Adaptation of surface water supply to climate change in central Iran
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ABSTRACT
Optimal reservoir operation changes and adaptation strategies for the Zayandeh-Rud River Basin's surface water supply system are examined for a changing climate during the 2015–2044 period. On average, the monthly temperature in the basin is expected to increase by 0.46–0.76 °C and annual precipitation is expected to decrease by 14–38% with climate change, resulting in a reduction of the Zayandeh-Rud’s peak stream flow and the amplitude of its seasonal range. Snowfall decrease in winter months will generally lead to an 8–43% reduction in annual stream flow under climate change. A reservoir operation model is developed and optimal reservoir operation strategies are identified for adaptation of the basin’s surface water supply to climate change in the face of the increasing water demand. Results indicate that the reservoir drawdown season starts 2 months earlier under climate change. Smaller storage levels and greater water releases must occur to meet the increasing water demand. The optimized water release can provide sufficient water for non-agricultural water demand, but agriculture will experience more severe water shortage under a changing climate. Having the highest vulnerability, the agricultural sector should be the main focus of regional management plans to address the current water challenge and more severe water shortages under climate change.

Key words | Iran, optimization, reservoir operation, water resources management, water supply, Zayandeh-Rud

INTRODUCTION
Expected impacts of climate change upon water availability will have important implications for socioeconomic growth in the future (Frederick & Schwarz 1999). Strategic adaptation strategies must be implemented to ensure sufficient supply and efficient consumption of water in response to new hydrological conditions. Adaptation can be defined as the adjustments which are applied in natural and human systems to exploit beneficial opportunities or reduce risk and damage from current or future harms (IPCC 2001). Water resources adaptations to cope with water scarcity resulting from climate change and increasing water supply demands of a growing population, include (UNEP 1998): (1) supply oriented strategies: development of new infrastructure, modification of existing infrastructure, and improved management of water supply systems; and (2) demand oriented strategies: conservation and improved water use efficiency, technological changes, and water marketing and virtual water transfer between different sectors.

Water managers should reevaluate the operation of existing water resources systems to consider the wide range of probable changes in climatic variables. By storing water in times of surplus and releasing it in times of shortage, reservoirs play an important role in regulating surface water under climatic and hydrologic changes. Reduction in stream flow and its pattern changes can significantly affect...
reservoir water supply, imposing additional water scarcity. Many current reservoir operation plans are likely to be inadequate to mitigate the negative impacts of climate change on water supply reliability. Therefore, optimized reservoir operation and adaptation has been the subject of many studies aimed at accommodating the seasonal changes of surface water under climate change and moderating the impacts of climate change on water resources (e.g. Medellin-Azuara et al. 2008; Adamec et al. 2010; Graham & Georgakakos 2010; Madani & Lund 2010; Minville et al. 2010; Olsson et al. 2010; Raje & Mujumdar 2010; Connelly-Buck et al. 2011; Ncube et al. 2011; Vicuna et al. 2011; Steinschneider & Brown 2012; Jamali et al. 2013).

Reservoir operation can be defined as the strategies of reservoir water management to achieve different objectives, such as providing water supply, hydropower production, flood control, or recreational opportunities (Rani & Moreira 2010). Reservoir planning and management deal with complex variables such as inflow, storage, release and different water demands to satisfy often conflicting and unequally weighted objectives. Optimization of reservoir operation to maximize the beneficiaries’ utilities, subject to the mass balance equation and other hydrological and hydraulic constraints, can help to determine balanced solutions for reservoir operations planning and management challenges (Ngo 2006; Stahl 2007; Wang et al. 2010).

