

# Assessment of Water Resources Development Projects under Conditions of Climate Change Using Efficiency Indexes (EIs)

Parisa-Sadat Ashofteh<sup>1</sup>  • Taher Rajaei<sup>1</sup> • Parvin Golfam<sup>1</sup>

Received: 25 November 2016 / Accepted: 5 May 2017 /  
Published online: 16 May 2017  
© Springer Science+Business Media Dordrecht 2017

**Abstract** The purpose of this study is to evaluate Gharanghu multi-purpose reservoir system (East Azerbaijan, Iran) using efficiency indexes (EIs) affected by climate change. At first, the effects of climate change on inflow to the reservoir, as well as changes in the demand volume over a time interval of 30 years (2040–2069) are reviewed. Simulation results show that inflow to the reservoir is decreased in climate change interval compared to the baseline interval (1971–2000), so that comparison of long-term average monthly inflow to the reservoir in climate change interval is reduced about 25% compared to the baseline. Also, water demand in climate change interval will increase, namely volume of water demand for agricultural, drinking and industrial, and environmental in climate change interval is expected to increase by 20%. The simulation results of the water evaluation and planning (WEAP) model is used to determine EIs of multi-purpose reservoir system. Next, three scenarios of water supply for climate change interval are introduced to WEAP model, keeping variable of parameter related to water demand volume (based on different percentages of supply) and keeping constant of the parameter related to the volume of inflow to the reservoir. Results show that system EIs in climate change interval will have a disadvantage compared to the baseline. So that, reliability, vulnerability, resiliency and flexibility indexes in climate change interval based on 100% of water supply compared to the baseline will decrease 18%, increase 150%, decrease 33%, and decrease 47%, respectively. These indexes based on 85% of supply compared to the baseline will decrease 12%, increase 75%, decrease 30%, and decrease 39%, respectively. Also, those based on 70% of supply compared to the baseline will decrease 1%, will be without change,

---

✉ Parisa-Sadat Ashofteh  
PS.Ashofteh@qom.ac.ir

Taher Rajaei  
trajaei@qom.ac.ir

Parvin Golfam  
P.Golfam@stu.qom.ac.ir

<sup>1</sup> Department of Civil Engineering, University of Qom, Qom, Iran

decrease 18%, and decrease 18%, respectively. Changes in indexes in future interval indicate the need to manage water resource development projects in the basin.

**Keywords** Multi-purpose reservoir · Water resource development projects · Supply scenarios · WEAP model · Climate change · Efficiency indexes

## 1 Introduction

Recent researches dealing with optimization approaches have included several fields of water resources, such as design-operation of pumped-storage and hydropower systems (Bozorg-Haddad et al. 2014), operating from reservoir (Ashofteh et al. 2015a, b), levee layout and design (Bozorg-Haddad et al. 2015), and developments in algorithms (Ashofteh et al. 2015a, b). However, in the analysis of some systems, it is not possible to apply the optimization approach for solving the problem. In such cases, simulation approach can be employed as an appropriate strategy. To extract operating policy through the use of simulation models, only a few of these researches have regarded climatic changes in hydro-systems.

Climate change phenomenon is caused due to greenhouse gases emission resulting from human activities such as development of agricultural, change in land use, etc. (Ashofteh et al. 2016). This phenomenon has been made changes in the hydrological cycle, reducing rainfall, rising temperature, sea water level rise, changes in river runoff and groundwater flow. These changes in addition to the amount, affect on their time distribution. Following these changes, effects such as degradation of water quality as well as stress creation on fragile balance of water resources and water uses, will be created. Under these conditions, water resources management approach should also be changed.

In these circumstances, regard to recent literatures about real-life case studies of contemporary modeling techniques in hydrologic engineering is important. For example, Gholami et al. (2015) studied groundwater level fluctuations to manage disasters and water resources in Iran. Dendrochronology and an artificial neural network (ANN) were used to evaluate groundwater level fluctuations. Taormina and Chau (2015) presented a novel approach for Input Variable Selection (IVS) that employed Binary-coded discrete Fully Informed Particle Swarm optimization (BFIPS) and Extreme Learning Machines (ELM) to develop fast and accurate IVS algorithms for rainfall-runoff modeling in the Kentucky River basin. Results showed that the proposed techniques were suited for modeling. Wu et al. (2009) coupled three data-preprocessing techniques, moving average (MA), singular spectrum analysis (SSA), and wavelet multi-resolution analysis (WMRA), with ANN to improve the estimate of daily flows for Lushui and Daning watershed in China. The results showed that ANN-MA model was optimal, then the ANN-SSA, and finally the ANN-WMRA. Wang et al. (2015) presented the auto-regressive integrated moving average (ARIMA) model coupled with the ensemble empirical mode decomposition (EEMD) for forecasting annual runoff time series. The results showed that the applied approach improved forecasting accuracy of annual runoff from Biuliuhe reservoir, Dahuofang reservoir and Mopanshan reservoir, in China. Chen et al. (2015) investigated three algorithms, i.e. differential evolution (DE), artificial bee colony (ABC) and ant colony optimization (ACO), to determine the optimal one for forecasting Altamaha river flow of Georgia. The results showed that performance of algorithms was successful. Chau and Wu (2010) developed a hybrid model integrating artificial neural networks and support vector

regression for daily rainfall prediction. Results showed that the performance of hybrid support vector regression model was the best.

From the distant past to the present, construction of dams have had important role in storage of water resources as well as mitigation of risks due to drought. Dams with water storage and proper release play the most important role in the field of water resources management both in terms of quantity and temporal. In recent years and following the occurrence of climate change, role of reservoirs management have been evident more and more. Change in timing of rainfall and its amount, increase of temperature and consequently increase of evaporation from the dam lake, changes in inflow into the reservoir due to the phenomenon on the one hand and the increase of dam downstream demand as a result of factors such as population growth, the increase of area under cultivation, change in pattern of land use, industrial development, etc. on the other hand, has been caused that the status of water supply be in a crisis conditions. Thus, to apply the proper operating rules of reservoirs in conditions associated with climate change is necessary. The EIs of reservoir are effective factors in the evaluation of the reservoir behavior in operating time interval. By determining these indexes, appropriate and efficient policies can be adopted to supply the demand in climate change interval. In the following, researches on assessment of water resource development projects have been presented.

Raskin et al. (1992) developed the WEAP for simulating water balance and evaluating water management strategies in the Aral Sea region. The scenario approach provided flexible representation of alternative development patterns and supply dynamics. Léville et al. (2003) investigated the pros and cons of using the WEAP via its application to the Olifants River in South Africa. This model provided the simulation and analysis of various water allocation scenarios as well as scenarios of users' behavior. Results showed that model was useful for discussions on water resources management among stakeholders. Droogers and Aerts (2005) compared adaptation strategies between basins ranging from wet to dry and from poor to rich using WEAP, soil water atmosphere plant (SWAP), water and salinity basin model (WSBM), etc. They explored adaptation strategies to climate change and climate variability to enhance food quantity and security and environmental quality and security for seven basins. Climate change projections were scaled to local conditions. For the seven basins selected, impacts and adaptation strategies at field scale indicated that overall food productions will increase in the future. Results showed that appropriate adaptation strategies were different between these seven basins. Also, results indicated that the studies on these adaptation strategies could not be performed only at one scale. Assaf and Saadeh (2008) assessed water quality management options in the upper Litani Basin, Lebanon, using an integrated geographic information system (GIS)-based decision support system (DSS). They provided an overview of the development and implementation of an integrated DSS designed to help policy makers. The DSS was developed based on the WEAP. The DSS was used to assess two main water quality management plans taking into consideration hydrological, spatial and seasonal variability's. An incremental cost-effectiveness analysis was performed. The results indicated the importance of taking immediate action on curbing this onslaught on this valuable and scarce fresh water resource. Yilmaz and Harmancioglu (2010) developed a water resources management model for the Gediz River Basin in Turkey. The model facilitated indicator-based decisions with respect to environmental, social and economic dimensions. The basic input of the model was the quantity of surface water. The model was applied under three different hydro-meteorological scenarios. WEAP was used to assess the performance of possible management alternatives. The results of the study showed that the Basin was sensitive to drought conditions,

and the agricultural sector was affected by irrigation deficits. Results showed that the negative impacts of climate change can exacerbate the water crisis. Also, results indicated that efficient water management was crucial to ensure the sustainable use of water resources with respect to environmental, social and economic dimensions. Varela-Ortega et al. (2011) achieved to a comprehensive tool for analyzing the spatial and temporal effects of various agricultural policies in semi-arid regions by combining an economic optimization model and WEAP. The results showed hedging policies might reduce agriculture water consumption, but it is not able to improve aquifer status as well as to reduce damages, especially in times of drought. Haddad et al. (2013) described the development of a DSS for groundwater management of the Zeuss Koutine aquifer in southeastern Tunisia using the WEAP-MODFLOW framework. A monthly MODFLOW model was developed to simulate aquifer. A conceptual model was designed using WEAP. Other water resources available in the region, such as desalination plants and groundwater, were taken into consideration in this DSS. The results indicated that the DSS developed was able to evaluate water management scenarios. Li et al. (2015) analyzed the future water situation in the Binhai New Area (BHNA), by setting different scenarios of socio-development and urbanization until 2020. WEAP was applied to evaluate the sustainability of water resources management strategies in region. Three scenarios (urbanization, industrial structure adjustment, and the policy change of water resources allocation) were set up for the region. The results indicated that the pressure on the region water resources will increase in the future.

