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ORIGINAL ARTICLE

Toward an analysis of water resources components through the Budyko approach in a large-scale framework, Iran

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Abstract

Analyzing the water resources components and connecting these components in the large-scale framework lead the decision makers and scientists to find better innovative and more effective solutions to water crisis challenges. Hence, in this study, the trend in the water balance components during 1984–2010 has been analyzed in all 30 major basins in Iran through the Budyko framework considering the role of nature and humans in the water systems. The results show that the evaporation ratio (E/P) is higher than one in the hyper-arid and arid areas, especially in the years with less precipitation. It indicates that in these regions, the basins are under non-steady-state conditions and do not follow the Budyko framework. The trend analysis shows that in the western parts of the country, precipitation is considerably decreasing, leading to less runoff and available surface water and more demand for groundwater extraction. However, the basins in these areas are still under steady-state conditions with inconsiderable water crises. We argue that policymakers need to provide appropriate long-term plans for drought and climate change adaptation focusing on groundwater management to avoid the critical water challenges in these areas.

Keywords Groundwater · Water crisis · Budyko framework · Trend analysis

Introduction

Human population growth and lifestyle changes have caused an increased demand for good quality water globally (Gleick 1993). Inappropriate spatiotemporal distribution of population and unsustainable development worldwide have led to an overdraft of groundwater reservoirs. Climate change and prolonged drought have exacerbated the situation and intensified groundwater depletion (Mianabadi et al. 2021b). Groundwater depletion may increase the salinity in the soil and water, soil fertility, land subsidence (Ashraf et al. 2021), land degradation, desertification, and changes in the hydrological regime (Madani 2014). These consequences, in turn, affect agricultural and industrial activities, food security, and the life of people, leading to economic, social, political, and environmental challenges. It is more evident, especially in arid and semi-arid regions where 60% of the population is dependent on groundwater as the main water source (Richts and Vrba 2016) for agricultural, industrial, and domestic consumption (Mianabadi et al. 2020b). Overexploitation and groundwater depletion in many river basins worldwide are too much to recover even in wet periods (Rodell et al. 2018). These challenges make it serious to determine the sustainable portion of groundwater withdrawal and to put aside parts of groundwater as a reliable strategic reserve for future droughts (Mianabadi et al. 2021b). However, the current and upcoming groundwater depletion reduces this strategic groundwater reserve with potential remarkable water shortages and related social tensions (Mianabadi et al. 2020b).

Iran, as an arid country, also encounters many water-related issues; drying water bodies, decline in groundwater levels, dust storms, land degradation, desertification, soil erosion, soil/water salinity, and social conflicts are among these issues (Alborzi et al. 2018; Danaei et al. 2019; Saemian et al. 2020; Madani 2021). Like the other countries in

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the Middle East, the water crisis in Iran is mainly caused by bad water governance and water mismanagement, rooted in an oil-based economy with considerable socioeconomic changes such as urbanization, infrastructure development, living standards rising, and high rates of consumption. However, droughts, climate change, and its consequences have exacerbated these degradations and consequences in some regions.

The Budyko framework (Budyko 1974) is an efficient tool that can differentiate between the role of nature (climate change/variability) and human interventions on the basins. According to the Budyko framework definition (Fig. 1), it was primarily developed for the steady-state basins that are natural and closed with negligible water storage change. It means that the local precipitation, as key input forcing, is the only available water source for evaporation (Du et al. 2016). In these basins, the mean annual evaporation (E) is controlled by precipitation (P) and potential evaporation (E_P), as the water and energy availability, respectively. It is worth noting that the term "evaporation" encompasses the combined evaporation from interception (Ei), soil (Es), and open water bodies (Eo), as well as transpiration (Et) (Shuttleworth 1993; Savenije 2004).

