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Climate-environment-water: integrated and non-integrated approaches to reservoir operation

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Abstract Integrated water planning and management face multiple challenges, among which are the competing interests of several water-using sectors and changing climatic trends. This paper presents integrated and non-integrated climate-environment-water approaches for reservoir operation, illustrated with Karkhe reservoir, Iran. Reservoir operation objectives are meeting municipal, environmental, and agricultural water demands. Results show the integrated approach, which relies on multi-objective optimization of municipal, environmental, and agricultural water supply, improves the municipal, environmental, and agricultural objectives by 70, 32, and 65% compared with the objectives' values achieved with the non-integrated approach, which implements a standard operating policy.

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Introduction

Water shortage has become more frequent in many regions of the world, threatening agriculture, urban, and rural communities. The uneven regional distribution of precipitation and water resources combines with increasing population and economic activity thus making effective water management a rising challenge. Shiau (2003) reported water release policies for the Shihmen reservoir (Taiwan) to cope with water supply during droughts. Yan et al. (2018) explored two water availability and three water use scenarios to assess and manage water shortage in the Pearl River Basin (China). Four strategies were defined for Pearl River Delta water use, irrigation water use, and manufacturing water use. Shiau et al. (2018) analyzed water deficit frequency in Taiwan and proposed hedging rules for reservoir operation to meet water demands during droughts. Rashid et al. (2018) optimized irrigation deficit of multipurpose series reservoirs with the genetic algorithm (GA). The latter authors coupled simulation-optimization tools involving hydropower generation, sediment removal, and flood-damage reduction benefits associated with the Tarbela and DiamerBasha reservoirs in Pakistan.

Climate change caused by natural processes and by human-induced emission of greenhouse gases (GHGs) by burning fossil fuels has introduced further complexities in the water management industry (Sarzaeim et al. 2017a). Several studies have addressed climate change and its effects on water resources management. Aiwen (2000) forecasted annual average temperatures would increase in China up to the year 2030, with the gradient variation in southern China forecasted to be less than in northern China. Water shortage may cause 1300 million to 4400 million yuan losses by 2030. Conly and Kamp (2001) proposed hydrologic monitoring networks to detect the effects of climate change and land use changes. Wilby and Harris (2006) presented a probabilistic framework for combining information from an ensemble of four general circulation models (GCMs), two greenhouse gas emission scenarios, two statistical downscaling techniques, two hydrological model structures, and two sets of hydrological model parameters. Xu (2000) forecasted the effects of climate change on the flow regimes of a basin in central Sweden applying a conceptual monthly water balance model. Model predictions indicated significant hydrologic implications for future water resource planning and management. Krysanova et al. (2010) considered three European river basins, two African basins, and the Amudarya basin in Central Asia to probe climate-change adaptation strategies in these basins. The latter authors reported that adaptation to climate change has started in all basins, but progresses slowly. Veijalainen et al. (2010) estimated the effects of climate change in three lakes of the Vuoksi watershed (Finland) in 2010–2039, 2040–2069, and 2070–2099 relying on conceptual modeling. Krol et al. (2011) demonstrated climate change impacts on small and large reservoirs, which call for resilient water engineering. Mujumdar (2013) reviewed challenges to water management in developing countries under climate change conditions. Abrahão et al. (2015) studied a 752-ha catchment located on the left margin of the Ebro River Valley, in Northeastern Spain to assess impacts of climate change on the catchment's water cycle and adaptation strategies. Goodarzi et al. (2016) evaluated the effects of climate change on groundwater recharge in the Najafabad plain. Tramblay et al. (2018) studied the largest dams in Algeria, Morocco, and Tunisia for climate change impacts in terms of evapotranspiration. The latter authors estimated reference evapotranspiration with the air temperature-solar radiation based on the Hargreaves-Samani (HAR) equation and with the FAO's Penman-Monteith (PM) equation, which accounts for air temperature, wind speed, solar radiation, relative humidity, and transfer resistances. Their results suggest the need for improved management of surface water resources to respond to future climatic conditions.

Challenges to food security under water shortage and climate change conditions must be addressed timely to avoid future crises. The agricultural sector is the largest water-using sector worldwide, which governs the food supply chain. Thus, it is imperative to address the water-food nexus under growing population and changing climate. Integrated water management considers human and environmental water needs to achieve sustainable water resource utilization assuring suitable water supply for humans while maintaining ecosystem health under a changing climate. There are numerous publications in the fields of climate changing, environment, and water management; yet, it is necessary to study all factors simultaneously.