In most issues related to water resources management, the impacts of climate change on reservoir performance as well as effects of demand volume changes has not been considered in the formulation of management scenarios. In this paper the effects of climate change on water resources and water uses and also EIs of a multi-purpose reservoir are evaluated as well as the best management scenario in Gharanghu basin located in East Azarbaijan, Iran, are examined. Values of EIs (i.e. reliability, resiliency, vulnerability, and flexibility) are obtained using WEAP under three scenarios of demand supply in climate change interval (2040–2069) and results are compared with corresponding values in the baseline (1971–2000).

In the present study, it is tried to minimize the effects of shortages resulting from climate change in sections of water resources and water uses with a proper management. It is noteworthy that, among adaptation strategies to climate change that may be considered for the planners in the present study is the use of deficit irrigation approach. Other adaptation strategies that can be considered including changes in cultivation area, changes in cropping pattern and usage of the crop with lower water irrigation requirements and increasing irrigation efficiency and etc. For this purpose, scenarios of 100, 85 and 70% of water demand supply are evaluated for use of deficit irrigation approach; and optimal management of the reservoir is simulated for these scenarios using WEAP. The rest of the paper is organized as following: At first climatic pre-processes are presented. Next, water resources and consumptions models are described, and then the EIs are calculated using WEAP. In following, the approach application for a real world problem and results are presented at next sections. The conclusion will be the last section.

## 2 Research Structure

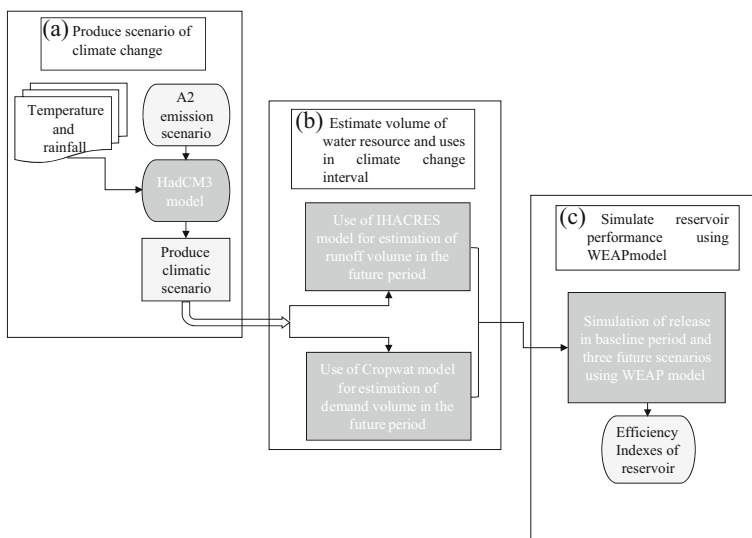
In this study, climatic data including temperature and rainfall (as input data to rainfall-runoff model) are processed in climate change interval using Hadley Centre Coupled Model, version

3 (HadCM3) (under emission scenario A2). Values of inflow to reservoir are simulated using Identification of Hydrographs And Components for Rainfall, Evapotranspiration and Streamflow data (IHACRES) model, and values of demand volume are calculated using Cropwat in future interval. Then, reservoir performance in climate change and baseline intervals is simulated under three scenarios and then EIs are calculated. Research overall process has been presented in Fig. 1.

## 2.1 Production of Climate Change Scenario

In this study, climatic data of temperature and rainfall were obtained using HadCM3 (A2 emission scenarios) in the baseline and future intervals. HadCM3 is one of the main models used in the third assessment report (TAR) of intergovernmental panel on climate change (IPCC) (IPCC 2011). HadCM3 is one of atmospheric-ocean general circulation models (AOGCM) (Wilby and Harris 2006). From its features can mention to high ability for separation of the ocean component and lack of need to flux adjustment for better simulation. One of the important inputs such models is greenhouse gas emission. Since the emission of these gases in the future is not clear, situation of their emission is defined under four main groups of scenarios A1, A2, B1, and B2. Due to more emission of carbon dioxide (CO<sub>2</sub>) in scenario A2, the mentioned scenario will be used in the present study. Emission scenario A2 is a region-based scenario, with considering the effect of population increase, as well as increase of temperature from 2 to 4.5 °C, which it emphasis on economic development of the region. Characteristics of HadCM3 available on the IPCC website have been presented in Table 1 (Carter 2007).

After extracting the monthly climatic variables from HadCM3 in baseline and climate change intervals, climatic scenarios are calculated according to Eqs. (1) and (2). Finally, time series of climatic variables are determined according to Eqs. (3) and (4), by adding climatic scenarios of temperature to basin observed temperature and by multiplying climatic scenarios of rainfall to basin observed rainfall. It should be noted that information related to climatic



**Fig. 1** Flowchart of research

**Table 1** Characteristics of HadCM3

Model	Spatial resolution of AGCM (degree) (length × width)	Spatial resolution of OGCM (degree) (length × width)	Simulation period of greenhouse gases in the past	Period length of simulation (year)	Simulated scenarios
HadCM3	3.57 × 2.8	3.57 × 2.8	CO2: (1881–1989) SO4: (1860–1989)	Control period: 240 Scenario of SRES: 1950–2099	A2, B2, A2b, A2c

AGCM, Atmosphere general circulation model; OGCM, Ocean general circulation model; SRES, Special report on emission scenarios

variables are extracted from a cell of HadCM3 that basin has been located within it (Wilby and Harris 2006).

$$\text{delta } TE_j = \overline{TE}_{Had,f,j} - \overline{TE}_{Had,b,j} \tag{1}$$

$$\text{delta } RA_j = \overline{RA}_{Had,f,j} + \overline{RA}_{Had,b,j} \tag{2}$$

$$TE_j = TE_{o,j} + \text{delta } TE_j \tag{3}$$

$$RA_j = RA_{o,j} + \text{delta } RA_j \tag{4}$$

in which,  $\text{delta } TE_j$  and  $\text{delta } RA_j$  = climatic scenarios related to long-term average of temperature and rainfall for month  $j$ , respectively;  $\overline{TE}_{Had,f,j}$  and  $\overline{RA}_{Had,f,j}$  = long-term average of temperature and rainfall simulated by HadCM3 in climate change interval (future interval) for month  $j$ , respectively;  $\overline{TE}_{Had,b,j}$  and  $\overline{RA}_{Had,b,j}$  = long-term average of temperature and rainfall simulated by HadCM3 in the baseline interval for month  $j$ , respectively;  $TE_{o,j}$  and  $RA_{o,j}$  = time series of temperature and rainfall observed for month  $j$ , respectively; and  $TE_j$  and  $RA_j$  = time series of temperature and rainfall resulting from climate change for month  $j$ , respectively.

### 2.2 Estimation of Water Resources

Water resources of present research include surface flow of the river and the reservoir. Therefore it is necessary to present the factors affecting reservoir general balance, before estimating the status of water resources. Continuity equation is used in order to simulate reservoir system behavior, according to Eq. (5):

$$S_{t+1} = S_t + Q_t - Re_t - Ev_t - Sp_t \tag{5}$$

in which,  $S_{t+1}$  = reservoir storage volume in period  $t + 1$ ;  $S_t$  = reservoir storage volume in period  $t$ ;  $Q_t$  = inflow volume to reservoir in period  $t$ ;  $Ev_t$  = evaporation volume in period  $t$ ;  $Re_t$  = release of reservoir in period  $t$ ;  $Sp_t$  = spill volume in period  $t$ .

One of the most important factors in the Eq. (5) is inflow to reservoir. Therefore, explanations related to the simulation of the inflow to reservoir are presented in the following.

The IHACRES semi-conceptual model is used for estimating inflow to reservoir in climate change interval. This model need to little data as input including observed temperature, rainfall and discharge (Ashofteh et al. 2013). The other feature of model is its high speed and also simple algorithm. In this model, first the climatic variables in each time interval are converted to effective rainfall by non-linear module and then effective rainfall is converted to the surface flow through a linear module at the same time step and thus inflow to the reservoir is simulated.

