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Compounding effects of human activities and climatic changes on surface water availability in Iran

Samaneh Ashraf[1,2] • Amir AghaKouchak[1] • Ali Nazemi[3] • Ali Mirchi[4] • Mojtaba Sadegh[5] • Hamed R. Moftakhari[1,6] • Elmira Hassanzadeh[7] • Chi-Yuan Miao[8] • Kaveh Madani[9,10] • Mohammad Mousavi Baygi[2] • Hassan Anjileli[1] • Davood Reza Arab[11] • Hamid Norouzi[12] • Omid Mazdiyasni[1] • Marzi Azarderakhsh[13] • Aneseh Alborzi[1] • Mohammad J. Tourian[14] • Ali Mehran[15] • Alireza Farahmand[16] • Iman Mallakpour[1]

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Abstract
By combining long-term ground-based data on water withdrawal with climate model projections, this study quantifies the compounding effects of human activities and climate change on surface water availability in Iran over the twenty-first century. Our findings show that increasing water withdrawal in Iran, due to population growth and increased agricultural activities, has been the main source of historical water stress. Increased levels of water stress across Iran are expected to continue or even worsen over the next decades due to projected variability and change in precipitation combined with heightened water withdrawals due to increasing population and socio-economic activities. The greatest rate of decreased water storage is expected in the Urmia Basin, northwest of Iran, (varying from ~ − 8.3 mm/year in 2010–2039 to ~ − 61.6 mm/year in 2070–2099 compared with an observed rate of 4 mm/year in 1976–2005). Human activities, however, strongly dominate the effects of precipitation variability and change. Major shifts toward sustainable land and water management are needed to reduce the impacts of water scarcity in the future, particularly in Iran's heavily stressed basins like Urmia Basin, which feeds the shrinking Lake Urmia.

1 Introduction

Strong interactions between human and water systems are widely recognized (Mirchi et al. 2014). Important economic activities, such as agriculture and eco-tourism, are directly impacted by the temporal and spatial availability of freshwater resources (Leng et al. 2015). While the availability of freshwater resources is naturally determined by geography, hydrology, and near-

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✉ Amir AghaKouchak
amir.a@uci.edu

surface meteorology, human interventions through land and water management have significantly changed the characteristics of freshwater resources (Nazemi and Wheater 2015a, b; Mehran et al. 2017; Frans et al. 2013). Humans alter water availability through a set of interventions related to storage, redistribution, and consumption of water resources (Mirchi et al. 2014; Sadegh et al. 2010). These interventions have heavily affected regional hydrologic cycle around the globe (Hanasaki et al. 2008; Mirchi et al. 2012; Wada et al. 2010; Wang and Hejazi 2011), creating "anthropogenic droughts" (AghaKouchak et al. 2015b) that reflect human-induced water stresses caused by unsustainable management of the available water (AghaKouchak et al. 2015b).

Assessing the future outlook of water scarcity has a global priority as nearly one third of the world's population live under water-stressed conditions, particularly in arid and semi-arid regions such as southwest Asia, the Middle East, and North Africa as well as the Mediterranean region (Alcamo et al. 2007; Arnell 2004; Rockström et al. 2009; Vörösmarty et al. 2000). Water stress is more significant in these regions as their environment is highly vulnerable to change in water availability (Newman et al. 2006). Furthermore, many already-stressed regions have undergone significant socio-economic developments and population growth (Di Baldassarre et al. 2017; Mehran et al. 2017; Scanlon et al. 2012; Van Loon et al. 2016a, b). The increasing trends of anthropogenic drivers are expected to continue in the future and will be superimposed on the unfolding effects of climate variability and change at global and regional scales (Nazemi et al. 2017; Jaramillo and Nazemi 2017). Therefore, it is essential to consider the compounding effects of both natural and anthropogenic drivers of water availability to improve water resource management in water-stressed regions (Leng et al. 2015). Even if future natural water supply remains unchanged, societies should be prepared for increasing consumption and competition over more limited water resources under the growing population and increasing anthropogenic water demands (Madani et al. 2016; Mehran et al. 2017).