Labadie (2004) and Rani & Moreira (2010) reviewed the application of numerous optimization techniques in reservoir operation systems. Based on the forms of objective function and constraints, the developed optimization approaches have been classified into linear programming (LP), non-linear programming (NLP) and dynamic programming (DP) techniques (Simonovic 2009). LP is used for problems with linear objective functions and constraints. Even with the non-linear nature of problems in the real world, LP is one of the most widely used optimization approaches in water resources systems analysis (e.g. Needham et al. 2000; Tu et al. 2003; Vedula et al. 2005; Vicuna et al. 2008, 2011; Madani & Lund 2009, 2010; Yu 2009). NLP is used to optimize problems with non-linear objective functions and constraints (e.g. Caia et al. 2001; Teegavarapu & Simonovic 2002; Chang et al. 2005a, 2005b; Reddy & Kumar 2007; Afshar et al. 2009; Brandão 2010; Madani 2011). As another powerful optimization method, DP (Bellman 1957) has been frequently used to exploit the consecutive decision structure in order to provide optimized operation of water resources systems in non-linear optimization problems (e.g. Chang et al. 2002; Teixeira & Marino 2002; Kumar & Baliaiswine 2003; Liu et al. 2006; Jothipraakash & Shanthi 2009; Kumar et al. 2010; Olivares & Lund 2012).

The Zayandeh-Rud River Basin is one of the most studied basins in Iran (Ganji et al. 2007), Karamouz & Araghinejad (2008), Zahraie et al. (2008), Madani & Mariño (2009), Homayoun-far et al. 2010, Gohari et al. (2013a, 2013b), among others), due to its unique and complex hydro-environmental and socioeconomic characteristics. As the home to the historic city of Isfahan (former capital of Iran), the internationally recognized Gav-Khouni Marsh with a valuable and vulnerable ecosystem, major agriculture in central Iran, and many inhabitants, the Zayandeh-Rud River Basin is the most important basin in central Iran. Due to watershed development and population growth, increasing water demand and associated competition for water have posed a great challenge for water resources management in the basin in the past decades (Madani 2007). While the annual yield of the Zayandeh-Rud River has been dramatically increased through major water transfers in the past decades, the basin is still suffering from serious water shortages, making the reliability of water transfer as a solution to water shortage questionable (Madani & Mariño 2009; Gohari et al. 2013b).

Climate change projections have indicated a 1.1 to 1.5 °C increase in monthly temperature and 11–31% reduction in annual precipitation in the basin during the near-term future (2015–2044) (Gohari et al. 2013a). The negative impacts of climate change on water resources, coupled with increasing water demand, will intensify the current water scarcity in the basin. The appropriate operation of the Zayandeh-Rud Reservoir can play a key role in surface water supply to moderate the negative impacts of watershed development and global warming in the future. Impacts of climate change and potential adaptation strategies with respect to climate change risk and uncertainty have not been investigated for the Zayandeh-Rud River Basin. Therefore, this study tries to bridge the gap in the decision makers’ understanding of climate change effects on the Zayandeh-Rud River Basin’s surface water.
system to identify effective climate change adaptation strategies, considering the uncertainties involved in climate change projections.

The paper is structured as follows. The following section provides an overview of the case study and the Zayandeh-Rud Reservoir. The selected climate change scenarios with hydrological models and the optimization method are described next. The subsequent section presents the results of future hydrological regimes and optimized reservoir operation, followed by a discussion of the major limitations of this study. Finally, the main conclusions and recommendations for adapting surface water supply to climate change are presented.

CASE STUDY

The Zayandeh-Rud River Basin, with an area of about 26,917 km², is located in central Iran (Figure 1). In recent decades, due to high agricultural and industrial development potential, the basin has witnessed economic growth and increased population (Madani & Mariño 2009). Currently, more than 3.7 million people live in the basin, making it the second most populated water basin in Iran. As the major water consumer, the agricultural sector uses more than 73% of water supply (Zayandab Consulting Engineering Co. 2008). Cultivation of high water demand crops (i.e. rice, corn, wheat and barley) and low irrigation efficiency (low ratio of water stored in the soil depth inhabited with active plant roots to water applied by the irrigation system) of 34–42% contribute to the high agricultural water demands.