The system of Fig. 2 is calibrated and verified with the introduction of climatic variables in the baseline interval as well as comparison with time series of observed inflow. Then, inflow to the reservoir is simulated in future conditions with the introduction of climatic variables in climate change interval [Eqs. (3) and (4)].

### 2.3 Estimation of Water Uses

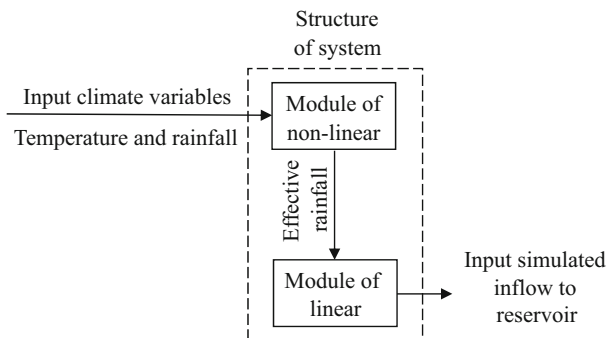
Water consumptions of the dams can include different purposes. Purposes of dam construction in the present research are irrigation network development and other uses, such as drinking and industrial and environmental. Since the highest water consumption in Iran is allocated to the agricultural sector (about 92%), so the effect of climate change on agricultural water use is discussed in the following.

In the present study, Cropwat model will be used to calculate agriculture water consumption. This model is capable to estimate crops water requirement (*CWR*), efficiently. Inputs of this model are climatic data and also information related to crop for calculating *CWR* as well as irrigation water requirement (*IWR*). In this model, the amount of reference evapotranspiration is calculated by FAO-Penman-Monteith equation and based on minimum and maximum climatic data of temperature, relative humidity, solar radiation and wind speed according to Eq. (6):

$$ET_{0_t} = \frac{[0.408 \cdot \Delta_t \cdot (Rn_t - G_t)] + \left\{ \gamma_t \cdot \frac{890}{TE_{avg} + 273} \cdot U_{2mt} \cdot [(e_s)_t - (e_a)_t] \right\}}{\Delta_t + \gamma_t (1 + 0.34 U_{2mt})} \tag{6}$$

in which,  $ET_{0_t}$  = reference crop evapotranspiration or potential evapotranspiration in month  $t$  ( $mm/month$ );  $\Delta_t$  = the slope of the saturation vapor pressure with temperature in month  $t$

**Fig. 2** Simulation of inflow to reservoir by IHACRES



( $KPa/^\circ C$ );  $Rn_t$  = net radiation flux at ground level in month  $t$  ( $10^6 J/m^2/month$ );  $G_t$  = heat flux in month  $t$  ( $10^6 J/m^2/month$ );  $[(e_s)_t - (e_a)_t]$  = saturation vapor pressure deficit in month  $t$  ( $KPa$ );  $TE_{avg}$  = the average temperature in during interval ( $^\circ C$ );  $U_{2m}$  = wind speed at a height of 2 m above ground level in month  $t$  ( $m/s$ ); and  $\gamma_t$  = psychrometer coefficient in month  $t$  ( $KPa/^\circ C$ ).

To be able to generalize calculation results of reference crop evapotranspiration  $ET_0$  to the desired crop, it is necessary to multiply  $ET_0$  obtained values and the crop coefficient; and thus  $CWR$  is achieved according to Eq. (7):

$$CWR_t = ET_{0_t} \times KC_t \quad (7)$$

in which,  $CWR_t$  = crop water requirement in month  $t$  ( $mm/month$ ); and  $KC_t$  = crop coefficient in month  $t$  (dimensionless).

In the Cropwat,  $IWR$  is a requirement that must be available for crop through irrigation systems. So,  $IWR$  is obtained by the difference between the effective rainfall from  $CWR$ . The effective rainfall is part of rainfall that has placed in the crop root development depth and effectively is available for crop. The effective rainfall is determined according to the Eq. (8). This formula was recommended by The United States Bureau of Reclamation (USBR) (Smith 1988):

$$ERA_t = \begin{cases} \frac{RA_t}{125}(125-0.2RA_t) & RA_t \leq 250 \text{ mm} \\ 0.1 RA_t + 125 & RA_t > 250 \text{ mm} \end{cases} \quad (8)$$

in which,  $ERA_t$  = the effective rainfall in month  $t$  (mm).

In order to estimate the agricultural water consumption volume with regard to constant cultivation area, Eq. (9) is used:

$$VolAD_t = A \times IWR_t \times 10^{-5} = A \times (CWR_t - ERA_t) \times 10^{-5} \quad (9)$$

in which,  $VolAD_t$  = water demand volume in agricultural section in month  $t$  ( $10^6 m^3$ );  $A$  = Area under cultivation (ha); and  $IWR_t$  = irrigation water requirement in month  $t$  (mm).

With regard to trend of industrial development and population growth, increase of drinking and industrial requirements in climate change interval (future), is considered about 25% compared to the baseline interval. Meanwhile, environmental requirement in climate change interval is regarded similar to the baseline interval.

## 2.4 Simulation of the Performance of Water Supply System

In this study WEAP will be used for simulation of the water supply system performance. This model is developed by Stockholm environment institute, and it is a type of DSS. The characteristics of this model can be listed as the following: flexibility, user friendly, connectivity ability to software's such as Leap, Modflow etc., economic estimations, qualitative simulation, taking into account environmental objectives, simulation of hydropower, optimization based on linear programming (LP), creating scenario, having high graphics and free access. Calculations in WEAP are based on the water balance.

Since the water supply system in the present research is consisted of surface flow and reservoir, the operating rules of this water supply system will be described in the following.



## (a) Operating rule of reservoir

Operating rules of the reservoirs contains a set of guidelines, approaches, in which how to manage reservoirs in each time interval is determined according to the specifications of the dam, change in the volume of inflow to the dam, as well as demand. These rules are expressed by rule curve of reservoir. To prepare the reservoir rule curve, different models are applied such as yield optimization model, standard operating policy (SOP) and etc. In general, there are different models of operating rules, including optimization, simulation or a combination of these two models. In this study, reservoir simulation model will be used which is described in the following.

In simulation models the first inflow to reservoir, demand and losses (such as the evaporation from reservoir lake) is determined in each time interval. Equation of reservoir balance in all of simulation models was presented in Eq. (5). Also, the availability of reservoir water will be as Eq. (10):

$$WA_t = S_t + Q_t - Ev_t \quad (10)$$

in which,  $WA_t$  = the availability of reservoir water in month  $t$ .

## (b) Flexibility index of supply system

The results of the simulation will be used to determine operating policies of reservoir and to develop management scenarios using calculation of EIs. These indexes are mainly used to measure the performance of water supply system, and those play an essential role in the process of decision-making by managers and stakeholders. Hashimoto et al. (1982) introduced three indexes of reliability, resiliency and vulnerability for evaluating the performance of reservoirs. These indexes are one of the most practical and the most comprehensive of approaches to assess the probability of failure or success of a water system.

Reliability is the most important criterion in the design of water supply systems, and it is classified to three types of time reliability, volume reliability, and annual reliability. In this study, time reliability has been used. Time reliability shows the possibility that the system is in desirable condition (satisfaction in water supply) at a specified time interval and it can be expressed as follows:

$$\alpha = \frac{N}{T} \quad (11)$$

$$N = \sum_{t=1}^T Count_t(Re_t \geq De_t) \quad (12)$$

in which,  $\alpha$  = time reliability (%);  $N$  = the number of months in which the release from reservoir is equal to or greater than the demand in dam downstream (being in situation of desirable);  $T$  = the total time interval of operating (month);  $De_t$  = demand volume in dam downstream in month  $t$ ;  $Re_t$  = release volume from reservoir in month  $t$ ; and  $Count_t$  = counting function (for a situation in which the release is more than the demand in total interval of operating).

Resiliency index indicate the speed of the system in restoration of its undesirable state (i.e. failure). If the restoration of system performs slowly it indicates a serious flaw in the system performance. In other words, if undesirable state takes a long time, there is a need to redesign the system. Moy et al. (1986) defined resiliency index as maximum intermittent time interval that the system spends in undesirable state. Resiliency index is as follows:

$$\beta = \frac{N'' [def_t | (Re_{t+1} > De_{t+1})]}{N'} \quad (13)$$

$$def_t = \sum_{t=1}^T |Re_t - De_t| \quad (14)$$

$$N'' = \sum_{t=1}^T Count'_t(Re_t < De_t) \quad (15)$$

in which,  $\beta$  = resiliency index (%);  $N''$  = the number of months in which the release is less than the demand (being in situation of undesirable);  $def_t$  = system deficiency (absolute of difference between the volume of release and demand);  $Re_{t+1}$  = release volume from reservoir in month  $t + 1$ ;  $De_{t+1}$  = demand in dam downstream in month  $t + 1$ ; and  $Count'_t$  = counting function (for a situation in which the release is less than the demand in total interval of operating).