The overwhelming impacts of human-induced water stress have prompted many studies on how different adaptation strategies and/or human activities affect the characteristics of regional water cycles (Abbaspour et al. 2009; Allen and Ingram 2002; Held and Soden 2006; Huntington 2006; Döll & Siebert, 2002; Elliott et al., 2014; Gleick et al., 2013; Gohari et al. 2014, 2017; Hanasaki et al. 2013; Hejazi et al., 2015; Mehran et al. 2017; Mirchi et al. 2013; Pokhrel et al. 2016; Döll et al. 2012). Previous studies have mainly focused on how climate change and variability affect the characteristics of natural water availability by forcing impact models, mainly hydrology and land-surface models, with future climate projections (Ashraf et al. 2017; Nazemi and Wheater 2014). Hydrological and/or land-surface models used for climate change impact assessments are typically not well equipped to examine the compounding effects of water management on the hydrological cycle due to lack of representation of human interventions (Mehran et al. 2015; Döll et al. 2012; Loucks 2015; Nazemi and Wheater 2015a, b; Oki and Kanae 2006; Scanlon et al. 2012; Sivapalan 2015; Wheater and Gober 2015; Hassanzadeh et al. 2017). Thus, there is a need for alternative approaches that can accommodate both natural and anthropogenic drivers of future hydrological change into a unified assessment framework.

This paper presents a generic framework to quantify the effects of anthropogenic water withdrawal on surface water budget. We apply the framework to Iran, one of the most water-stressed countries in the world facing chronic and intensifying water sustainability challenges (Madani 2014; Madani et al. 2016), and evaluate the compounding effects of human activities and precipitation variability and change on its regional surface water availability during the twenty-first century. The implemented framework combines both a bottom-up approach, i.e., ground-based water withdrawal observations, and a top-down approach, i.e., climate models' precipitation projections. This framework allows us to put the anthropogenic component of water availability in all major basins of Iran into perspective.

2 Materials and methods

2.1 Study area and data

We investigate 30 major river basins in Iran—Fig. S1 in Supplementary Materials. Iran has diverse climatic conditions ranging from arid to humid; however, as a whole, the country is characterized by an arid/semi-arid climate (Ashraf et al. 2014; Madani 2014). We obtain annual surface water balance components, including precipitation, evapotranspiration, surface water outflows, water withdrawals (based on demand in different sectors such as agriculture, domestic and industry), and return flows, for all 30 basins for the period of 1976–2005 from Iran's Ministry of Energy. These data are recorded by gauge stations that are located in each basin. Gauge information are then interpolated, using elevation and distance between the observing stations, and used to calculate mean areal values.

We retrieve projected precipitation from 25 models from the coupled model intercomparison project phase 5 (CMIP5) experiment (Taylor et al. 2012)—see the list of general circulation models (GCMs) in Table S1. Multi-model ensembles help represent large uncertainties in GCM projections as compared with single GCM projections (Cheng and AghaKouchak 2015; Miao et al. 2014; Stevens and Madani 2016). We use historical simulations (1901–2005) and future climate projections for early (2010–2039), middle (2040–2069), and end (2070–2099) of the twenty-first century under two representative concentration pathways (RCPs) 4.5 and 8.5. The CO_2-equivalent concentrations for RCPs 4.5 and 8.5 in the year 2100 are 538 ppm and 936 ppm, respectively (Miao et al. 2014). We also use ground-based precipitation measurements at synoptic stations, available from Iran Meteorological Organization, for selecting the best GCMs for the study area. This is due to the fact that some GCM projections may represent regional climate characteristics better than others in specific regions (Santer et al. 2009; Liu et al. 2014; Nasrollahi et al. 2015), and hence, several studies recommend sub-sampling or weighting GCMs based on their performance (Cheng and AghaKouchak 2015; Knutti et al. 2010). Here, we evaluate and compare historical (1976–2005) precipitation simulations of 25 individual GCMs relative to the observations using Taylor diagrams (Taylor 2001; Wang et al., 2017).

2.2 Direct human-hydrologic interactions

We quantify direct human-hydrologic interactions through analyzing the water budget at the basin scale, including water withdrawal (H_{out}) and return flows (H_{in}) as follows (Weiskel et al. 2007):

$$(P-\mathrm{ET}) + H_{\mathrm{in}} - \mathrm{ds/dt} = \mathrm{SW}_{\mathrm{out}} + H_{\mathrm{out}} = F_{\mathrm{n}} \quad (1)$$

where P, ET, ds/dt, and SW_{out} represent precipitation, evapotranspiration, change in surface water storage, and surface water outflows, respectively. The terms H_{in} and H_{out}

denote human-induced inflows (e.g., return flows from urban and rural areas) and outflows (e.g., water withdrawal). Human water outflows (H_{out}) can be normalized relative to the net flux (F_n) (Vogel et al. 2015):