This paper proposes an integrated water management approach with an application to Karkhe reservoir operation and compares results with those arising from non-integrated management. The paper's methodology objective is to meet reservoir stakeholders' water demands in the municipal, environmental, and agricultural sectors blending simulation and optimization methods. Standard operational policy (SOP) and the non-dominated sorting genetic algorithm (NSGA)-II are two methods applied to meet water demands. SOP and NSGA-II have been implemented in previous reservoir operation studies. This paper applies a new integrated approach in which climate change conditions modify environmental demands and other demand sectors. This work's results illustrate the management differences that arise by applying integrated and non-integrated approaches to reservoir operation.

Climate change conditions

Climate change is a long-term global phenomenon driven by natural causes and in the modern era also by human emissions of GHGs. Climate processes involve the terrestrial, atmospheric, and oceanic components of the earth system and may be affected by human activity. The Intergovernmental Panel on Climate Change's (IPCC) AR5 5th assessment report of 2014 proposed four representative concentration pathways (RCPs) based on the possible GHG concentration pathways through the twenty-first century. The RCPs cover a range of possible radiative forcing values in the mid-

(2046–2065) and late-21st (2081–2100) century relative to pre-industrial values. According to the RCP assumptions, a likely range of global warming ranges between 3.0 and 12.6 °C by the end of the twenty-first century. RCP projections are listed in Table 1 (see also Fujino et al. 2006; Riahi et al. 2011; Thomson et al. 2011; Van-Vuuren et al. 2011; and Wayne 2013).

This paper projects temperature and precipitation projections for the Karkhe Basin (Iran) made with the CanESM2 GCM. The projections were downloaded from the www.ccds-dscc.ec.gc.ca website. The GCM's projections were downscaled for application to basin-scale analysis. This paper implements the statistical downscaling method (SDSM) proposed by Wilby et al. (2002) to downscale the CanESM2 climatic projections for the Karkhe Basin. The statistical (or regression) downscaling has five steps: (1) screening of variables: suitable predictor(s) are chosen. This means potential predictors such as daily precipitation, maximum and minimum temperatures, wind speed, and solar radiation are assessed as predictors of the downscaled climate scenario; (2) model calibration: multiple linear regressions are developed and a model structure is determined applying unconditional and conditional models to link regional-scale climate predictors with local climate predictions; (3) synthesis of observed data: enables the verification of calibrated models, and ensemble members are considered equally plausible local climate scenarios realized by a common suite of regional-scale predictors; (4) generation of scenarios: ensembles of synthetic climatic series are produced; and (5) statistical analysis of the SDSM derived scenarios were carried out (Wilby et al. 2002). Projections of runoff are calculated by means of the identification of unit hydrographs and component flows from rainfall, evaporation, and streamflow data (IHACRES) model that simulates runoff based on surface air temperature and rainfall inputs. The IHACRES model features two modules: (1) effective rainfall estimation using temperature and rainfall as model inputs and (2) streamflow simulation by effective rainfall (Croke and Jakeman 2008).

Reservoir operation

Reservoirs and their dams are commonly large-scale water infrastructure built to store river streamflow and release it in a controlled manner to meet multiple functions. Reservoir operation can be optimized within an integrated water management approach wherein water for municipal use, food production (i.e., agricultural water supply), to meet environmental (riverine water) demand, and climate change are taken into account. This paper reports optimized reservoir operation associated with integrated water management considering climate changing scenarios RCP2.6, 4.5, and 8.5 (see Table 1 listing the characteristics of the RCPs). Integrated water management via reservoir operation relies on three objective functions that account for municipal, environmental, and agricultural water sectors' water demands. The objective functions are given by Eqs. (1), (2), and (3) where N denotes the number of times when the water release is less than the water demand in any period t through the entire operational period:

Municipal water supply:

$$\text{Maximize} \quad Z1 = \left(1 - \frac{\overset{T}{\underset{t=1}{N}} \left(\text{Re}_t^{\text{Muni}} < De_t^{\text{Muni}}\right)}{T}\right) \times 100 \quad (1)$$

Table 1 RCP projections (IPCC 2014 and Weyant et al. 2009)

Name	Radiative forcing	Increasing mean annual temperature (°C) average and (range in 2046–2065)	Increasing mean annual temperature (°C) average and (range in 2081–2100)
RCP 2.6	3 W/m^2 before 2100, declining to 2.6 W/m^2 by 2100	1 (0.4–1.6)	1 (0.3–1.7)
RCP 4.5	4.5 W/m^2 post 2100	1.4 (0.9–2.0)	1.8 (1.1–2.6)
RCP 6	6 W/m^2 post 2100	1.3 (0.8–1.8)	2.2 (1.4–3.1)
RCP 8.5	8.5 W/m^2 in 2100	2.0 (1.4–2.6)	3.7 (2.6–4.8)