Hence, the evaporation ratio (E/P) is limited by available water and energy (see water- and energy-limited lines in Fig. 1) based on the aridity of the region (Gerrits et al. 2009). In these conditions, the data are located in the Budyko space (Fig. 1). However, the steady-state conditions are not valid for many watersheds in the world as its presumption and the hydrological cycle and water balance of the watersheds have changed due to human mal-adaptive activities (Mianabadi et al. 2020a; Huang et al. 2022). The Budyko framework is eligible to detect the behavior of the watersheds under non-steady-state conditions as well. When the plots of E/P versus E_P/P are located out of the Budyko space (i.e., $E/P > 1$), it can be inferred that the basins are under non-steady-state conditions. It should be noticed that the uncertainty of the data, especially E, may contribute to this behavior; however, Chen et al. (2013) believed that this uncertainty is just not enough to explain this discrepancy from the framework in extremely dry years. Accordingly, in this study, the trend in the water balance components has been analyzed in all 30 major basins in Iran considering the role of nature and humans in the water systems through the Budyko framework. In addition to detecting the state of the basins (steady/non-steady), this may help to understand how natural events and human activities compound together to affect the groundwater extraction in Iranian basins.

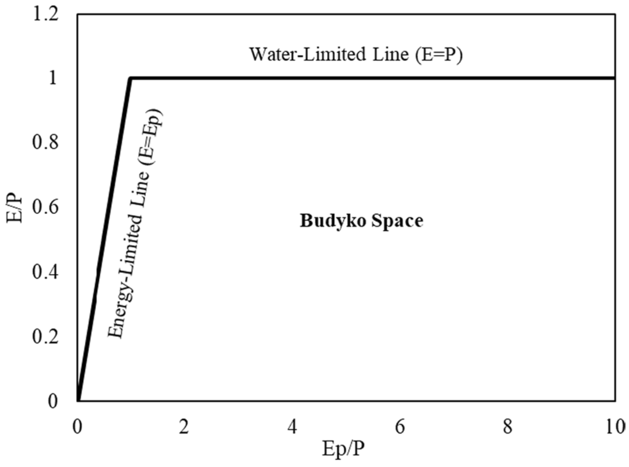


Fig. 1 Schematic view of the Budyko framework

Material and methods

Case study

Iran covers an area of 1,648,195 km^2 in the southwest of Asia (Fig. 2a) and is the second-largest nation in the Middle East (Madani 2014). The country is generally classified as an arid region (Fig. 2b). The mean annual precipitation during 1960–2016 has been around 225 mm year^{-1} (Saemian et al. 2022), less than one-third of global mean annual precipitation. The mean annual temperature varies from 10 °C in the western part to 35 °C in the central regions. The location of the Seas and the mountain regions cause a high spatiotemporal variable climate in Iran (Sanjani et al. 2011). The less amount of receiving precipitation in Iran makes the groundwater to be the major water resource for different sectors' (i.e., domestic, industrial, and agricultural) consumptions (Jafary and Bradley 2018). Increased water demand for these consumptions has led to an overdraft of groundwater, such that the country is one of the top groundwater miners in the world (Gleeson et al. 2012; Döll et al. 2014). The vast groundwater depletion in the country is mainly anthropogenic; however, it has been exacerbated by changes in climate conditions. WMO (2013) reported about 1 °C increase in temperature in Iran for the period of 2001–2010. During 1966–2015, mean annual temperature and mean annual precipitation have been increasing and decreasing, respectively (Mianabadi et al. 2019). Some previous studies also predicted that the country will be drier and warmer due to climate change (e.g., Madani et al. 2016; Doulabian et al. 2021).