$$h_{out} = H_{out}/F_n \tag{2}$$

To evaluate the compounding effects of future climate variability and heightened water withdrawals on surface water availability, we select four basins in western Iran: Urmia, Karun, Karkheh, and Jarrahi Basins (Fig. S1 in supplementary materials). We select these basins because (1) while the annual average precipitation of these basins are above the country's climatological annual precipitation (approximately, 372, 540, 472 and 775 mm/year for Urmia, Karun, Karkheh, and Jarrahi basins, respectively), they have endured major increases in water withdrawals; (2) they have experienced relatively dry years between 1995 and 2005, compared to the preceding decade of 1985 to 1995 (Fig. S2 in Supplementary Materials); (3) they are all densely populated with significant population growth over the past few decades; and (4) a large acreage of the country's irrigated cropping is located in these basins (Mesgaran and Azadi 2018). These key characteristics mark the selected four catchments as hotspots of water security with immense regional management concerns.

2.3 Merging "top-down" and "bottom-up" approaches to vulnerability assessment

We develop a holistic approach to provide basin-wide vulnerability assessment by considering increasing anthropogenic water demand scenarios in a changing climate. To achieve this, we integrate the strengths of both "top-down" and "bottom-up" approaches in a unified assessment framework for evaluating surface water availability in the four selected basins of Iran during the early, middle, and end of the twenty-first century. In brief, we implement the "top-down" approach to assess the key climatic driver of water availability (i.e., P term in Eq. 1) under future climate condition. For this, we use 11 GCMs projections from CMIP5 and estimate basin-wide precipitation changes based on the representative concentration pathways (RCPs) 4.5 and 8.5 projections during 2010–2039, 2040–2069, and 2070–2099. Changes in precipitation are assumed to cause no significant changes in water withdrawals.

We represent the changes in water withdrawal through a simple "bottom-up" perturbation of the historical observed data (i.e., H_{out} in Eq. 1)—see Nazemi et al. (2013) and Mehran et al. (2015). In conjunction with the current withdrawal conditions, we consider three potential scenarios for the relative increases in water withdrawal, i.e., + 10% (H1); + 30% (H2); and + 50% (H3). These demand scenarios represent low, moderate, and high increases in water withdrawals that include collectively various levels of population, industrial, and agricultural growth along with changes in consumption behavior that are expected in the upcoming decades at the basin scale. Indeed, we do not argue that these are the projected future realities; rather, we take them as feasible futures with which the critical threshold under the changing condition can be revealed (see Nazemi and Wheater 2014).