Environmental (riverine) water supply:

$$\text{Maximize} \quad Z2 = \left(1 - \frac{\overset{T}{\underset{t=1}{N}} \left(\mathrm{Re}_t^{\mathrm{EN}} < De_t^{\mathrm{EN}} \right)}{T} \right) \times 100 \qquad (2)$$

Agricultural water supply:

$$\text{Maximize} \quad Z3 = \left(1 - \frac{\overset{T}{\underset{t=1}{N}} \left(\mathrm{Re}_t^{\mathrm{Agri}} < De_t^{\mathrm{Agri}} \right)}{T} \right) \times 100 \qquad (3)$$

in which, $Z1$, $Z2$, and $Z3$ are, respectively, the first, second, and third objective functions corresponding to the municipal, environmental, and agricultural sectors; De_t^{Muni}, De_t^{EN}, and De_t^{Agri} are municipal, environmental, and agricultural water demand during the t^{th} operational period (of monthly duration), respectively; $\mathrm{Re}_t^{\mathrm{Muni}}$, $\mathrm{Re}_t^{\mathrm{EN}}$, and $\mathrm{Re}_t^{\mathrm{Agri}}$ are municipal, environmental, and agricultural water releases during the t^{th} operational period, respectively; and T is the number of operational periods. The objective functions Eqs. (1), (2), and (3) take values equal to 0 whenever the reservoir releases are less than the water demands in all the operational periods; they take a value equal to 1 whenever the reservoir releases equal or exceeds the water demands in all the operational periods. Equations (1), (2), and (3) represent indices of water supply reliability for the three water-user sectors.

The reservoir water balance or continuity equation is given by:

$$S_{t+1} = S_t + Q_t - R_t^{\mathrm{Muni}} - R_t^{\mathrm{EN}} - R_t^{\mathrm{Agri}} - \mathrm{SP}_t - \mathrm{s}_t \qquad (4)$$

where the total reservoir release is given by:

$$R_t = R_t^{\mathrm{Muni}} + R_t^{\mathrm{EN}} + R_t^{\mathrm{Agri}} \qquad (5)$$

in which, S_t and S_{t+1} are reservoir storage at the beginning of the t^{th} and $(t+1)^{\mathrm{st}}$ period, Q_t is the reservoir inflow volume during the t^{th} operational period, SP_t is the spill from the reservoir during the t^{th} operational period, Loss_t reservoir losses from the reservoir during the t^{th} operational period by evaporation, and $R_t$is the total reservoir release during the t^{th} time operational period. The reservoir losses are calculated with the following equation:

$$\mathrm{Loss}_t = \mathrm{Ev}_t \times \overline{A}_t \qquad (6)$$

$$\overline{A}_t = \left(\frac{A_t + A_{t+1}}{2} \right) \qquad (7)$$

in which, $\overline{A}_t$ the average reservoir surface during the t^{th} period, Ev_t is the evaporation depth during the t^{th} period, and A_t and A_{t+1} are, respectively, the reservoir area at the start and end of the t^{th} period. Moreover, the storage in each period is limited to fall in the range S_{Min} through S_{Max} which denotes the minimal and maximal allowable reservoir storage, respectively.

Case study

The Karkhe River has a length of 900 km within the Karkhe Basin in southwestern Iran. This river discharges to the Hoor-al-Azim wetland located on the Iran-Iraq border. Thus, its discharge affects the Hoor-al-Azim wetland ecosystem, which includes seasonal migratory birds. The Karkhe River supplies domestic, industrial, and agricultural water demands that vary during the year. These multiple functions of the Karkhe River are testimony to its importance in the regional water resources. Karkhe reservoir with a capacity of 5346 10^6 m^3 is located on the Karkhe River and stores and releases water for various sectors (Fig. 1). The annual average temperature and precipitation in the Karkhe Basin equal 12.22 and 36.0 °C, respectively. Climate projections indicate future changing conditions within the Karkhe Basin, which would have an impact on the reservoir operation to meet water supply. This paper considers several RCPs in the analysis of Karkhe reservoir operation under future climate conditions. There are published works dealing with water resource management in the Karkhe Basin under climate change conditions (see, e.g., Sarzaeim et al. 2017a, b, and Sarzaeim et al. 2018; and Zolghadr-Asli et al. 2019).