One of the most important indexes considered in issues related to climate change, is vulnerability index. Vulnerability index is defined as ratio of system deficit (sum of deficiencies) to the total volume of water demand in downstream:

$$\nu = \frac{def_t}{T \cdot De_{max}} \quad (16)$$

in which,  $\nu$  = vulnerability index (%); and  $De_{max}$  = maximum of demand in total operating interval.

Since the indexes mentioned above do not have the trend of convergence in itself changes, analysis of operating policies of reservoir, and creation of management scenarios will be faced with a problem. To solve this problem Loucks (1997) defined a new index that is a combination of the above three indexes, and all aspects of reservoir performance can be seen in it. This index is called flexibility that is the most efficient index for policy makers in the design and operation of water supply systems. Flexibility index is expressed as follows:

$$\gamma = \alpha\beta(1-\nu) = \frac{N}{T \cdot N'} \times N'' [def_t | (Re_{t+1} \geq De_{t+1})] \times \left( 1 - \frac{\sum_{t=1}^T def_t}{T \cdot De_{max}} \right) \quad (17)$$

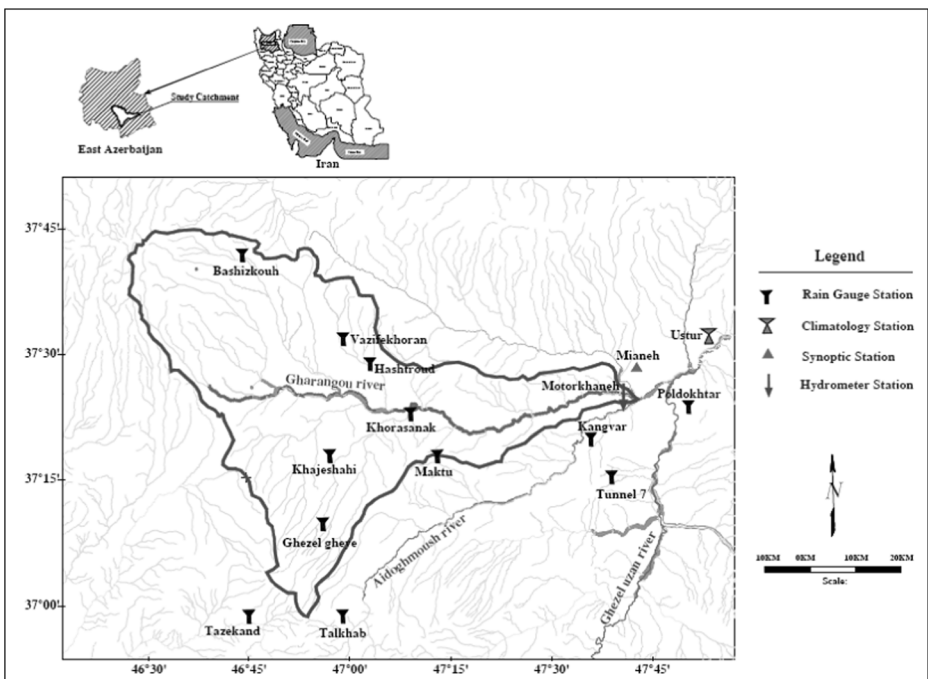
in which,  $\gamma$  = flexibility index (%).

### 3 Case Study and Definition of Scenarios

#### 3.1 Project Region

Region under study is Gharanghu basin that has located in northwestern Iran (East Azerbaijan province) between  $45^{\circ} 25'$  longitude and  $47^{\circ} 55'$  latitude. This basin has placed in the eastern slopes of Sahand Mountain (48 km from Hashtrood city) with an area of  $3590 \text{ km}^2$  (Fig. 3). In terms of hydrological division of Iran, this basin is belong to basin of Caspian Sea and sub-basin of Great Sefidrud. Gharanghu River with a length of approximately 120 km has east-west direction. Gharanghu river annual discharge is  $149 \times 10^6 \text{ m}^3$ . The highest point of the basin is Bozdagh mountaintop, with a height of 3605 m in the North West. The lowest point of the basin is in the basin outlet with a height of 1043 m. The maximum and minimum slope of basin is 5.36 and 0.2%, respectively. Annual rainfall average in the basin is 403.7 mm and the rainiest months are March, April and May. Since the stations in the basin have 1971–2000 time interval data, so based on the recommendation of the national meteorological organization (WMO), mentioned time interval is considered as the baseline interval (IPCC-TGCIA 1999). In Table 2 characteristics of meteorological stations in the region have been presented.

Eight rivers in this basin flow, that Gharanghu dam has been constructed at the confluence of two rivers Almaloo and Gharanghu. Normal level of Gharanghu reservoir water is 1600.3 m above sea level. Total capacity of reservoir, live and dead storage of reservoir is 165, 135 and  $17 \times 10^6 \text{ m}^3$ , respectively.



**Fig. 3** Layout of meteorological stations in Gharanghu basin

**Table 2** Characteristics of available meteorological stations

Name of station	Type of station	Height of basin (m)	Longitude	Latitude
Vatifeh Khoran	Rain gauge	1760	46° - 59'	37° - 32'
Mianeh Sobat	Rain gauge	1100	47° - 42'	37° - 25'
Hashtrood	Rain gauge	1750	47° - 03'	37° - 29'
Tunnel 7	Rain gauge	1100	47° - 37'	37° - 24'
Khajeh Shahi	Rain gauge	1600	46° - 57'	37° - 18'
Ustur	Climatology	1200	47° - 54'	37° - 30'
Pole Dokhtar	Rain gauge	1200	47° - 49'	37° - 21'
Motorkhaneh	Rain gauge	1060	47° - 43'	37° - 23'
Tazeh kand	Rain gauge	1850	46° - 45'	37° - 59'
Kangvar	Rain gauge	1320	47° - 36'	37° - 18'
Ghezel Ghiyeh	Rain gauge	1499	47° - 32'	37° - 16'
Maktu	Rain gauge	1690	47° - 13'	37° - 18'
Mianeh	Synoptic	1200	47° - 38'	37° - 24'

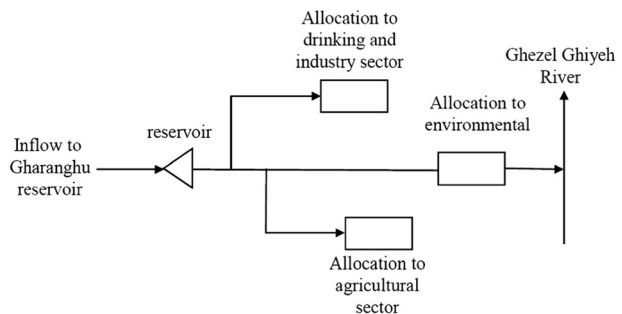
### 3.2 Prioritization of Water Allocation to Uses

The main purpose of the project is to adjust Gharanghu river water by constructing dam as well as to allocate reservoir water for major part of the land with area of 14,500 ha by building irrigation network. Also, other purposes of the reservoir are to supply the domestic, industrial, and environmental demands. Drinking, industrial and environmental consumptions in the baseline interval are equal to 3, 3 and  $5 \times 10^6$  m<sup>3</sup> per year, respectively. The first priority of the allocation of water resources has been considered for drinking and industrial consumptions, the second and third priority is to meet the environmental and agricultural demand, respectively. Schematic of basin modeling by WEAP has been presented in Fig. 4.

### 3.3 Scenarios under Review

In this study three scenarios resulting from climate change (the first scenario, taking into account the effect of the change in inflow to the reservoir and the volume of water demand based on supplying 100%; the second scenario, based on supplying 85%; and the third scenario, based on supplying 70%), are simulated for climate change and the baseline intervals using WEAP.