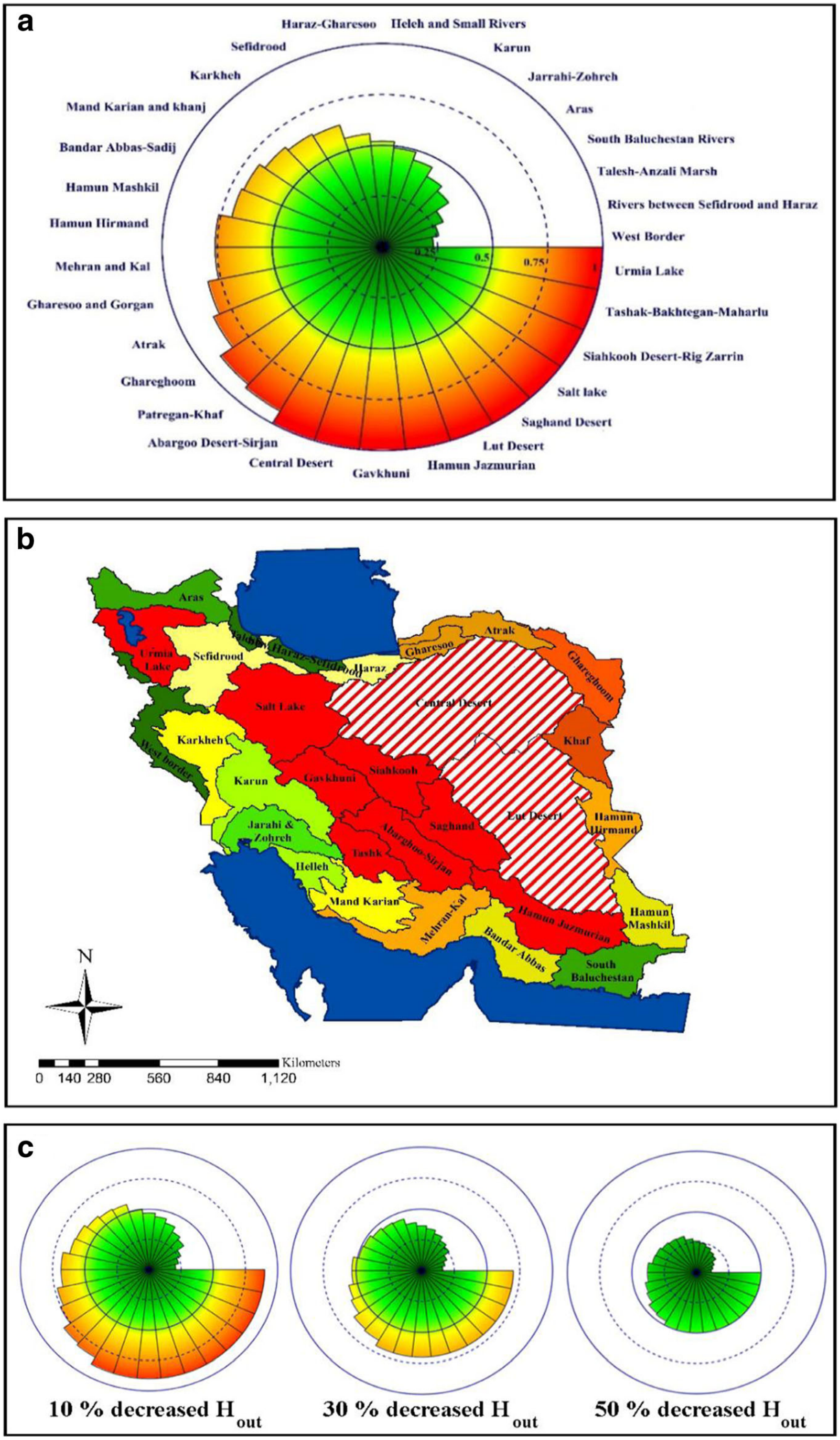
To assess the compounding effects of climate variability and human activities on surface water availability, we mix-and-match top-down projections with bottom-up scenarios (i.e., 2 ensemble precipitation projections with RCP 4.5 and 8.5 and 3 increased water withdrawal scenarios represented by H1, H2, and H3) over the 3 projection periods. The 6 potential combinations are then fed to Eq. 1 as the building block of this modeling effort, in which P is derived from the top-down projections and human withdrawal terms are acquired from the bottom-up scenarios. It should be noted that we characterize changes in climate only through changes in precipitation and, therefore, ignore changes in evaporation. This marks a conservative assumption, particularly under warming conditions, as increased evaporation rates due to higher intensity and longer duration of warm seasons only intensify the water shortage in already water-stressed regions. As a result, our analyses can be taken as an optimistic look of the future water stress in Iran.

3 Results and discussion

Figure 1A shows normalized human outflow (Eq. 2) in the 30 main river basins over 1976–2005 across Iran. This figure shows the ratio of water withdrawal to natural water fluxes in each basin, supported by ground-based information, where values close to 1 represent a high percentage of water withdrawal relative to natural fluxes and values close to 0 represent relatively low amounts of water withdrawal with respect to natural fluxes. We show that the reduction of water supply in 16 of the 30 basins across Iran was heavily dominated ($h_{out} > 0.75$) by human activities over the period of 1976–2005, while only seven of the basins were dominated by the natural fluxes ($h_{out} < 0.5$). The Karun basin has the largest amount of water withdrawal ($H_{out} = 181.48$ mm/year) (Table S2), which accounts for 49% of its net outflow, and is approximately three times larger than the basin's inflow (H_{in}). The South Baluchestan basin has the smallest amount of water withdrawal ($H_{out} = 9.33$ mm/year) (Table S2), which is rather expected given its arid climate and low level of socio-economic development.

Figure 1B shows the locations of the basins presented in Fig. 1A (color coded based on h_{out} values). It must be noted that the analysis of this study does not include the Central and Lut Deserts (hatched areas in Fig. 1B), because they are sparsely populated and include negligible water availability and socio-economic development. This figure portrays that water withdrawal heavily dominates ($h_{out} > 0.75$) ~ 41% of the Iranian basins' water availability, while ~ 17% of Iran's basins are moderately dominated ($0.5 < h_{out} < 0.75$) by water withdrawal. This shows the dominant impact of human water withdrawal over the variability and change in climate-induced water availability (i.e., precipitation minus evapotranspiration), and the fact that changes in natural water availability are only responsible partly for the decrease in water availability across the majority of Iran's basins.