Data

Precipitation (P), evaporation (E), runoff (R), and terrestrial water storage capacity (TWSC) were obtained from https://hydrology.princeton.edu/data/mpan/WC_MULTISOURCES_WB_050/ in NetCDF files. These data are

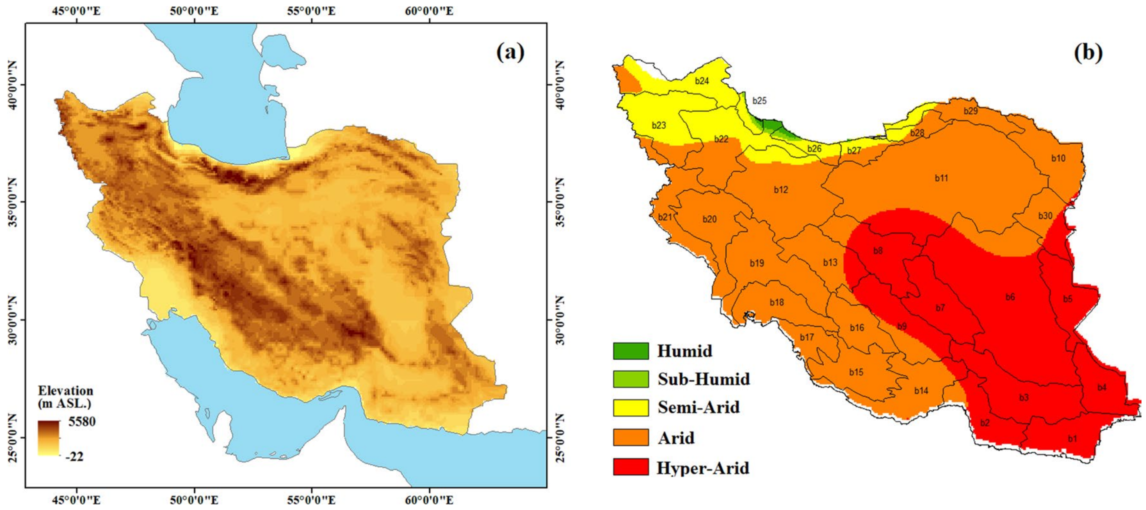


Fig. 2 **a** Geographical location and digital elevation model (DEM) of Iran, **b** Budyko Aridity Index (adapted from Mianabadi et al. 2019). b1 to b30 illustrate the major basins in Iran

available monthly from 1984 to 2010 with a spatial resolution of 0.5° × 0.5°. The data are provided based on a systematic method which optimally combines multiple available data sources for P, E, R, and TWSC and obtains water budget closure such that P–E–R–TWSC = 0. The method has been developed using a constrained Kalman filter (CKF) data assimilation technique (Zhang et al. 2018).

Potential evaporation (E_P) data were obtained from the Center for Environmental Data Archival website [http://catalogue.ceda.ac.uk/uuid/4a6d071383976a5fb24b5b42e28cf28f; (University of East Anglia Climatic Research Unit 2014)]. $\mathrm{E_P}$ has been calculated by the FAO-Penman–Monteith equation (Allen et al. 1998). The data are available at the monthly timescale over 1901–2013 with 0.5° × 0.5° spatial resolution. We applied the data for the period 1984–2010 to be in consistent with the other data set.

The numbers of the wells and their extraction (depletion, D) were acquired from the Water Resources Management Company of Iran for the study period (i.e., 1984–2010).

Budyko framework

To use the Budyko framework for our case study, we plot the evaporation ratio (E/P) versus aridity index (E_P/P) and TWSC. The behavior of these variables in the Budyko space can reveal if a given basin is under steady or non-steady-state conditions (Istanbulluoglu et al. 2012; Greve et al. 2014). It helps us to distinguish the role of natural and anthropogenic components on the water balance of the basins.

Trend analysis

The nonparametric Mann–Kendall test (Mann 1945; Kendall 1975) is commonly applied for trend analysis of climatological and hydrological data time series (Nalley et al. 2013; Pingale et al. 2014; Degefu et al. 2019). It can be performed to all probability distributions, and the normality assumption of the data does not have to be met. The Mann–Kendall (MK) test is defined as the following equation:

$$z_{\mathrm{MK}} = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{cases} \tag{1}$$

where

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sign}\left(x_j - x_k\right) \tag{2}$$

$$V(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i\left(t_i - 1\right)\left(2t_i + 5\right)\right]}{18} \tag{3}$$

in which $V(S)$ is the variance of S, t_i is the number of ties for the i-th value, n and m are the number of data points and tied groups, respectively, and x_j and x_k are the sequential data values. The positive/negative value of z_{MK} indicates an increasing/decreasing trend in the series. The trend analysis was conducted for 30 major basins of Iran classified as four climatic regions; hyper-arid, arid, semi-arid, and humid/sub-humid (Fig. 2), according to the Budyko aridity index (Mianabadi et al. 2019). In this study, we categorized the basins into three classes: hyper-arid, arid, and overlapped, the latter are the ones shared between two classes of climatic regions.