**Fig. 4** Schematic of water resources allocation



## 4 Results

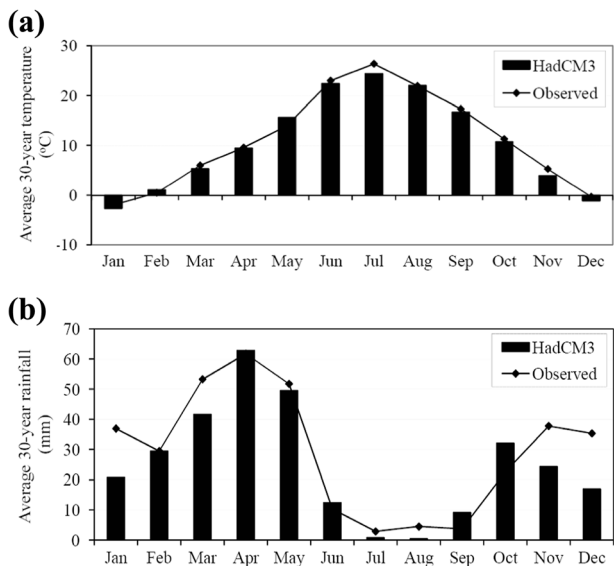
### 4.1 Evaluation of the Performance of Climatic Models

In this study, the HadCM3 (under the emission scenarios A2) was used for the simulation of climatic variables. By entering the coordinates of the meteorological stations in the basin for desired time interval and using GCM retrieve data program (GCM-RDP) (Ashofteh et al. 2013), time-series of climatic variable related to computational cell of HadCM3 that is included the basin, is achieved. The GCM retrieve data program applies the approach of proportional downscaling [or change factor approach (Jones and Page 2001)]. Then, to evaluate the performance of the model, the monthly 30-year average of climatic variables in the baseline interval was calculated and compared with the observed corresponding values. The results of this comparison have been presented in Fig. 5. As shown in Fig. 5, the overall performance of climatic variables simulation model has been successful for the baseline interval which it is more evident for temperature than rainfall. In other words, output of its results in the simulation of climatic variables for climate change interval can be trusted.

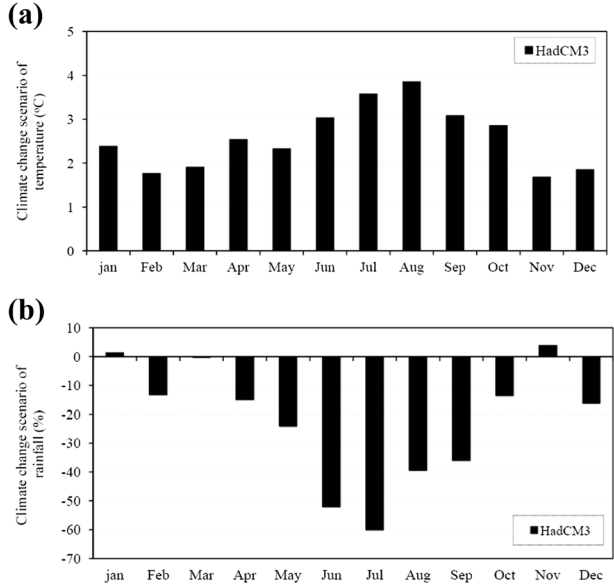
### 4.2 Calculation of the Time Series of Climatic Scenarios in Climate Change Interval

By calculating the average long-term of monthly climatic variables in climate change and baseline interval by HadCM3 and using Eqs. (1) and (2), how changing climatic variables were specified in the interval of climate change relative to the baseline that the results were presented in Fig. 6. As shown in Fig. 6, the basin temperature in climate change interval increases between 1.7 to 3.9 °C relative to the baseline interval. Also, range of rainfall changes in climate change interval will be between -60 to 3.8% compared to the baseline. Then, after calculating  $\Delta TE_j$  and  $\Delta RA_j$ , and using Eqs. (3) and (4), time series of climate scenarios is produced, and average monthly long-term of climatic variables in climate change and baseline intervals is compared, which those has been shown in Fig. 7. As shown in Fig. 7, comparing

**Fig. 5** Results of climatic model performance for (a) temperature and (b) rainfall

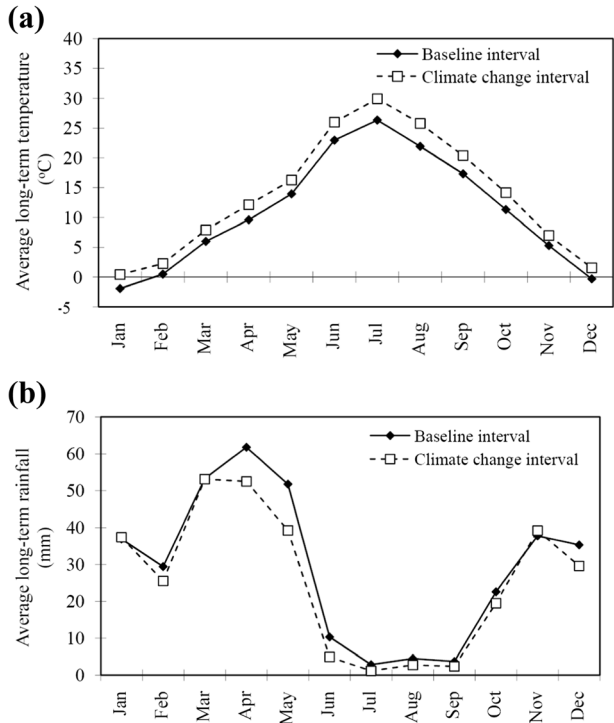


**Fig. 6** Calculation of climate change scenarios from HadCM3 for (a) temperature and (b) rainfall



the average monthly long-term of temperature in climate change interval will increase about 23% compared to the baseline, while this comparison for rainfall in climate change interval will decrease about 12% compared to the baseline, and this reduction is more significant for the months of April and May compared to the other months.

**Fig. 7** Comparison of the average monthly long-term of (a) temperature and (b) rainfall, in climate change and the baseline intervals



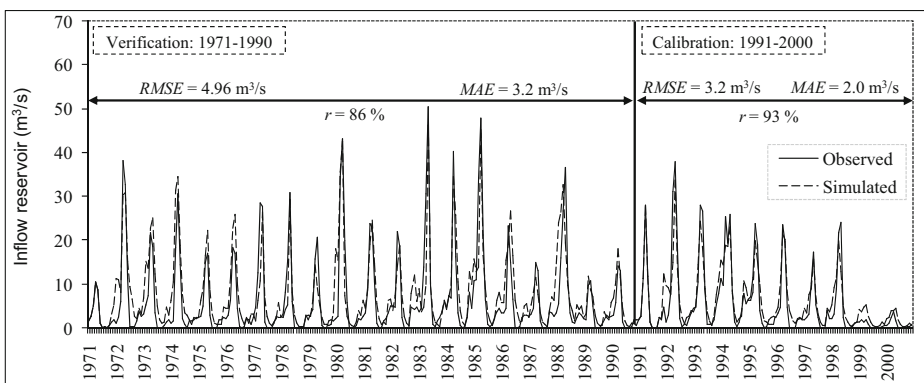
### 4.3 Simulation of Hydrological Model

Before simulation of inflow to the reservoir simulation in climate change interval, it is necessary to calibrate and verify the hydrological model. Results of calibration for 1991–2000 and results of verification for 1971–1990 have been presented in Fig. 8. As shown in Fig. 8, hydrological model calibration results show that the criteria of root mean square error (*RMSE*), mean absolute error (*MAE*), and correlation coefficient (*r*) are equal to 3.2 m<sup>3</sup>/s, 2.0 m<sup>3</sup>/s, and 93%, respectively. It indicates that performance of hydrological model has been successful. After calibration, the model was verified in 1971–1990. Validation results showed that the criteria mentioned above, have been equal to 4.96 m<sup>3</sup>/s, 3.2 m<sup>3</sup>/s, and 86%, respectively. Thus, results show that the hydrological model can simulate the inflow to reservoir in climate change interval. So with the introduction of HadCM3 results in climate change interval, as input to hydrological model, inflow to reservoir will simulate which results have been presented in Fig. 9. Results of Fig. 9 shows the time series of inflow to the reservoir in climate change interval is reduced compared to the baseline, so that comparison of average monthly long-term of inflow to the reservoir in climate change interval is reduced about 25% compared to the baseline.

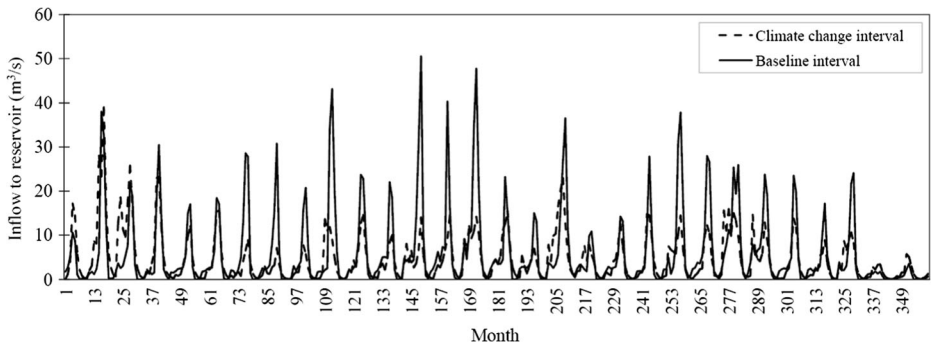
### 4.4 Simulation of Cropwat Model and Estimation of Total Demand Volume

It was not possible to provide all input information for the calculation of irrigation requirement such as relative humidity and wind speed in climate change interval, thus the generalized equation of temperature and *ET*<sub>0</sub> in the baseline (with a correlation coefficient of 96%) was used for climate change interval. Then, by entering temperature data in climate change interval, *ET*<sub>0</sub> was calculated for corresponding interval. Next, the volume of agricultural water demand in climate change interval was estimated using the equations described in section of “Estimation of water uses” that results have been presented in Fig. 10a, compared to the corresponding values in the baseline interval. Also, the water demand volume in sectors of drinking and industrial, environmental, as well as total demands in climate change and baseline intervals have been showed in Fig. 10b–d, respectively.