To highlight the anthropogenic drought on Iran's basins during the recent past (i.e., baseline period of 1976–2005), we implement three what-if scenarios of 10%, 30%, and 50% reductions in human withdrawal (i.e., H_{out} in Eq. 2). Figure 1C shows the results, indicating the dominating role of the human water withdrawal on the basin-wide water availability in Iran, which is over-allocated. Our results vividly portray that only with a 50% decrease in historical water withdrawal could have turned all Iran's basins to naturally dominated water systems ($h_{out} < 0.50$). Obviously, we are not suggesting these declined levels of human water withdrawals were feasible in the past, given the major socio-economic and population growth in the country since 1976 as well as political barriers of water security in the region (see, e.g., the discussion of Nazemi and Madani 2017). Rather, we aim at using these numbers to demonstrate the significance of water withdrawal rates relative to the net flux in the country, which clearly highlight the extensive over-allocation of water resource in Iran's basins, rooted in unsustainable population growth and agricultural expansion. In the past five decades, the country's population has increased from 21.9 million to 79.3 million (Fig. S3) and the country's total production and harvest area of water-intensive crops such as summer vegetables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Haraz-Gharesoo
Heleh and Small Rivers
Sefidrood
Karun
Karkheh
Jarrahi-Zohreh
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Bandar Abbas-Sadij
South Baluchestan Rivers
Hamun Mashkil
Talesh-Anzali Marsh
Rivers between Sefidrood and Haraz
Hamun Hirmand
West Border
Mehran and Kal
0.25
0.5
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1
Urmia Lake
Gharesoo and Gorgan
Tashak-Bakhtegan-Maharlu
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Ghareghoom
Salt lake
Patregan-Khaf
Saghand Desert
Abargoo Desert-Sirjan
Lut Desert
Central Desert
Hamun Jazmurian
Gavkhuni
b
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◀ **Fig. 1** (A) Normalized human outflow (h_{out}) in all major basins of Iran (B) in the baseline period (1976–2005). (C) Normalized human outflow considering 10%, 30%, and 50% decrease in human water withdrawals (H_{out}) relative to initial amounts

and fodder crops, which almost entirely relies on irrigation water, have substantially increased over the past three decades (Mesgaran and Azadi 2018). It is estimated that the agricultural sector uses more than 90% of Iran's total freshwater resources of the country (Fig. S4)-see also World Bank (2017) as well as IR WRM Co (2018).

Before using climate model projections as a basis for assessing the change in future water availability, we evaluate historical simulations of climate models against observations. Figure 2 demonstrates the results of several statistical metrics (correlation and RMSE) for the 25 CMIP5 precipitation simulations and historical observations with a Taylor diagram. As a polar-style graph, Taylor diagram summarizes three statistics including correlation coefficient (R), root-mean-square error (RMSE), and standard deviation (SD) between simulations and observations using a single point. The radial distance from the origin reflects SD, whereas the cosine of azimuth angle denotes R, and the radial distance from the observed points is proportional to the RMSE difference. We select 11 of the 25 models with the best statistics over the baseline period (1976–2005). Of the selected models, correlation coefficients between