This paper considers municipal and agricultural water demands that are based on urban and agricultural development horizons under baseline and climate change conditions reported by Sarzaeim et al. (2017b). Moreover, environmental demands of the Karkhe River under RCPs 2.6, 4.5, and 8.5 have been determined by Sarzaeim et al. (2017a), in which the environmental demand in month k ($k = 1, 2, \ldots, 12$) of a year was calculated by using the 25% and 75% quartiles of the river flows in month k determined based on the previous

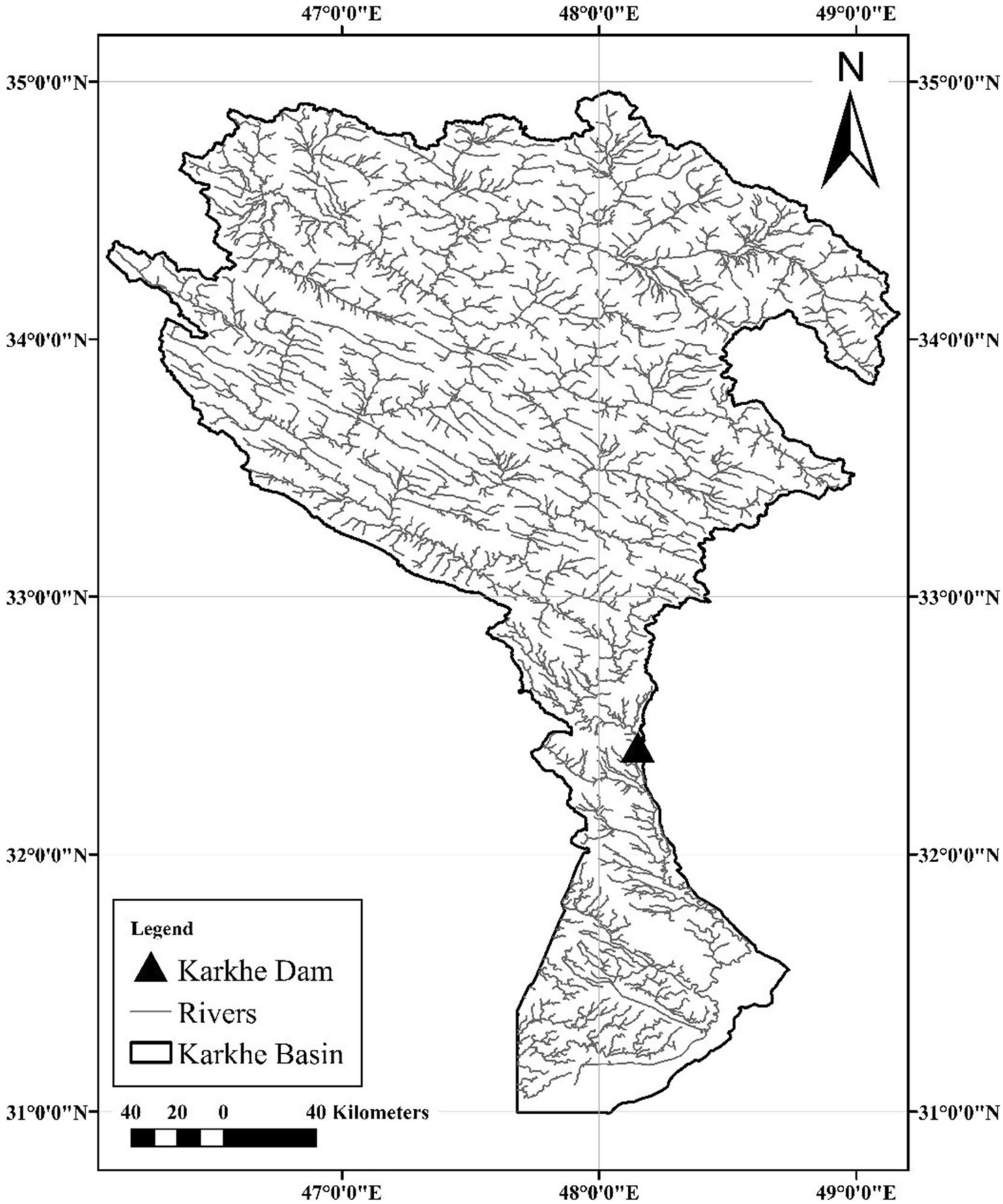


Fig. 1 Location of the Karkhe Basin and reservoir

20 years of e river flow data. For example, the minimum and maximum environmental demands in January of year 2000, respectively, equal the 25 and 75% quartiles of the January river flows calculated from the 1980–1999 data. Similarly, the environmental demands for other months of year 2000 (or any other years being assessed) are calculated in an analogous manner (Sarzaeim et al. 2017a).