As shown in Fig. 10, water demand will increase in climate change interval compared to the baseline. Annual average of water demand volume increases from 157 (×10<sup>6</sup> m<sup>3</sup>) in the baseline to 188 (×10<sup>6</sup> m<sup>3</sup>) in climate change interval, namely water demand volume for



**Fig. 8** Results of the hydrological model calibration and verification



**Fig. 9** Monthly inflow to reservoir in climate change and baseline intervals

agriculture, drinking and industry, and environmental in climate change interval is expected to increase by 20%.

#### 4.5 Simulation of the Multi-Purpose Reservoir Performance by WEAP

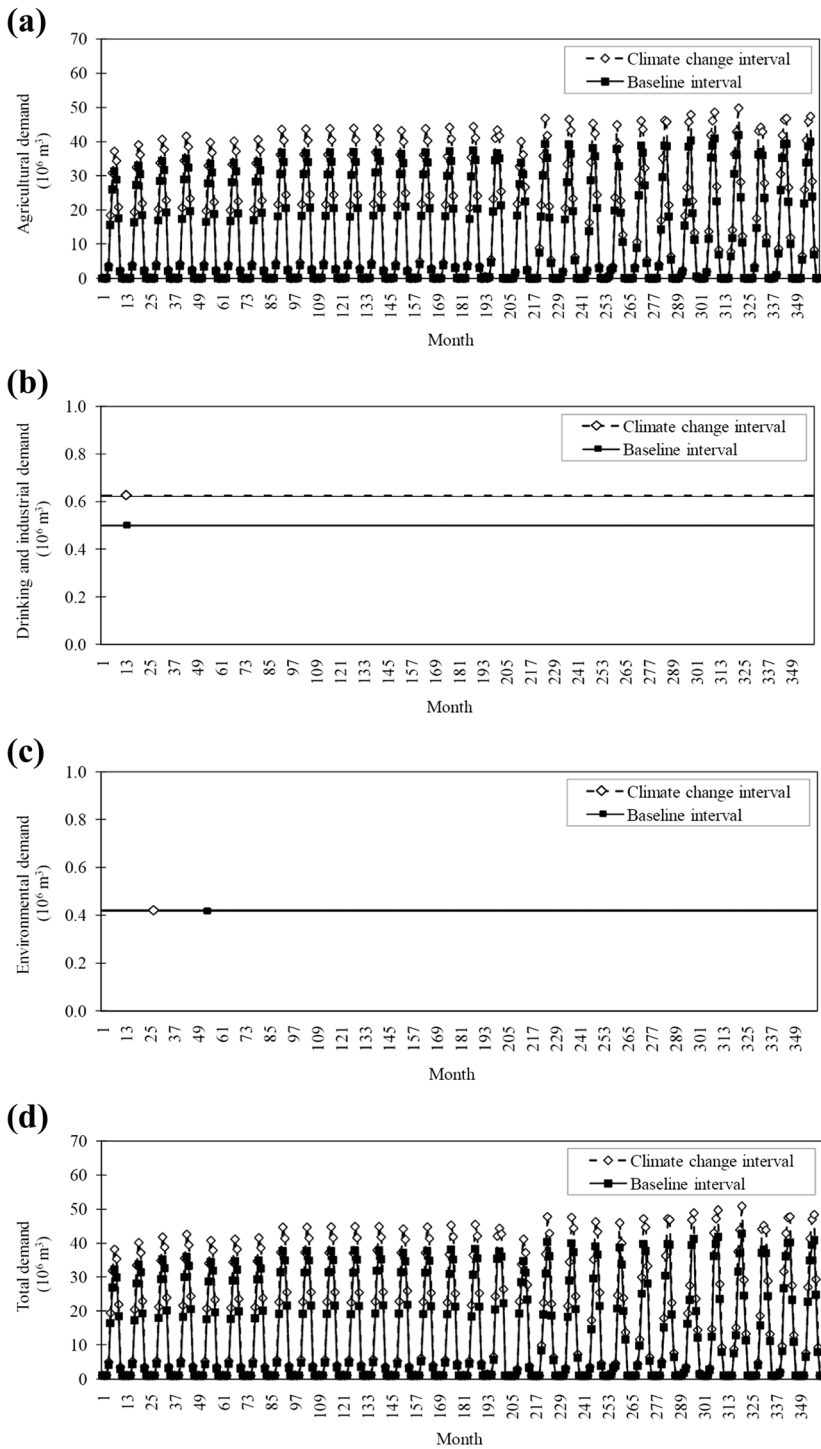
In order to assess the performance of Gharanghu multi-purpose reservoir in the delivery of water demand volume to agricultural, drinking and industry, and environmental, WEAP has been used based on the volume of inflow to the reservoir. With keeping parameter related to water demand volume as variable (based on the different percentage of supply), and with keeping parameter related to volume of inflow to reservoir as constant, three scenarios of water supply in climate change interval (given in section “scenarios under review”) were introduced to WEAP, which results related to release of reservoir and deficit of water supply have been presented in Fig. 11 and Fig. 12, respectively.

Since water demand in climate change interval has increased about 20%, and also inflow volume has decreased about 25%, optimal water allocation in some months has been less than demand that of course it is tried to minimize impacts of this shortage with proper management. The same investigation has been conducted for conditions of 85 and 70% of water demand supply, and optimal management of reservoir has been also simulated for these conditions. As seen in Figs. 11 and 12, shortages have reduced in 85% of supply, and it is the lowest in 70% compared to 100% of supply.

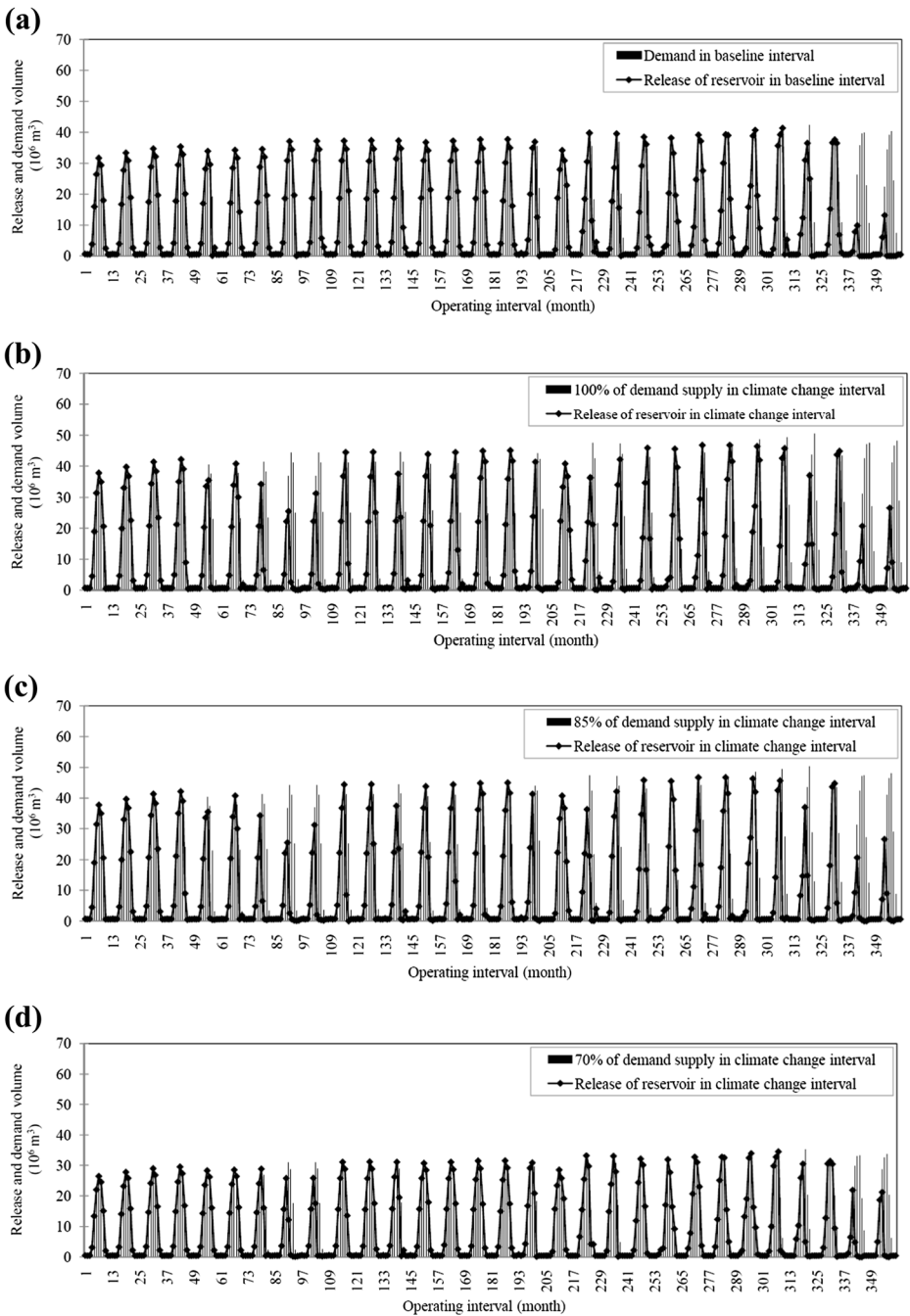
The results show that in case of supply of 100 and 85% of demand, deficiency in climate change interval relative to baseline has increased about 67 and 48%, respectively. However, supply of 70% will be caused decrease of 10% of deficiency. Therefore, making strategies for reduction of demand is the inevitable. Then, by extracting results of WEAP simulation, and using mentioned equations, EIs of reservoir in two intervals of climate change and baseline were calculated and results were showed in Table 3. Changes of indexes in Table 3 indicate that EIs of reservoir in the baseline interval relative to climate change interval will have a more appropriate status.