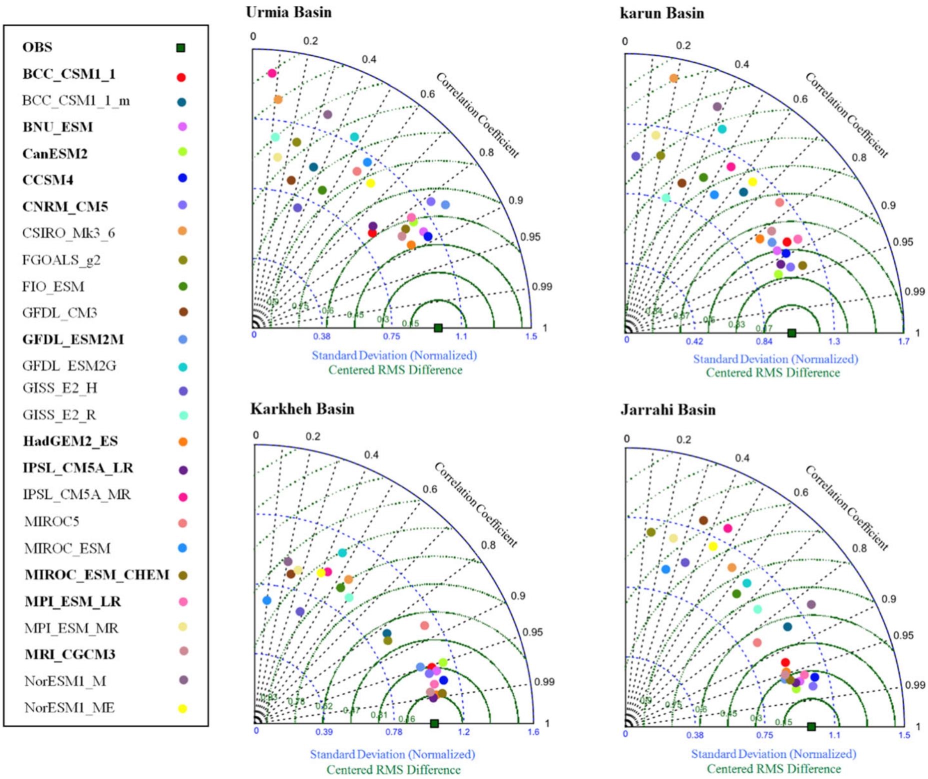

Fig. 2 Taylor diagrams comparing simulated precipitation from 25 GCMs against ground-based observations (1976–2005) in four selected basins. This diagram summarizes the correlation coefficient (dashed black lines), the ratio of the standard deviations (blue curves), and the RMSE (green curves). The closer the points to the observations (squares in x axes), the better is the agreement between simulations and observation

model simulations and observations across all basins lie between 0.7 and 0.99, and RMSE values range between 0.16 and 0.65 mm/year. Selecting GCMs with the best representation of regional characteristics ensures more accurate projections of future climatic conditions. For each RCP scenario (4.5 and 8.5), we use the ensemble mean of the selected models as the representative projections.

Figure 3 shows the percentage of change in projected precipitation during the early (2010–2039), mid (2040–2069), and late (2070–2099) twenty-first century under RCP scenarios of 4.5 and 8.5, relative to the baseline period of 1976–2005 (also see boxplot in the supplementary materials, Fig. S5). The Lake Urmia Basin shows the highest decreasing trend in precipitation, where the ensemble mean shows ~0.27% and ~5.85% decrease during 2010–2039 and 2070–2099 periods, respectively, under climate scenario RCP 4.5. The Jarrahi basin shows the highest increase in precipitation, where the ensemble means increase by 3.5% during the late twenty-first century under climate scenario RCP 4.5. Under the same scenario, the ensemble mean of all selected basins shows a decrease of ~0.3%, ~9.5%, and ~10.5% in precipitation during the early, mid, and late twenty-first century, respectively. This indicates an overall drying trend in the region. Given the fact that this is an optimistic picture of the future, because increased evapotranspiration due to global warming is ignored, policy makers in Iran must implement solid mitigation strategies in light of population growth and increased water consumption in future.

Figure 4 shows individual and combined impacts of a changing precipitation regime and increased water withdrawal rates on water storage (ds/dt) during the early, mid, and late twenty-first century, relative to the baseline period (1976–2005). The first column in Fig. 4 displays that precipitation decrement is projected in most of the basin/period conditions, which declines gross water availability in future periods, assuming no change in the rate of water withdrawals. These results correspond with the results presented in Fig. 3. For example, we

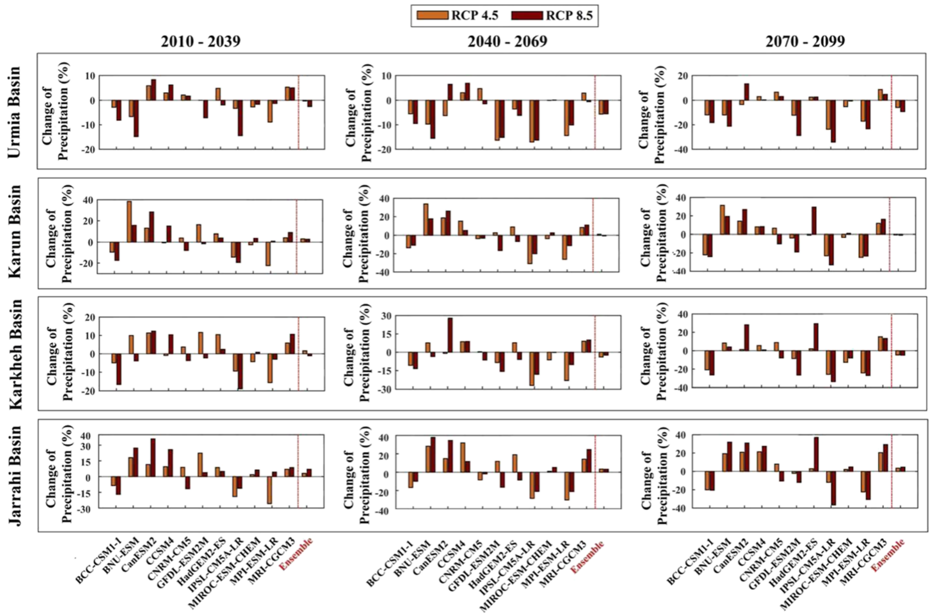

Fig. 3 Percent change (%) in projected precipitation in early, middle, and end of the twenty-first century relative to base period (1976–2005) based on best GCM simulations (individually and their ensemble mean) under two RCPs in the four selected basins in Iran