Results and discussion

Figures 3 and 4 illustrate the evaporation ratio (E/P) in terms of aridity index (E_P/P) and TWSC, respectively, for the years 1984–2010. Based on these figures, most years show an E/P higher than 1. It is more evident in the years 1985, 1987, 1990, 1993, 1995, 1998, 2001, 2008, and 2010 when E/P even reaches close to 4. As observed in Fig. 4, in these years, the TWSC is mostly negative. According to Fig. 5, in the above-mentioned years, most parts of the country experienced a negative TWSC indicating more surface/ground

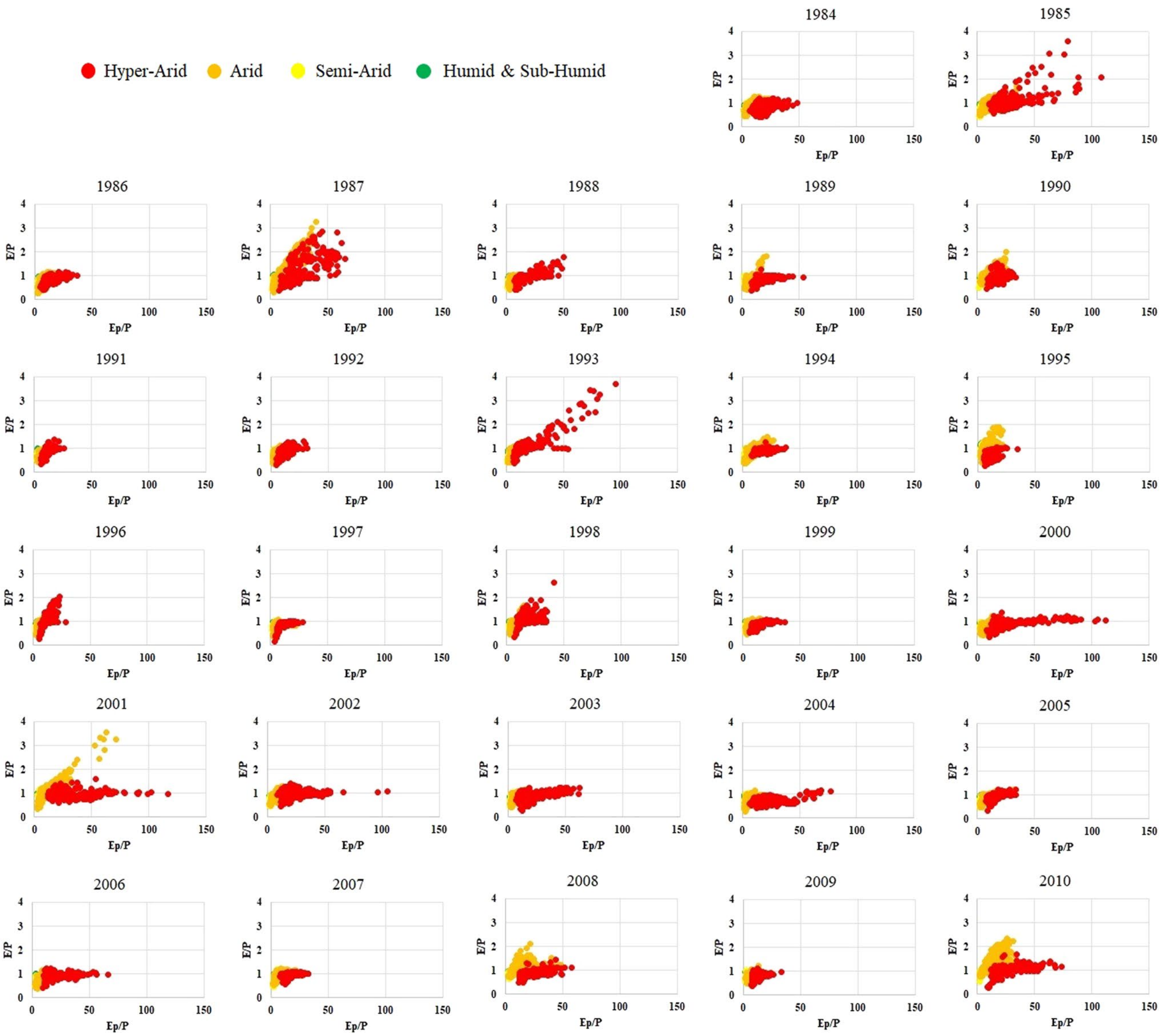


Fig. 3 Evaporation ratio in terms of aridity index through the Budyko Framework during 1984–2010 for each climatic region