The Zayandeh-Rud River, with an average flow of 1,400 million cubic meters (MCM) per year (44.39 cubic meters per second), including 650 MCM of natural flow and 750 MCM of transferred flow (provided from neighbouring water basins through water transfer projects), starts in the Zagros Mountains to the west of the basin and flows into the Gav-Khouni Marsh to the east of the basin. The river has been tapped by increasing water consumption within
and outside the basin. The Zayandeh-Rud River is the most important water resource in the basin for its residents and their urban, industrial and agricultural uses, as well as for the survival of the ecosystem of the Gav-Khouni Marsh, recognized by the Ramsar Convention (1971).

The Chadegan (Zayandeh-Rud) Dam, with physical characteristics as listed in Table 1, was built in 1971 mainly for flood control, water supply and hydroelectricity generation. In past decades, population growth and watershed development, coupled with the occurrence of severe droughts, have intensified water scarcity in the basin. During the recent water shortage, the water managers in the basin decided to operate the Zayandeh-Rud Reservoir only for water supply. The spillway gates of the reservoir have been closed during spring and summer to store sufficient water to supply the domestic and industrial sectors, as the most important water user sectors to the operators. Aggressive upstream water uses coupled with the current operation of the reservoir have resulted in drying and parching of the Zayandeh-Rud riverbed during summer, which has caused the Gav-Khouni Marsh to be considered by many environmental activists as an already-dead wetland.

**METHOD**

This study uses the projected climate change variables for the Zayandeh-Rud River Basin supplied by Gohari et al. (2013a), based on their suggested probabilistic multi-model framework. In this framework, the uncertainties of global climate models (GCMs), emission scenarios and climate variability of daily time series are handled by a combination of change factors and the LARS-WG stochastic weather generator (Semenov 2007). In their study, monthly climate change scenarios of temperature and precipitation were first developed, using 10 GCMs. Then, cumulative probability distributions for climate change scenarios were developed and climate scenarios corresponding to the 25th, 50th and 75th probability percentiles were extracted. This was followed by using the LARS-WG stochastic downscaling method (Semenov & Barrow 2002) to generate daily temperature and precipitation time series at different probability percentiles. In this study, monthly runoff at different probability percentiles is generated by a lumped IHACRES model (Jakeman & Hornberger 1993). Then, a non-linear reservoir operation model is developed to optimize the operations of the Zayandeh-Rud Reservoir to minimize water shortage under different climate change and water demand scenarios. For better illustration, the approach taken by Gohari et al. (2013a) to generate the input data needed for this study is briefly explained below. Readers can consult the original work for further details.

**Daily climate variables’ time series under climate change**

Future daily time series of climate variables, namely precipitation (mm) and maximum and minimum temperatures (°C) were generated for climate change scenarios within the study region. The uncertainties of GCMs, emission scenarios and climate variability of daily time series were dealt with through a combination of change factors and a weather generator.

**Extraction of climate change scenarios**

Monthly temperature and precipitation variables for the baseline period (1971–2000) and future period (2015–2044) were extracted from 10 GCMs (described in Gohari et al. (2013a) for two emission scenarios (A2 and B1) from the Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR4)). The differences of temperature and relative precipitation in the 30-year monthly average future period (2015–2044) and baseline period (1971–2000) were calculated for each month.

**Probability distribution of climate change scenarios**

The ranges of extracted climate change scenarios were not the same for different GCMs, due to their dissimilar
capabilities in simulating the regional climate. Therefore, each of the 10 GCMs was weighted based on the Mean Observed Temperature-Precipitation method (Massah Bavani & Morid 2005), which weighs GCMs based on their ability to simulate the observed climate variables for the baseline period.