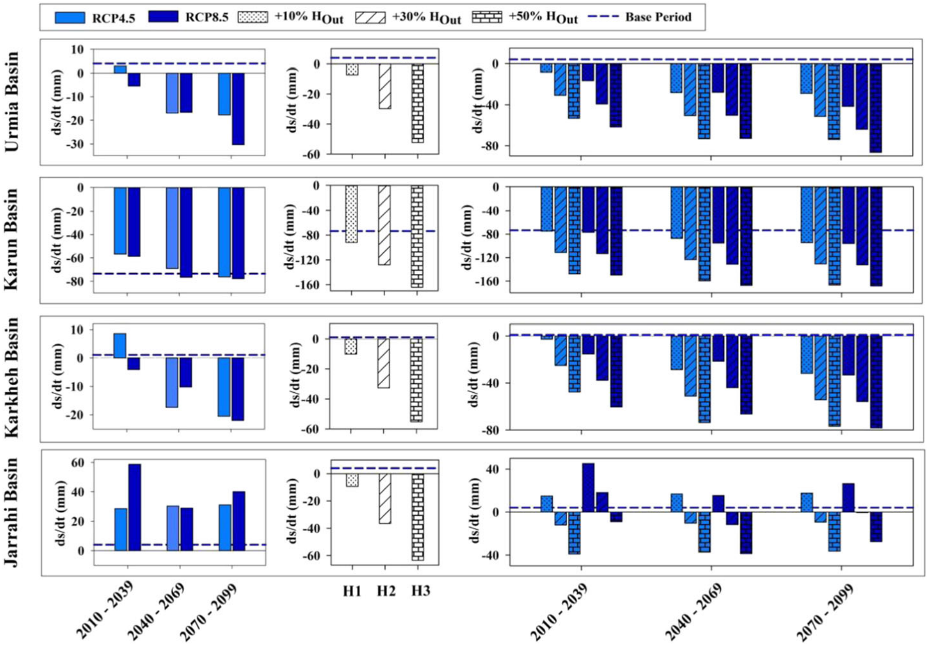

Fig. 4 Changes in basin storage (ds/dt) in early, middle and end of the twenty-first century relative to the baseline period (1976–2005) based on the ensemble mean of GCMs simulations and two RCPs (left panels), three water withdrawals scenarios (middle panels), and their compounding effects (right panels) in the four selected basins in Iran

project the Lake Urmia basin will have a ~25% decrease in storage in the early twenty-first century under RCP scenario 4.5, which will be expanded up to ~550% by the end of the century. The middle column in Fig. 4 exhibits the percentage of decrease in water storage associated with increasing water withdrawal scenarios. We show that an increase in the water withdrawal rates has a significant impact on the water storage across the selected basins. The right column shows the compound effects of increasing water withdrawal rates and variations in gross water availability, represented by precipitation, due to climate change on basin-wide water storage. Karkheh and Karun basins demonstrate the lowest decline in projected water availability among the four basins (right panel in Fig.4). It is interesting to note that despite the projected increase in precipitation across the Jarrahi Basin, the compounding effects of water withdrawal will likely lead to a considerable decline in water storage throughout the twenty-first century (e.g., ~1075% decrease under climate scenario RCP 4.5, combined with 50% increase in water withdrawal).