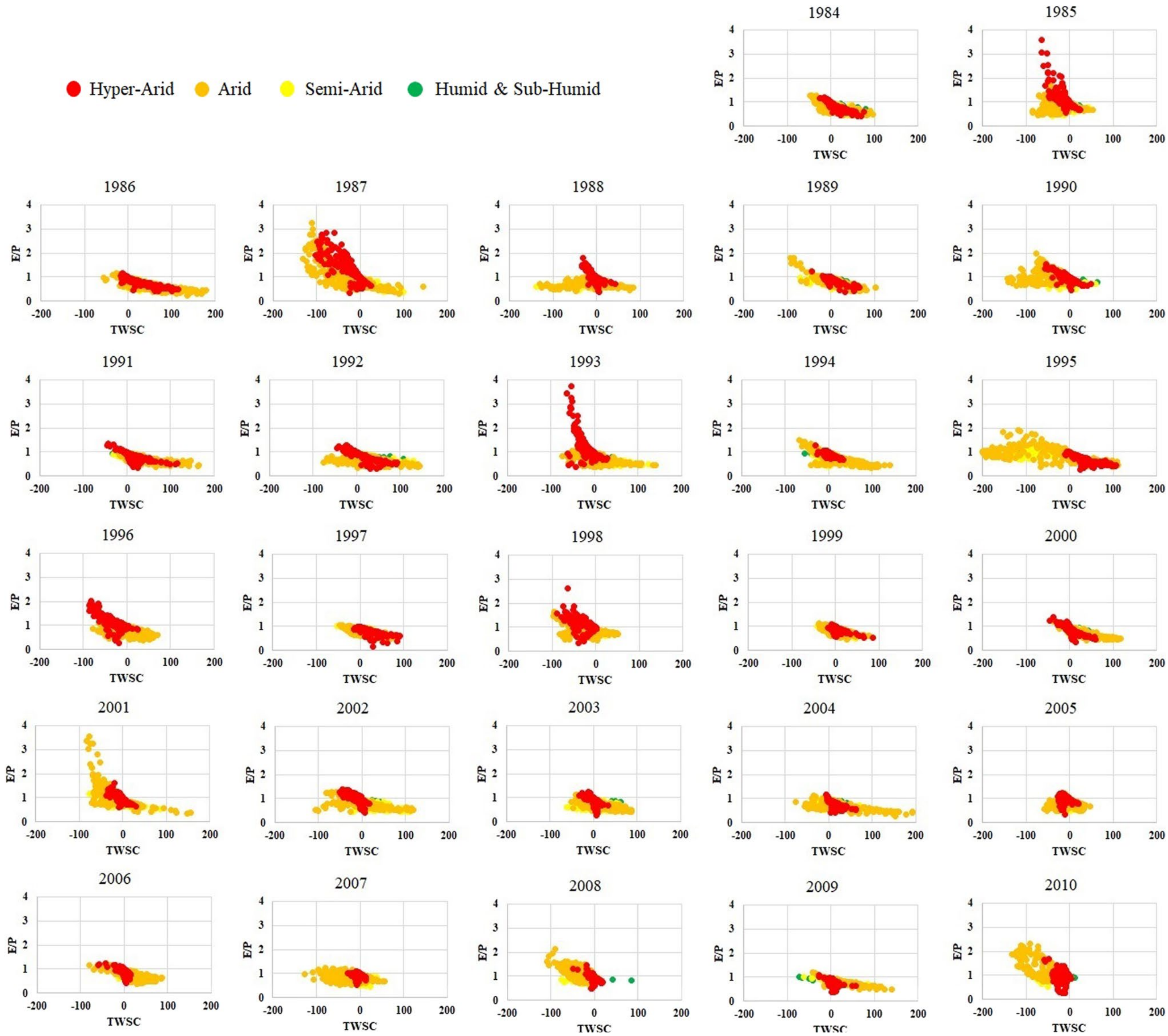


Fig. 4 Evaporation ratio in terms of TWSC during 1984–2010 for each climatic region

water extraction. The spatial distribution of precipitation (Fig. 6) also reveals these years received the least amounts of precipitation. Such situations are more evident in the hyper-arid and arid than in the semi-arid, humid, and sub-humid areas. For example, the year 1993 receives one of the highest amounts of precipitation in Iran during 1984–2010 (see Table 1). However, based on Figs. 3 and 4, the highest amount of *E*/*P* and negative TWSC are observed. In 1993, the average amount of precipitation in the country was high, with the most precipitation falling in humid, semi-humid and semi-arid regions. Nevertheless, hyper-arid regions only received 108 mm of precipitation, which is close to the average for these regions (107 mm). This led to more groundwater depletion in these areas than in other regions, resulting in the highest *E*/*P* and negative TWSC.

Figure 7 shows the relationship between the percentage of pixels with $E/P > 1$ and potential evaporation and precipitation for each climatic region. According to Fig. 7a, potential evaporation is not a limiting factor for evaporation, especially in arid and hyper-arid regions, still less amount of