Baseline condition

The historic period (1980–2009) is used as a climatic baseline for Karkhe reservoir operation to supply the municipal, environmental, and agricultural sectors, which are assigned first, second, and third supply priorities, respectively. The environmental (riverine) water demand was calculated with the Montana method (Tennant 1976), which sets the environmental water demand equal to a percentage of the average annual flow, and varies with the season of the year. The SOP is applied as the reservoir operational rule curve. The SOP fully meets downstream water demands whenever there is available water in storage; otherwise, downstream water demands are not fully met, thus creating water shortages according to the water supply priorities. The SOP applied to Karkhe reservoir operation in the historic period constitutes the non-integrated water management approach. Notice there is no optimization in this approach. Results obtained with the SOP in the historic period show the values of water supply indices $Z1$ (Eq. (1), water supply for municipal water), $Z2$ (Eq. (2), water supply for environmental water), and $Z3$ (Eq. (3), water supply for agricultural water demand) equal 58.83%, 56.17%, and 50.33%, respectively, which implies water supply meets water demands at most 58.83% of the time according to Eqs. (1), (2), and (3). These results establish the SOP's poor performance applied to Karkhe reservoir during the baseline period. Figures 2 and 3 display the storage in and water releases from Karkhe reservoir corresponding to the non-integrated approach. It follows from Figs. 2 and 3 that there are water shortages in the Karkhe Basin that most likely would be accentuated in a warmer climate. The proposed integrated water management approach considers all water demands and projections of climate change and optimizes reservoir operation to achieve the best possible supply of water demands.

Climate change condition

The first step of the integrated water management approach is to project temperature and rainfall under RCPs 2.6, 4.5, and 8.5 within the Karkhe Basin. The CanESM2 GCM's temperature and rainfall projections for 2009–2059 were adopted. These projections were downscaled with the SDSM for input to basin-scale hydrologic modeling. Figure 4 compares average annual temperature and rainfall projections under the adopted climatic scenarios in 2009–2059 and the historical period (1980–2009). Figure 4 shows increasing future temperature and precipitation in the Karkhe Basin relative to the historic period.

The projected temperature and rainfall data were downscaled and input to the IHACRES model to project monthly runoff in the Karkhe River. The IHACRES model was calibrated with data from 1980 to 1990 and validated with data from 1991 to 1993. Average monthly streamflow for historical and RCP-based scenarios is depicted in Fig. 5. It is evident in Fig. 5 that the maximum streamflows of the historic data occur in March and April, whereas the maximum monthly streamflow associated with RCP-based projection would occur in January, February, and March. The historic streamflows and the RCP-based streamflows are smallest in July, August, September, and October, with the RCP-based projections being slightly larger than the historical streamflows except in October. The projected monthly streamflows were applied to optimize Karkhe reservoir operation by means of the objectives $Z1$, $Z2$, and $Z3$ written in Eqs. (1), (2), and (3), respectively. There are techniques which transform multi-objective problems to a single-objective one by means of a weighted sum of objectives. In the case of a 3-objective problems, there would be three weights, i.e., one for each of the objectives $Z1$, $Z2$, and $Z3$. Therefore, optimal solutions are paired with specific combinations of the weights (Fallah-Mehdiour et al. 2012). The subjective weighting