Reliability index in climate change interval based on 100, 85, and 70% of water supply compared to the baseline, will decline 18, 12, and 1%, respectively. Reliability index of 75% means that system in during operating period will not be able to meet demand in 75% of operating period. But it should be noted that although the higher reliability index indicates better performance of the system, design of water supply system with high reliability index is not realistic as well as economic. Because certainly, the system in during operating period will



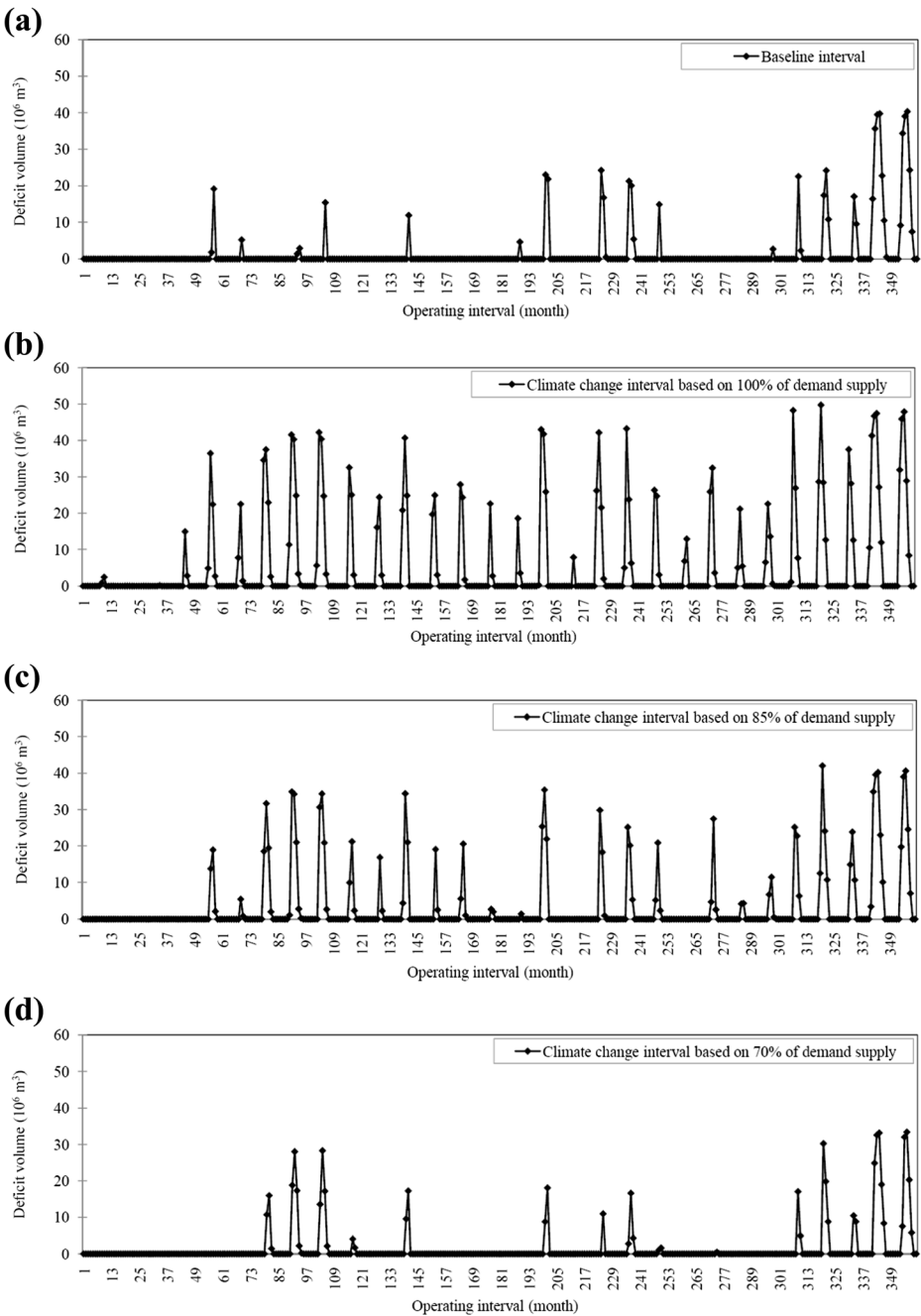


**Fig. 10** Comparison of the water demand volume in sectors of (a) agriculture, (b) drinking and industry, (c) environmental, and (d) all sectors in climate change interval compared to the baseline



**Fig. 11** Changes of the release and demand volume in (a) baseline interval, (b) climate change interval (based on 100% of supply), (c) climate change interval (based on 85% of supply), and (d) climate change interval (based on 70% of supply) with WEAP simulation

not be able to meet all demands due to unforeseen changes in dam downstream such as population growth, increase of area under cultivation and etc. Due to the adverse effects of



**Fig. 12** Changes of the deficit volume in (a) baseline interval, (b) climate change interval (based on 100% of supply), (c) climate change interval (based on 85% of supply), and (d) climate change interval (based on 70% of supply)

climate change on water resources, including reducing the volume of inflow to the reservoir, this index will be reduced in the future periods. But the downturn in its value has the inverse

**Table 3** Calculation of EIs of reservoir

Index	Percent			
	Operating interval			
	Baseline	Climate change (100% of water supply)	Climate change (85% of water supply)	Climate change (70% of water supply)
Reliability	92	75	81	91
Vulnerability	4	10	7	4
Resiliency	43	29	30	35
Flexibility	38	20	23	31

relation with downstream demand volume, and will increase with reducing the demand percentage. Vulnerability index shows that the system in operating interval will not be able to meet a few percent of demand. For example, vulnerability of 10% of system in climate change interval means that the system in during operating interval will not be able to supply of 10% of demands, and failures occur in during this interval. The results show that vulnerability index in climate change interval based on 100 and 85% of water supply compared to the baseline, will increase 150 and 43%, respectively. However, this index will be unchanged based on 70% of the water supply in climate change interval relative to the baseline. Resiliency index indicates that how fast will return system from the happened failure situation to the normal operating situation. The results show that the resiliency index in climate change interval based on 100, 85, and 70% of water supply compared to the baseline will be reduced 33, 30, and 19%, respectively. Index of flexibility is the ability of response to deficiencies with the least damage possible. The results show that flexibility index in climate change interval relative to the baseline based on 100, 85, and 70% of water supply will be reduced about 47, 39, and 18%, respectively.