In the next step, probability distribution functions (PDFs) of climate change scenarios were developed for each month. These PDFs associate the ‘30-year monthly average of temperature and precipitation changes’ with the ‘weight of corresponding GCM’, helping with converting discrete probability distributions of climate change scenarios to continuous probability distributions. The Gamma distribution function with two parameters was then used to develop continuous synthetic monthly PDFs, followed by finding the monthly cumulative distribution functions (CDFs) of climate change variables. The values of climate change scenarios for temperature and precipitation were extracted at three percentiles (25th, 50th and 75th) from the developed CDFs, with the 25th probability percentile representing low temperature and high precipitation changes and the 75th probability percentile reflecting high temperature and low precipitation changes.

**Regional climatic variable time series**

Stochastic Weather Generators (WGs) can generate daily time series of climate variables. The LARS-WG (Semenov & Barrow 2002) is a powerful stochastic WG that can generate synthetic daily time series of climatic variables from the monthly data for the climate change scenarios. Gohari et al. (2013a) used LARS-WG to generate daily precipitation, maximum and minimum temperatures, and precipitation time series for the future study period (2015–2044), based on the observed daily time series of the 1971–2000 period and climate change scenarios at 25th, 50th and 75th probability percentiles at two stations, characterized in Table 2.

As their main drawback, WGs randomly produce various time series with similar monthly mean based on the local observed times series and climate change scenarios. To address this drawback and the uncertainty in the WGs’ outputs, LARS-WG was run to generate 300-year daily time series for the future study period at different probability percentiles under each emission scenario. Each one of the generated 300-year time series was then broken into 30-year daily time series and the average daily values of the resulting 10 time series (300/30) were calculated to handle the uncertainty in the generated climatic variables. More details about this process can be found in Gohari et al. (2013a).

**Simulation of monthly runoff**

The IHACRES model (Jakeman & Hornberger 1993) was used in this study to simulate rainfall-runoff processes in the basin. This conceptual-metric model imposes more detailed internal processes than a metric model to reduce the typical uncertainty of the parameters that exist in a pure conceptual model. Based on the concept of effective rainfall, a non-linear loss module was used to estimate the effective rainfall amount for each time step according to the rainfall depth and temperature. The effective rainfall was then used as an input for a linear unit hydrograph module to generate the runoff hydrograph. The IHACRES model was used to generate the runoff time series based on the temperature and precipitation time series for the future 2015–2044 period.

**Reservoir operation model**

A non-linear optimization model was formulated to adapt the operations of the Zayandeh-Rud Reservoir to climate change and increasing water demand in the future. The defined constraints in this model include the physical constraints of the Zayandeh-Rud Reservoir and water continuity equations. Given the existing water delivery priorities for the water managers in the basin, it was assumed that domestic and industrial water demand should be fully supplied in the planning horizon. In other words, the
minimum water release must satisfy both of the mentioned water demands in each month. The objective function of the model minimizes the sum of squared water shortage in the basin during the future 2015–2044 period

$$\min Z = \sum_{j=1}^{30} \sum_{i=1}^{12} Sh_{i,j}^2$$

subject to

$$DT_{i,j} - R_{i,j} \leq Sh_{i,j} \quad \forall i, j$$

$$0 \leq Sh_{i,j} \quad \forall i, j$$

$$DT_{i,j} = D_{Di,j} + D_{Ii,j} + D_{Ei,j} + D_{Ai,j} \quad \forall i, j$$

$$\begin{cases} S_{i+1,j} = S_{ij} + I_{ij} - R_{ij} & i = 1, 2, 3, \ldots, 11; \forall j \\ S_{1,j+1} = S_{ij} + I_{ij} - R_{ij} & i = 12; \forall j \end{cases}$$

$$0 \leq S_{ij} \leq S_{max} \quad \forall i, j$$

$$D_{Di,j} + D_{Ii,j} \leq R_{ij} \leq D_{Di,j} + D_{Ii,j} + D_{Ei,j} + D_{Ai,j} \quad \forall i, j$$