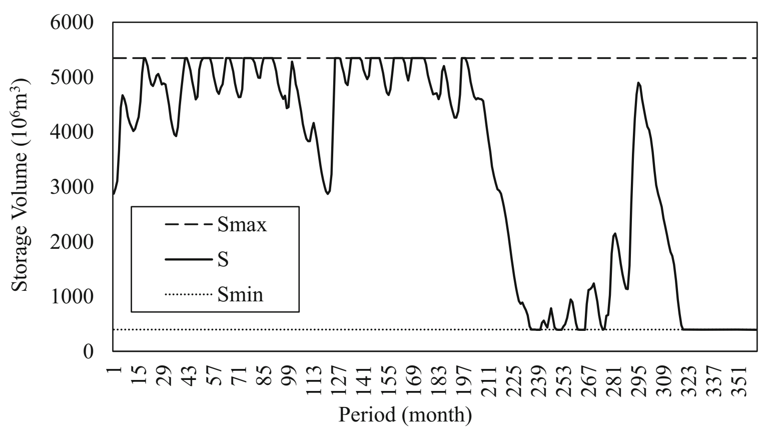


Fig. 2 Storage volume of Karkhe dam corresponding with non-integrated management

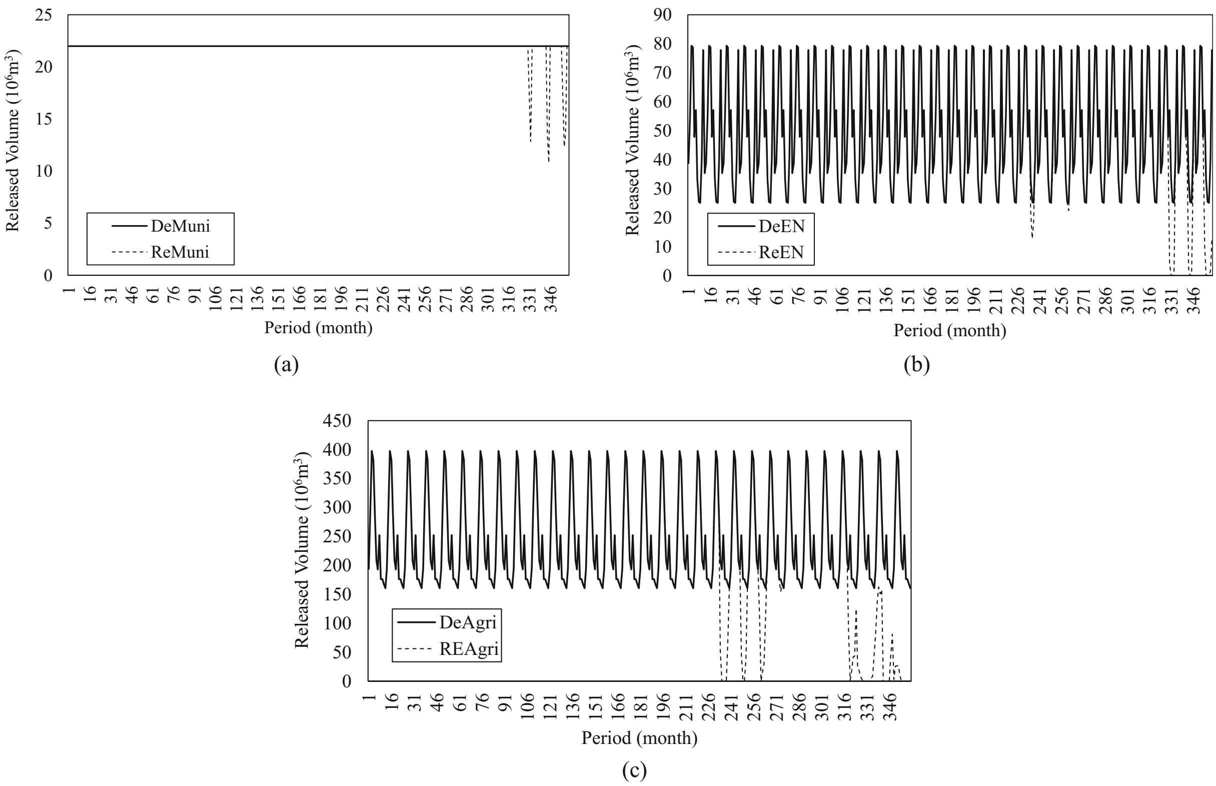


Fig. 3 Released water from Karkhe dam corresponding to non-integrated approach for **a** municipal, **b** environmental, and **c** agricultural uses

scheme can be improved by multi-objective evolutionary algorithms such as NSGA-II, which can determine sets of alternative optimal solutions (Pareto solutions). This work implements three objectives $Z1$, $Z2$, and $Z3$ that are simultaneously optimized to integrate stakeholders' water utilities. The optimal solutions are a Pareto front for each RCP. Therefore, collecting the best Pareto fronts from several RCPs defines appropriate water management plans for current and future operations of Karkhe reservoir.

The NSGA-II was herein implemented as the multi-objective optimization algorithm to calculate the optimal reservoir releases under the RCPs 2.6, 4.5, and 8.5. The NSGA-II was introduced by Deb (2001). Figure 6

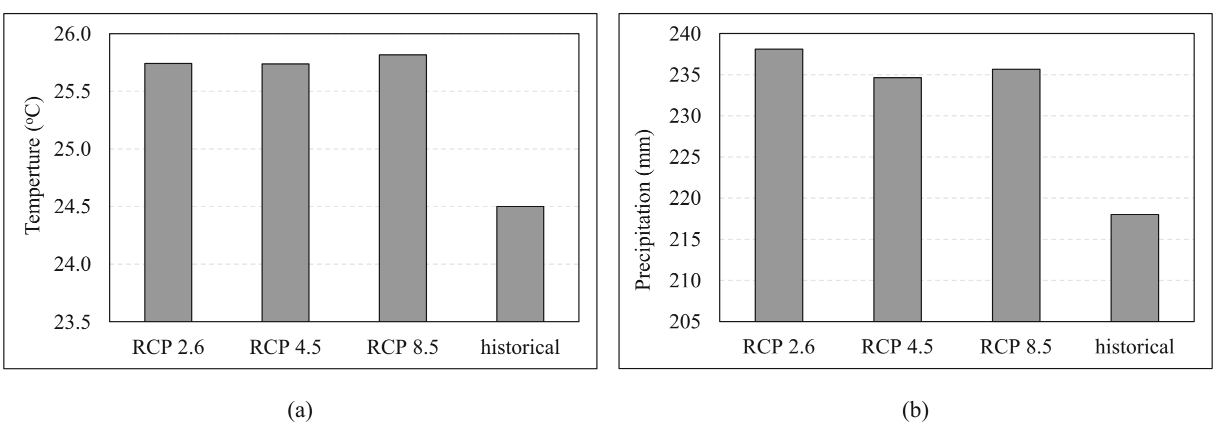
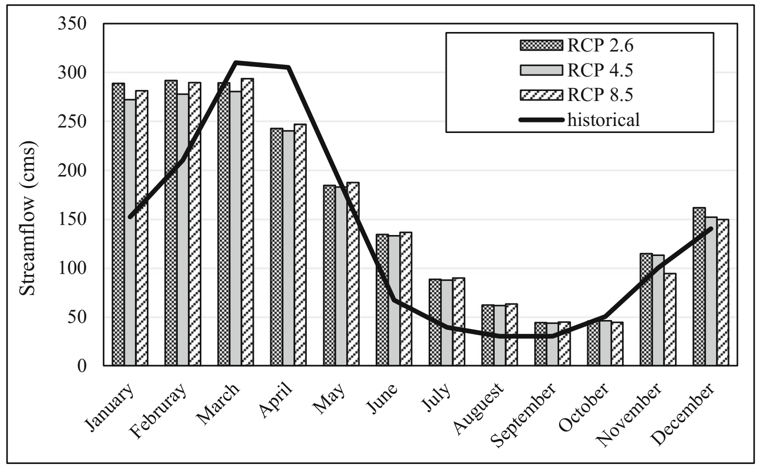


