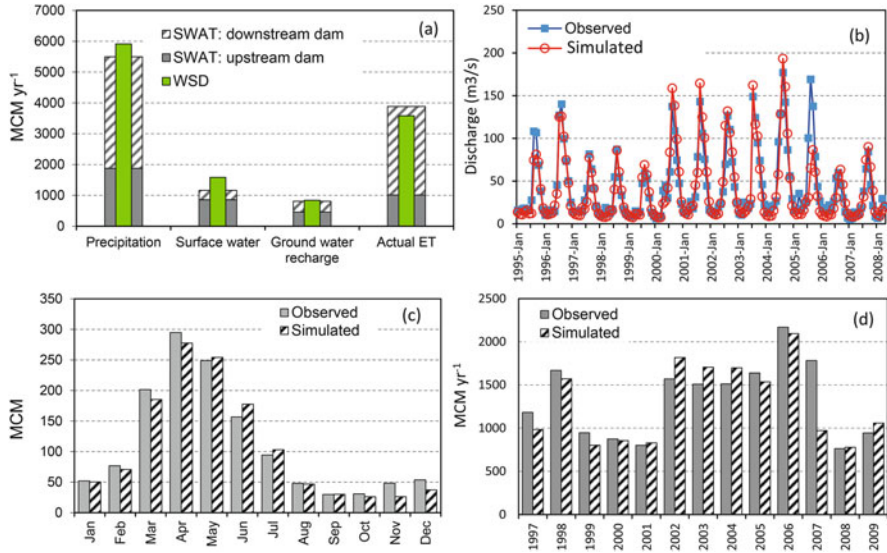


Fig. 14.12 Model verification through comparison of the simulated versus observed/reported data: water balance components (a), monthly stream flow entering the Zayandeh Rud Dam (b), long-term average (1995–2009) monthly volume of water entering Zayandeh Rud Dam (c), and total annual volume of water entering Zayandeh Rud Dam (d)

aggregated to account for the data of the MB-delineated catchments. Further, the simulated daily stream flows ($\text{m}^3 \text{sec}^{-1}$) was converted to $\text{liter km}^{-2} \text{day}^{-1}$ for each MB catchment. Figure 14.13 shows the SWAT sub-basins and the MB catchments for our study area where the two models interact in this project.

14.9 Remarks and Recommendations

In large scale hydrological models, precision of the parameter estimation depends on the quality and quantity of the available input data. In this study the available data generally allowed obtaining satisfactory results, but inclusion of a larger number of climate stations, especially in upstream highland terrain, could have improved the quality of the predictions. An advanced research study is required for better quantification of the hydrological behavior in tributary river basin (i.e. Shoor, Morghab and Dastkan). Calibration of the SWAT hydrologic model against other water cycle components (e.g. soil moisture, ground water recharge) rather than stream flow will increase model reliability.

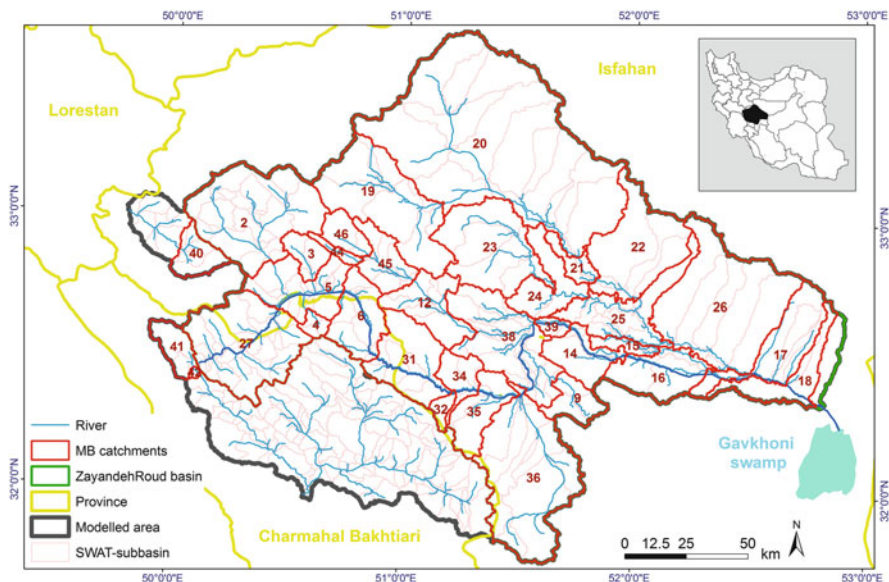


Fig. 14.13 Study area representing the 370 SWAT sub-basins and 33 MIKE BASIN catchments

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