where in month $i$ ($i = 1, 2, \ldots, 12$) of year $j$ ($j = 1, 2, \ldots, 30$): $Sh_{i,j}$ is water shortage; $R_{ij}$ is the water release from the reservoir; $DT_{i,j}$ is the total water demand; $D_{Di,j}$ is the domestic water demand; $D_{Ii,j}$ is the industrial water demand; $D_{Ei,j}$ is environmental water demand; $D_{Ai,j}$ is the agriculture water demand; $S_{ij}$ is the water storage in reservoir at beginning of the month; $I_{ij}$ is the reservoir inflow; and $S_{max}$ is the maximum possible water storage in the reservoir ($S_{max} = 1250$ MCM). In this model, end-of-period storage was set equal to the initial storage to avoid the full drawdown of the reservoir (by the optimization model) at the end of the planning horizon (Equation (6)).

The formulated optimization model is a monthly-step reservoir operation model with a non-linear quadratic objective function and linear constraints. The model was solved using the General Algebraic Modeling System (GAMS 23.5) software package to evaluate the impact of climate change on the optimal operation of the reservoir during the 2015–2044 period. To understand the effects of climatic and water demand changes on the optimal operation of the system, the optimization model was run for different combinations of seven climate and three water demand scenarios, described in Tables 3 and 4, respectively.

### Indices

Indices or performance measures are helpful in assessing the relative benefits of alternative water management strategies. Here, three indices were used to better understand the effects of climatic and demand changes on the Zayandeh-Rud River surface water system.

#### Table 3 | Reservoir inflow scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>Historical (1971–2000) flows</td>
</tr>
<tr>
<td>IA25</td>
<td>25th climate change probability percentile for the A2 emission scenario</td>
</tr>
<tr>
<td>IA50</td>
<td>50th climate change probability percentile for the A2 emission scenario</td>
</tr>
<tr>
<td>IA75</td>
<td>75th climate change probability percentile for the A2 emission scenario</td>
</tr>
<tr>
<td>IB25</td>
<td>25th climate change probability percentile for the B1 emission scenario</td>
</tr>
<tr>
<td>IB50</td>
<td>50th climate change probability percentile for the B1 emission scenario</td>
</tr>
<tr>
<td>IB75</td>
<td>75th climate change probability percentile for the B1 emission scenario</td>
</tr>
</tbody>
</table>

#### Table 4 | Water demand scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>Historical (1971–2000) water demand</td>
</tr>
<tr>
<td>DF1</td>
<td>Water demand will increase with the historical growth rate (domestic water demand growth rate of 1.7%; and industrial water demand growth rate of 3.2%)</td>
</tr>
<tr>
<td>DF2</td>
<td>High water demand (water demand equal to the 2044 water demand under DF1)</td>
</tr>
</tbody>
</table>
Reliability index

Reliability is the likelihood of full satisfaction of water demands during the planning period. The water reliability index is formulated as (Hashimoto et al. 1982)

\[ Re = \frac{\text{number of time-steps with } Sh = 0}{N} \]  

(9)

where \( Sh \) is water shortage and \( N \) is the number of time-steps (months here) in the planning period.

Vulnerability index

Vulnerability indicates the likely magnitude of water deficit, if it occurs, and can be expressed as the average value of deficit (Loucks & van Beek 2005):

\[ VuI = \frac{\left( \sum_{j=1}^{N} Sh_j \right) / \text{(number of time-steps with } Sh \neq 0)}{\text{water demand}} \]  

(10)

Resilience index

Resilience is defined as a system’s capacity to recover after a failure, that is, the probability that a successful period occurs after a period of failure (Moy et al. 1986). The resilience index is defined as

\[ Res = \frac{\text{number of times } Sh_j = 0 \text{ follows } Sh \neq 0}{\text{Number of time-steps with } Sh \neq 0} \]  

(11)

These indices can be calculated for the desired planning time-steps (annual, monthly, or weekly). Here, these indices were calculated on an annual basis.