Fig. 4 **a** Average annual temperature corresponding to climatic scenarios in 2009–2059 and the historic period 1980–2009. **b** Average annual rainfall corresponding to climatic scenarios in 2009–2059 and the historic period 1980–2009

Fig. 5 Average monthly streamflow in the historic period and RCP-based projections



a–c display 3-D Pareto fronts of optimal solutions corresponding to RCP 2.6, RCP 4.5, and RCP 8.5, respectively. As shown, in the optimized values of $Z1$ (Eq. (1), municipal water supply has the largest values among the three RCPs and its ranges are 85,100%; 83,100%; and 77,100% corresponding to RCP 2.6, RCP 4.5, and RCP 8.5, respectively. Recall the objective $Z1$ (water supply) has the highest water supply priority. Moreover, the

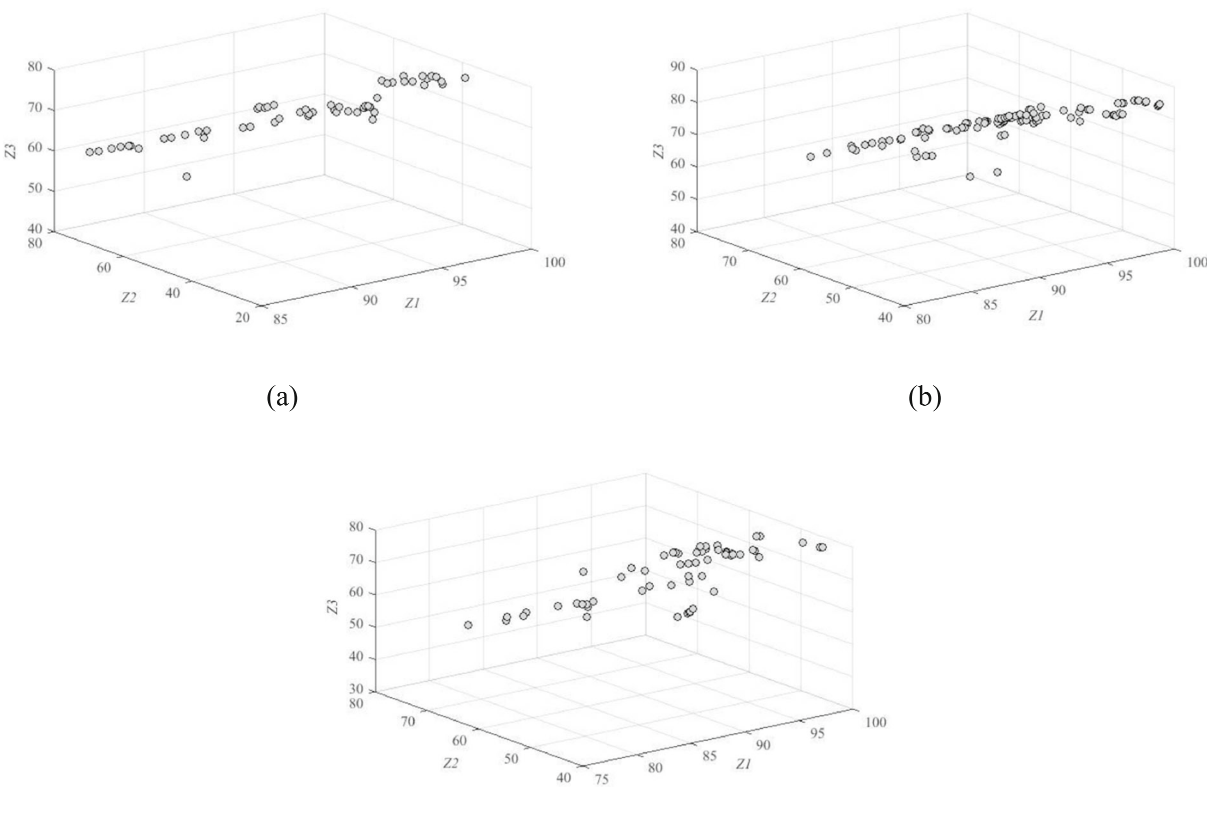
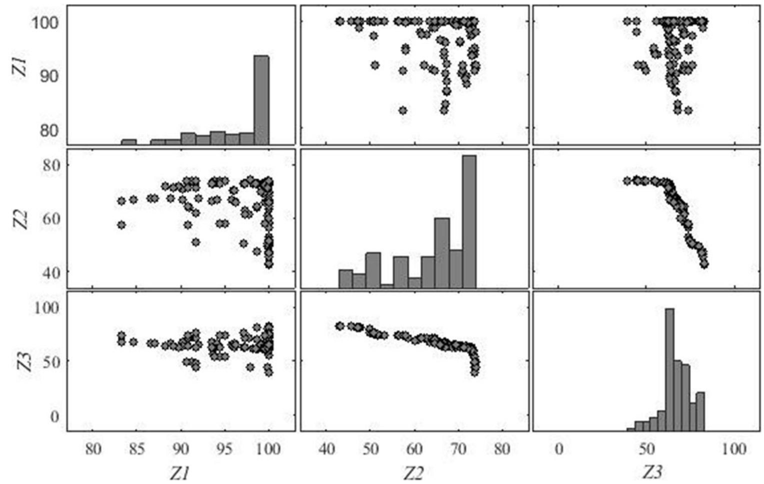