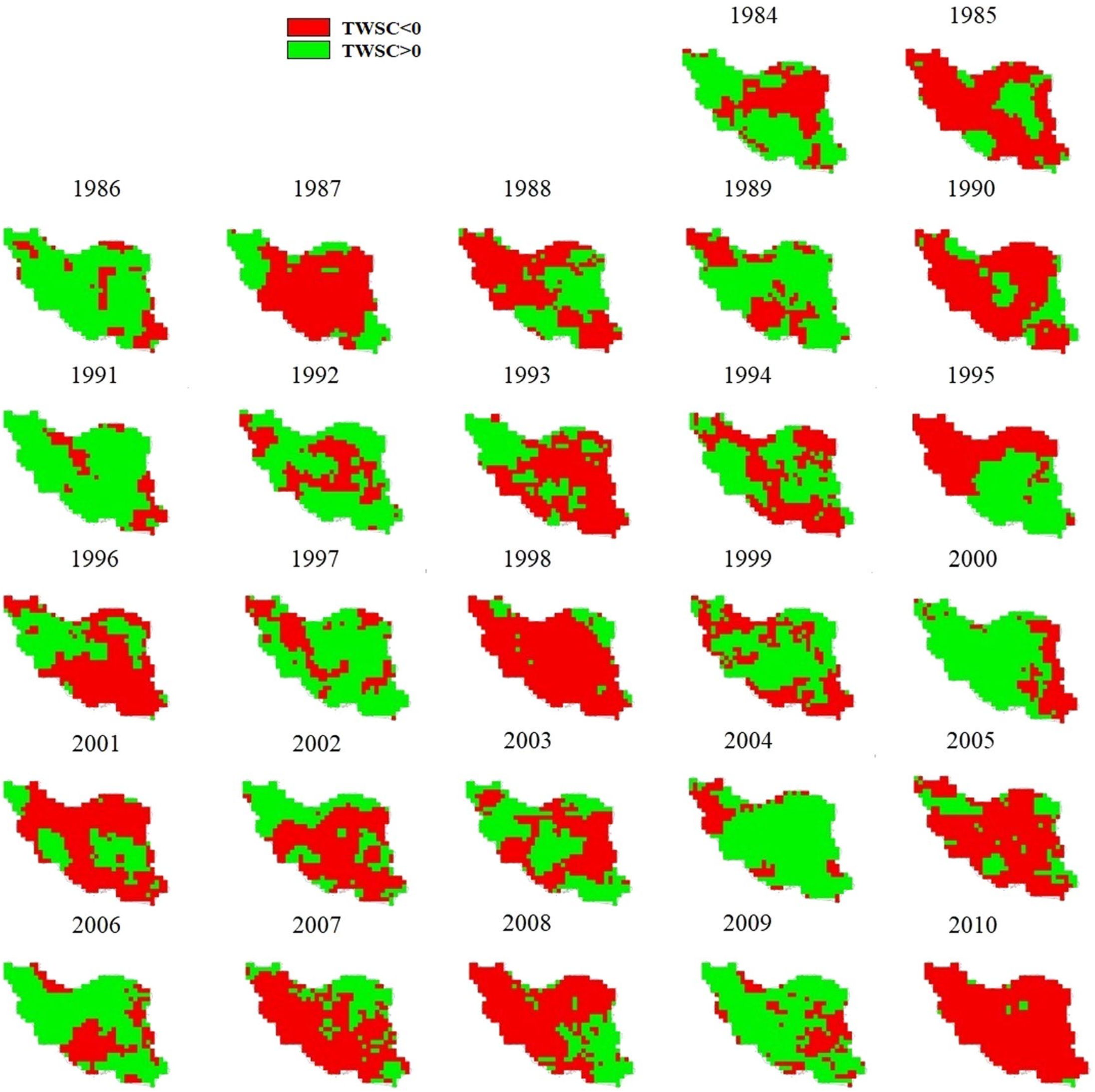


Fig. 5 Areas with TWSC > 0 and TWSC < 0 over Iran during 1984–2010

precipitation is the limiting factor. Figure 7b indicates that a decrease in precipitation leads to an increase in the percentage of pixels with $E/P > 1$. It is more evident in arid and hyper-arid regions (steeper slopes).

Figures 8, 9, and 10 show how the hydrological components (e.g., P, E, EP, and TWSC) interact at the basin scale. Comparison among these figures shows that the basins in arid and hyper-arid regions do not follow the Budyko framework. Among the basins in overlapped regions, the highest evaporation ratio during 1984–2010 was observed in b30, which is located in the arid and hyper-arid areas. The basins which are mostly located in semi-arid, humid, and sub-humid climates follow the Budyko framework. In hyper-arid and arid regions, potential evaporation is not the limiting factor for evaporation. Thus, all available water, including precipitation and depleted groundwater, evaporates in these regions. In contrast, potential evaporation limits evaporation in semi-arid, humid, and sub-humid areas reasonably. Furthermore, due to sufficient precipitation in wet months in these regions, parts of the groundwater depleted in summer return to the aquifers by infiltration in winter. Accordingly, while Figs. 8, 9, and 10 show that the number of wells and