RESULTS

Climate change impact assessment

Changes in temperature and precipitation

Figures 2 and 3, respectively, indicate the estimated monthly temperature and precipitation for various climate change scenarios based on Gohari et al. (2013a). In general, monthly temperature increases are expected under all climate change scenarios except in January and February. The values of projected temperature are larger under the B1 emission scenario than under the A2 scenario due to more rapid socioeconomic and population growth under this scenario. The maximum temperature rises are expected in summer and spring months. Similar to the temperature changes, the values of estimated precipitation under the B1 emission scenario are larger than the changes under the A2 emission scenario. Except for the wet conditions projected by the A2–25% scenario, the local precipitation changes show a general decreasing trend. The results suggest that the maximum reduction in monthly precipitation will happen in January. The projected annual and seasonal changes of the 30-year mean temperature and total precipitation were calculated under different probability percentiles under climate change (Table 5). With an annual 14–38% decrease in precipitation and an annual 0.46–0.76 °C increase in temperature, the basin will face warmer and drier conditions under climate change except in scenario A2–25%. The maximum seasonal changes are predicted for winter precipitation (6–55% reduction) and spring temperature (0.70–1.03 °C increase).

Changes in reservoir inflows

Figure 4 shows the average monthly reservoir inflows under different climate change scenarios. Temperature rise will
lead to more precipitation falling as rain, instead of snow, and the snowpack will melt earlier in the spring. The peak inflow usually occurs 1 month earlier in the year under climate change. Reduced snowfall due to increasing temperature in winter months will generally lead to a reduction in the reservoir inflow under climate change. The ranges of inflow reduction are larger under the B1 emission scenario than the A2 emission scenario. Global warming reduces the value of peak inflow and the amplitude of its seasonal range. The projected annual and seasonal changes of 30-year mean inflows under different climate scenarios are shown in Table 6. With the annual reduction of 8–43% in reservoir inflows and reduction of 27–48% in spring inflows, the current operation policies will be ineffective to minimize the negative impacts of climate change.

**Optimal surface water operation under climate change**

The reservoir operation model was run under different climate change and demand scenarios to find the optimal...
storage operation, water release and water shortage during the 2015–2044 period. The values of performance indicators were also calculated to better understand the effects of future climatic and socioeconomic changes on surface water management in the basin.

**Changes in storage operation**

Figure 5 shows the average monthly water storage in the Zayandeh-Rud Reservoir under climate change, assuming historical water demand (HD) for the future 2015–2044 period. Global warming will lead to a reduction in the amount of peak-storage in the reservoir and the peak storage will occur 2 months earlier in the spring with climate change. The general seasonal cycle of storage illustrates that the reservoir refills partially during autumn and winter months and then is drawn down until late summer. Climate change decreases the amplitude of seasonal cycle of storage in the reservoir. The storage levels under the A2 emission scenario are projected to be higher than the B1 scenario. The reservoir storage under climate change dominates historical storage levels during the new refilling stage of the cycle (autumn and winter months), but has lower levels until late summer.

The seasonal cycle of water storage with historical and different climate change hydrological conditions under DF1 and DF2 scenarios for the future 2015–2044 water demand are shown in Figures 6 and 7, respectively. The peak-storage will occur 1 month earlier under climate change for both water demand scenarios. In comparison with HD and DF2, increasing water demand under DF1 will lead to 1 month earlier peak-storage under historical
Global warming will lead to a reduction in the amounts of peak-storage under DF1 and DF2 scenarios. The lower levels of water storage overall are projected under DF2 scenario compared with HD and DF1 water demand scenarios. This is because further water release during the drawdown period will occur to meet greater water demand under DF2 scenarios.