We expect that an increase of 30–50% in water withdrawal across the Lake Urmia Basin will have a ~868 to ~1430% reduction in storage by 2040, and a ~1375 to ~1950% reduction in storage by 2100, relative to the baseline period under climate scenario RCP 4.5. Our results illustrate that the Lake Urmia Basin is already under the highest rate of water stress due to relatively high anthropogenic water withdrawal (Fig. 1). The significant storage reduction in this basin will have devastating regional environmental and socio-economic impacts. These compounding impacts have already triggered an unprecedented decrease of ~88% in the lake's surface area (AghaKouchak et al. 2015a) over the last 20 years. These drastic changes are primarily the consequences of unsustainable water and land management, manifested by aggressive surface- and groundwater consumption, intensive water redistribution, anthropogenic changes in land use, and upstream competition over water (Hassanzadeh et al, 2012; Sima & Tajrishy, 2013; Tourian et al, 2015; AghaKouchak et al. 2015a). Furthermore, the compounding impacts of hydrologic drought and human-induced water deficit over the last decade have caused a significant decrease in Lake Urmia Basin's groundwater storage (Ashraf et al. 2017; Forootan et al. 2014). This is a clear indication that the basin is "water bankrupt" (Madani et al. 2016), i.e., the natural water availability in the basin is not sufficient to meet the dramatically increasing water demand (Alborzi et al. 2018). Our analyses suggest that the Lake Urmia Basin will have the largest decrease in water storage in comparison to the other three selected basins in the future (2010–2099) Fig. 4. Nonetheless, the regional water systems in Karkheh, Karun, and Jarrahi basins will also be under stress in near future (2010–2039) mainly due to the pressures of increased water withdrawals—see Fig. S6 in supplementary materials.

4 Conclusions and outlook

We use an integrated assessment framework to assess the compounding effects of human activities and climate variability and change on surface water availability in Iran during the recent past and in the future. Using ground-based data of the basin-wide water balance components, we found that the effects of water withdrawals on water stress in Iran dominate the climate variability and change over the recent past, in which anthropogenic water demand has increased substantially due to population and socio-economic growth in ~60% of Iran's area. We argue that aggressive agricultural water withdrawals, driven by the country's focus on becoming self-sufficient in the production of strategic agricultural crops and combined with devastatingly low irrigation efficiency, are the main reasons for the country's increasing water withdrawals.

Our findings suggest that surface water availability will change significantly in response to the interplay between natural and anthropogenic forces, manifested by declining precipitation and inclining water consumption, over the next decades. The combined drying trend and increasing population/agricultural growth are projected to lead to substantial decreases in water availability across the majority of the basins in Iran. However, our investigation vividly shows that human activities strongly dominate the effects of change in the precipitation under the business-as-usual scenario. The Jarrahi Basin (Fig. 4, right panel) is a clear example showing that despite potential increase in precipitation based on two RCP scenarios, a significant decrease in water storage due to increased water withdrawals would be expected.

Our study is another evidence for the urgent need for improved understanding of the compounding effects of climate change and anthropogenic intervention on future hydrological states at the basin scale. We argue that assessing future water stress and proposing water resources management strategies without accounting for the various human interventions is rather unreliable. More specifically, we argue that continuation of unsustainable development in Iran (business-as-usual and/or increased rates of water withdrawals) and ignoring the significant role of humans in framing the country-wide water stress is naive and indeed short-sighted. Iran has no choice but to reduce its water consumption, particularly through major reforms in its agricultural sector to prevent considerable physical water scarcity in the future, particularly for already stressed basins like the Lake Urmia Basin. The combined effects of increasing water demand and climate change must be taken into account to plan for and mitigate water shortages in the region.

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Affiliations

Samaneh Ashraf[1,2] • Amir AghaKouchak[1] • Ali Nazemi[3] • Ali Mirchi[4] • Mojtaba Sadegh[5] • Hamed R. Moftakhari[1,6] • Elmira Hassanzadeh[7] • Chi-Yuan Miao[8] • Kaveh Madani[9,10] • Mohammad Mousavi Baygi[2] • Hassan Anjileli[1] • Davood Reza Arab[11] • Hamid Norouzi[12] • Omid Mazdiyasni[1] • Marzi Azarderakhsh[13] • Aneseh Alborzi[1] • Mohammad J. Tourian[14] • Ali Mehran[15] • Alireza Farahmand[16] • Iman Mallakpour[1]

1 University of California, Irvine, CA, USA

2 Ferdowsi University of Mashhad, Mashhad, Iran

3 Concordia University, Montreal, Canada

4 Oklahoma State University, Stillwater, OK, USA

5 Boise State University, Boise, ID, USA

6 University of Alabama, Tuscaloosa, AL, USA

7 Polytechnique Montreal, Montreal, Canada

8 Beijing Normal University, Beijing, China

9 Imperial College London, Kensington, London, UK

10 Stockholm University, Stockholm, Sweden

11 Rahbord Danesh Pooya Institute, Tehran, Iran

12 City University of New York, New York, NY, USA

13 Fairleigh Dickinson University, Teaneck, NJ, USA

14 University of Stuttgart, Stuttgart, Germany

15 University of California, Los Angeles, CA, USA

16 NASA Jet Propulsion Laboratory, Pasadena, CA, USA