## 5 Concluding Remarks

In this study, the effects of climate change on water resources and water uses in the multi-purpose reservoir downstream were studied. With regard to the occurrence of climate change and its adverse impact on the status of water resources, as expected, the deficiency of system in climate change interval will increase compared to the baseline. Also, the EIs of reservoir in climate change interval will not have a good situation compared to the baseline, which with managing volume of consumption and reducing demand, situation of EIs will be in better trend. In general, system behavior would be more ideal with higher reliability and resiliency, and lower vulnerability. Finally, the flexibility index that is combination of three mentioned indexes indicates the status of water supply system. This means that the higher the flexibility, the better the status of the water supply system, and critical periods (CP) are spent with the lowest risk. In the present paper, for supplying 100%, flexibility index in climate change interval will decrease 48% compared to the baseline, but if water consumption decrease only 15%, flexibility will decrease only 39%. The EIs of Reservoir are effective factors in the investigation of the reservoir behavior, especially determination of critical period in operating interval. By determining EIs with different levels of demand in the reservoir downstream, the reservoir can be designed to have ideal behavior. This means that the critical period is short and

has few occurrence numbers and also satisfactory situation is converted to the failure situation with an appropriate fast, i.e. flexibility of water supply system is maximized. By determining the critical periods, appropriate and efficient policies can be adopted for how to meet the demand in periods of deficit. Especially, in climate change interval that water stress is strongly exacerbated, the reservoir operating rules can be applied due to changes in EIs as well as critical period for optimal management of reservoirs.

There are several sources of uncertainty in different steps of studies for simulation of climatic variables by AOGCM models as well as for the correction of output of these models in order to use in simulation models of different systems including water resources and water consumptions that was not addressed in the present study. So when it could be stated that the output of water resources simulation models affected by climate change, have sufficient accuracy for decision-making, which the range of uncertainty in the calculations are applied and analyzed. This can be offered in future studies to improve results.

Thus, the uncertainties of the applied climatic and hydrological models and irrigation water demand models and also water planning models need to be addressed. In the present study, only a climatic model (i.e. HadCM3 due to high performance in simulation of climatic variables of basin), a hydrological model (i.e. IHACRES due to little input data and its high speed and also simple algorithm), an irrigation water demand model (i.e. Cropwat due to its efficiency for calculations related to water consumption of agricultural in Iran), and also a water planning models (i.e. WEAP model due to simple calculations based on LP) were used for evaluating the impacts of climate change on operating policies of reservoir with regard to inflow volume to reservoir and demand volume using EIs. Under- and over-estimation of any model may affect on results (Ashofteh et al. 2014). This issue needs to be further explored in further researches, because, such uncertainties may affect on predictions.

## References

- Ashofteh P-S, Bozorg-Haddad O, Mariño MA (2013) Scenario assessment of streamflow simulation and its transition probability in future periods under climate change. *Water Resour Manag* 27(1):255–274
- Ashofteh P-S, Bozorg-Haddad O, Mariño MA (2014) Discussion of “estimating the effects of climatic variability and human activities on streamflow in the Hutuo River Basin, China”. *J Hydrol Eng* 19(4):836–836. doi:10.1061/(ASCE)HE.1943-5584.0000834
- Ashofteh P-S, Bozorg-Haddad O, Akbari-Alashti H, Mariño MA (2015a) Determination of irrigation allocation policy under climate change by genetic programming. *J Irrig Drain Eng* 141(4):04014059. doi:10.1061/(ASCE)IR.1943-4774.0000807
- Ashofteh P-S, Bozorg-Haddad O, Loáiciga HA (2015b) Evaluation of climatic-change impacts on multi-objective reservoir operation with multiobjective genetic programming. *J Water Resour Plan Manag* 141(11):04015030. doi:10.1061/(ASCE)WR.1943-5452.0000540
- Ashofteh P-S, Bozorg-Haddad O, Loáiciga HA, Mariño MA (2016) Evaluation of the impacts of climate variability and human activity on streamflow at the basin scale. *J Irrig Drain Eng* 142(8):04016028. doi:10.1061/(ASCE)IR.1943-4774.0001038
- Assaf H, Saadeh M (2008) Assessing water quality management options in the upper Litani Basin, Lebanon, using an integrated GIS-based decision support system. *Environ Model Softw* 23(10–11):1327–1337. doi:10.1016/j.envsoft.2008.03.006
- Bozorg-Haddad O, Ashofteh P-S, Rasoulzadeh-Gharibdousti S, Mariño MA (2014) Optimization model for design-operation of pumped-storage and hydropower systems. *J Energy Eng* 140(2):04013016. doi:10.1061/(ASCE)EY.1943-7897.0000169
- Bozorg-Haddad O, Ashofteh P-S, Mariño MA (2015) Levee layouts and design optimization in protection of flood areas. *J Irrig Drain Eng* 141(8):04015004. doi:10.1061/(ASCE)IR.1943-4774.0000864
- Carter TR (2007) General guideline on the use of scenario data for climate impact and adaptation assessment. Finnish Environment Institute, Helsinki, pp 30–40

- Chau KW, Wu CL (2010) A hybrid model coupled with singular spectrum analysis for daily rainfall prediction. *J Hydroinf* 12(4):458–473
- Chen XY, Chau KW, Busari AO (2015) A comparative study of population-based optimization algorithms for downstream river flow forecasting by a hybrid neural network model. *Eng Appl Artif Intell* 46:258–268
- Droogers P, Aerts J (2005) Adaptation strategies to climate change and climate variability: a comparative study between seven contrasting river basin. *Phys Chem Earth, Parts A/B/C* 30(6–7):339–346. doi:10.1016/j.pce.2005.06.015
- Gholami V, Chau KW, Fadaee F, Torkaman J, Ghaffari A (2015) Modeling of groundwater level fluctuations using dendrochronology in alluvial aquifers. *J Hydrol* 529:1060–1069
- Haddad R, Nouiri I, Alshihabi O, Maßmann J, Huber M, Laghouane A, Yahiaoui H, Tarhouni J (2013) A decision support system to manage the groundwater of the Zeuss Koutine aquifer using the WEAP-MODFLOW framework. *Water Resour Manag* 27(7):1981–2000
- Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency and vulnerability criteria for water resources system performance evaluation. *Water Resour Res* 18(1):14–20. doi:10.1029/WR018i001p00014
- IPCC-TGICIA (1999) Guidelines on the use of scenario data for climate impact and adaptation assessment. Version 1. Prepared by Carter, T. R., Hulme, M. and Lal, M. Intergovernmental Panel on Climate Change. Task Group on Scenarios for Climate Impact Assessment, 69 p
- IPCC (2011) IPCC Intergovernmental panel on climate change web site: organization page. <http://www.ipcc.ch/organization/organization.shtml>
- Jones RN, Page CM (2001) Assessing the risk of climate change on the water resources of the Macquarie River Catchment. In: Ghassemi F, Whetton P, Little R, Littleboy M (eds) Integrating models for natural resources management across disciplines, issues and scales (part 2). Modsim 2001 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Canberra, pp 673–678
- Lévite H, Sally H, Cour J (2003) Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. *Phys Chem Earth, Parts A/B/C* 28(20–27):779–786. doi:10.1016/j.pce.2003.08.025
- Li X, Zhao Y, Shi C, Sha J, Wang Z-L, Wang Y (2015) Application of water evaluation and planning (WEAP) model for water resources management strategy estimation in coastal Binhai new area, China. *Ocean Coast Manag* 106:97–109. doi:10.1016/j.ocecoaman.2015.01.016
- Loucks DP (1997) Quantifying trends in system sustainability. *Hydrol Sci J* 42(4):513–530
- Moy W-S, Cohon JL, Reville CS (1986) A programming model for analysis of the reliability, resilience and vulnerability of a water supply reservoir. *Water Resour Res* 22(4):489–498. doi:10.1029/WR022i004p00489
- Raskin P, Hansen E, Stavisky D, Zhu Z (1992) Simulation of water supply and demand in the Aral sea region. *Water Int* 17(2):55–67
- Smith M (1988) Manual for CROPWAT version 5.2. FAO, Rome 45pp
- Taormina R, Chau K-W (2015) Data-driven input variable selection for rainfall-runoff modeling using binary-coded particle swarm optimization and extreme learning machines. *J Hydrol* 529(3):1617–1632
- Varela-Ortega C, Blanco-Gutiérrez I, Swartz CH, Downing TE (2011) Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: an integrated hydro-economic modelling framework. *Glob Environ Chang* 21(2):604–619. doi:10.1016/j.gloenvcha.2010.12.001
- Wang WC, Chau K-W, Xu D-M, Chen X-Y (2015) Improving forecasting accuracy of annual runoff time series using ARIMA based on EEMD decomposition. *Water Resour Manag* 29(8):2655–2675
- Wilby RL, Harris I (2006) A framework for assessing uncertainties in climate change impacts: low flow scenarios for the river Thames, U.K. *Water Resour Res* 42(2):W02419
- Wu CL, Chau KW, Li YS (2009) Methods to improve neural network performance in daily flows prediction. *J Hydrol* 372(1–4):80–93
- Yilmaz B, Harmancioglu NB (2010) An indicator based assessment for water resources management in Gediz River basin, Turkey. *Water Resour Manag* 24(15):4359–4379. doi:10.1007/s11269-010-9663-3