**Changes in water supply**

Optimized water releases under different hydrological conditions were compared to water delivery targets, which include domestic, industrial, agricultural and environmental water demands. The 30-year monthly average water release from the Zayandeh-Rud Reservoir under different hydrological conditions for the three water demand scenarios is shown in Figures 8-10. The results indicate that climate change decreases water releases and intensifies water scarcity in the basin. Based on Figure 8, surface water is not sufficient to even satisfy the historical demand in the basin. Therefore, groundwater has been heavily used as a secondary water supply source, resulting in strongly declining groundwater levels in the basin. The current groundwater withdrawal has been more than the safe groundwater yield and the basin is experiencing groundwater shortage issues. Therefore, the basin has no further opportunity for minimizing water deficit in the future through aggressive groundwater withdrawal.

The ranges of monthly water release vary between the historical and climate change scenarios for each water demand scenario. Generally, global warming will lead to a reduction in monthly water releases, especially under the B2 emission scenario. The smaller variability in seasonal water release amplitude under the B1 emission scenario corresponds to insignificant variability in annual stream flow in the Zayandeh-Rud River. There is no water shortage for the months of December through to February under climate change and historical hydrology conditions. Comparison of the optimized water release with water demand illustrates that non-agricultural water demand can be fully satisfied under different water demand scenarios, except for the B75 climate change scenario under DF2 water demand.

**Figure 7** Average monthly water storage for the Zayandeh-Rud Reservoir under different climate scenarios with the DF2 water demand scenario. As a reference for comparison, the HI scenario corresponds to optimal operations based the historical hydrology (1971–2000).

**Figure 8** Monthly water release from the Zayandeh-Rud Reservoir for different water demand levels under the historical hydrology. The circles, upper and lower whiskers, respectively, show the mean, maximum, and minimum water release during the future 2015–2044 period.
Table 7 presents the values of three indices, calculated to assess the effectiveness of changing reservoir operation policies as an adaptation measure to mitigate the effects of global warming. To better understand the climate change effects on each water sector, these indices have been calculated for each sector separately. Given that domestic and industrial water demands are fully satisfied in all cases here, the corresponding index values are not reported.

Due to the extreme importance of the Gav-Khouni Marsh (an internationally recognized marsh under the Ramsar Convention on Wetlands of 1971) as the main ecological resource of the basin, it is assumed that environmental water demand has the third priority (after domestic and industrial water demand), putting it above agricultural water demand. Fortunately, the basin’s environmental water demand can be fully satisfied under all scenarios (except for IB75 with DF2), if the operators give priority to ecosystem over agriculture in practice.

The reliability index values indicate that agricultural water demand cannot be fully satisfied under the different
hydrological scenarios. Lower values of the reliability index show that climate change intensifies agricultural water shortage in the future. The maximum and minimum values of the agricultural reliability index are projected to be 0.34 and 0, respectively, with the HD and IB75 hydrological conditions under the DF2 water demand scenario. The vulnerability index demonstrates that agriculture is the most vulnerable water sector to climate change. The optimized operation of the reservoir can provide sufficient water for environmental water demand even under drier conditions. The values of the resilience index suggest that the Zayandeh-Rud’s surface water supply system’s resiliency decreases with future socioeconomic and climatic changes.

**Water shortage**

Figure 11 shows the frequency of monthly relative water shortages (monthly water release/monthly water demand) during the 30-year study period under different hydrologic
conditions with HD. The results indicate that water shortages are likely in 65% of months, even with the historical hydrology. Climate change will intensify water shortages, increasing both shortage frequency and magnitude. Water shortage intensities are generally expected to be greater under the B1 than A2 emission scenarios. As indicated by Figures 12 and 13, growing water demand increases the shortage frequency and magnitude. The situation is expected to worsen by climate change. Under the extreme scenarios (e.g. IB75-DF2), water shortages are expected 100% of the time.