Fig. 6 Optimal Pareto fronts for Karkhe reservoir operation corresponding to **a** RCP 2.6, **b** RCP 4.5, and **c** RCP 8.5

Fig. 7 Merged optimal solutions for RCPs 2.6, 4.5, and 8.5



worst value of $Z1$ (see Eq. (1)) corresponds to RCP 8.5 because of lower projected streamflow for this RCP compared with RCPs 2.6 and 4.5. The objectives $Z2$ (Eq. (2)) and $Z3$ (Eq. (3)) exhibited lower values than those of $Z1$. Two-dimensional graphs of the multi-objective solutions are displayed in Fig. 6, and histograms of each objective are depicted in Fig. 7. The minimum value of $Z2$ (which concerns environmental water supply) equals 43%, which coincides with the maximum value of $Z3$ equal to 83% (which concerns agricultural water supply). Evidently, there is a tradeoff between objectives $Z2$ and $Z3$. The best joint performance of $Z1$, $Z2$, and $Z3$ corresponds to values 99, 74, and 65%, respectively.

Our results highlight that reservoir operation is stochastic in nature because of the randomness of reservoir inflow. Climatic changing conditions add further stochasticity to reservoir operation. Figure 6 illustrates how optimal reservoir operation may be implemented in the future. The results of Fig. 6 are useful and provide guidelines for water manager and reservoir operators in the Karkhe Basin in an uncertain future. Yet, the uncertainty introduced by the RCPs complicates decision-making. For these reasons, all the obtained objectives associated with the RCPs are merged in Fig. 7 to represent the best future objectives.

Concluding remarks

Climate, environment, and water are inseparable components of water resource management. This paper presents an integrated approach for reservoir operation involving these components by means of multi-objective optimization. The approach was applied to Karkhe reservoir in southwestern Iran considering water supply for the municipal, environmental, and agricultural sectors. There are some traditional methods such as SOP for reservoir operation. Those methods calculate water releases to meet multi-sectorial water use. Yet, they may also cause conflicts among stakeholder because they do not properly account for the multi-sectorial priorities. Multi-objective optimization overcomes this challenge by giving consideration to all sectors simultaneously. Multi-objective optimization calculates Pareto fronts that account for all water-using sectors under RCPs. Thus, each RCP corresponds to an optimal Pareto front. Merging all Pareto fronts provides water managers with the best operational options under uncertain climate.

This work's results demonstrate that linkages between climate, environment, and water components arise when there is optimization of water supply reliabilities for the three sectors. These paper results demonstrate the multi-objective results obtained with the integrated approach consistently exceed those obtained with the non-integrated approach associated with the reservoir standard operating policy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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