**LIMITATION**

Similar to all modeling studies, our results are associated with limitations which should not be overlooked when interpreting the results and developing policy advice (Madani 2013). Four specific limitations should be mentioned for this study. First, this study attempts to adapt the Zayandeh-Rud’s surface water supply to climate change. The operation of the Zayandeh-Rud Reservoir is optimized to minimize the impact of water shortage in the study region. However, groundwater is also recognized as
a backup water resource for domestic and agricultural water demand in the basin, while optimization of conjunctive surface and ground water use was not considered in this study. Currently, groundwater is used as a substitute for surface water. The high agricultural demand in the region has resulted in serious groundwater overdraft. Conjunctive use of groundwater with serious control of groundwater withdrawal becomes more important under climate change. Nevertheless, given that current groundwater withdrawals exceed the safe groundwater yield, withdrawal of additional groundwater to manage the expected water shortages is not reasonable.

Second, limitations relate to the bias implicit in the projection of future hydrology under climate change. The land use, soil moisture and soil physical characteristics are the main parameters which affect timing and amount of infiltration and runoff in the basin. The impacts of such parameters and their changes under climate warming and human development have not been considered in the runoff projections.

Third, water availability and water demand growth have a feedback relationship (Mirchi et al. 2012; Gohari et al. 2013b). So, the water demand scenarios of this study might be unrealistic as they have been assumed to be independent from water availability in the basin. Furthermore, here agricultural water demand was assumed not to increase in the basin in the future. Nevertheless, if agricultural activities are continued in the basin at the current level, future agricultural demand will be higher than the current rate due to higher water requirements of crops under climate change (Gohari et al. 2013a).

Fourth, the developed optimization model is deterministic with perfect foresight into future hydrologic conditions. This makes the model optimistic, as the prescribed performance quality of the operations is not achievable in practice given the uncertainties involved in reservoir operations. Future studies might address these limitations.

**CONCLUSIONS**

This study used a combination of water demand and global warming scenarios to study the impacts of future socioeconomic and climatic changes on surface water supply in the Zayandeh-Rud River Basin in central Iran. The IHACRES model, as a lumped hydrological model, was applied to simulate monthly reservoir inflow under climate change. The results indicate that global warming reduces the value of peak inflow and the amplitude of its seasonal range. Reduced snowfall due to increasing temperature in winter months will generally lead to a reduction in the reservoir inflow under climate change. On an annual basis, inflow will decrease by 8–43% under climate change. The maximum seasonal change is projected for spring inflow (27–48% reduction). The peak inflow is projected to occur 1 month earlier in the water year due to temperature rise and earlier snowmelt under climate change.

The Zayandeh-Rud River Basin with a semi-arid Mediterranean climate, as well as continuous watershed development and growing water demand, is a region with high vulnerability to climate change. Given the strategic importance of water availability in the basin for sustainable agriculture, socioeconomic development and ecosystem health in central Iran, adaptation strategies must be identified and timely actions taken to minimize the impacts of the expected climatic and socioeconomic changes in the basin. As the first step in adaptation of surface water supply to climate change in central Iran, this study focused on optimization of the operation of the Zayandeh-Rud Reservoir which serves as the major water supply source in the region. Modeling results indicate that changes in reservoir operations are required to minimize the undesirable impacts of future changes in the basin. In general, water storage levels are expected to decrease and the...
drawdown season is expected to start earlier under climatic and water demand change.

Generally, non-agricultural water demand can be satisfied to a great degree in the future. As the most vulnerable water use sector, agriculture will witness more water shortage under climate change even if water demand remains unchanged. This could lead to more groundwater withdrawals from groundwaters which are already experiencing declining levels. Given the unavailability of sufficient groundwater to compensate for the surface water losses and inefficiency of supply oriented strategies, such as water transfer, in satisfying the increasing water demand in the basin (Gohari et al. 2013b), it is necessary to implement demand management strategies for sustainable water management in the region. Water management in the basin has no alternative other than limiting agricultural development, discontinuing growing water-intensive crops (e.g. rice, alfalfa and corn), expanding rainfed agriculture (to replace the lost irrigated lands), and selecting an appropriate crop portfolio with special attention to water availability in the basin. Furthermore, there is a serious need to increase water use efficiency in irrigation and drainage networks to reduce water waste in the existing outdated irrigation systems.

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