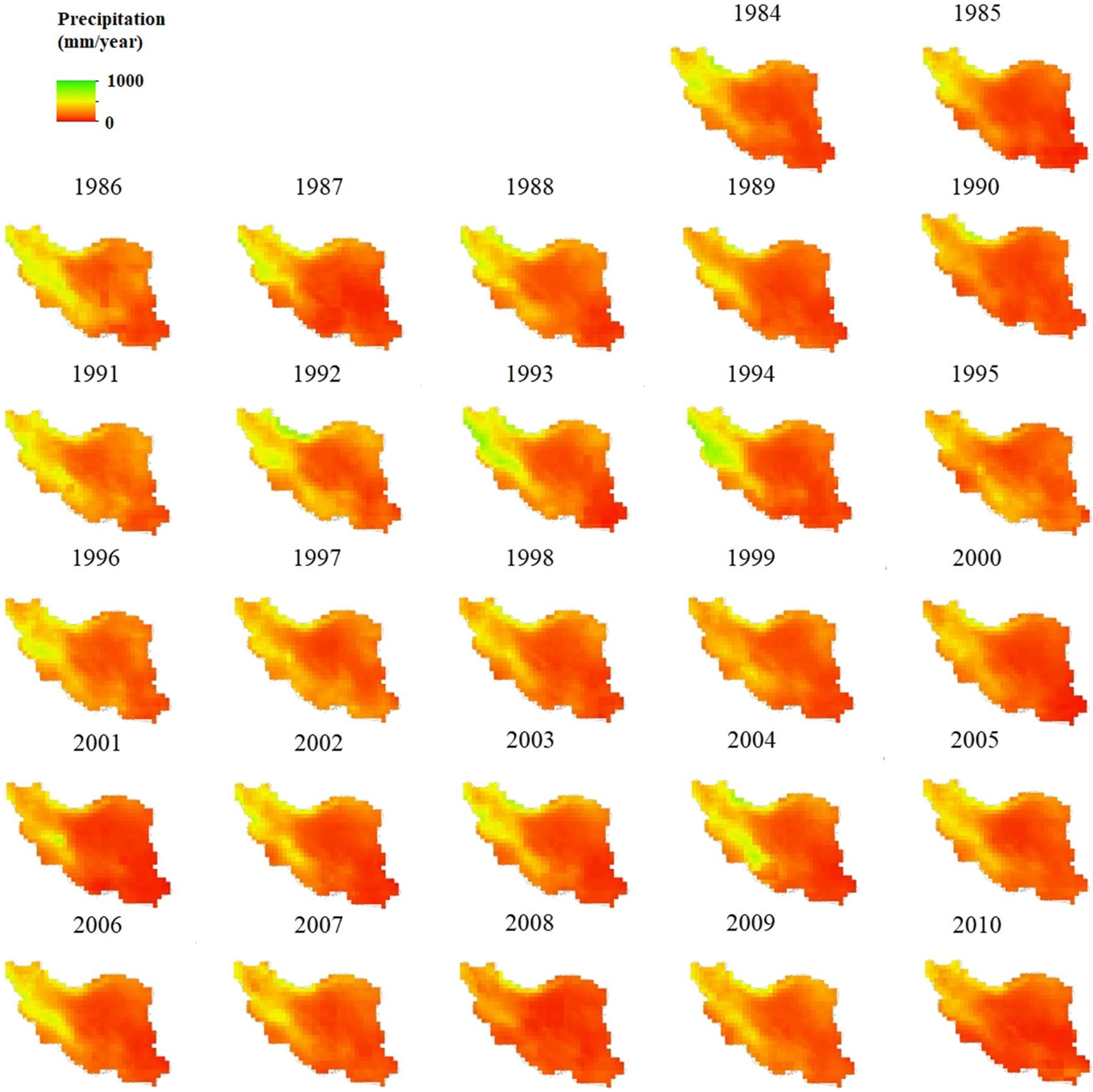


Fig. 6 Spatial distribution of precipitation over Iran during 1984–2010

groundwater extraction increased in 2010 compared to 1984 in all basins (the numbers with sign %), the annual evaporation ratio in arid and hyper-arid regions is more than the semi-arid, humid and sub-humid regions. This suggests that the increased number of wells in these regions has caused more extraction than in other basins.

In 1984, there were 188,760 wells in Iran, and by 2010, this number had increased to 753,437, representing a growth of 299% over the 27-year period. The number of wells in hyper-arid, arid, and overlapped regions has increased by 259%, 263%, and 355%, respectively. The decrease in precipitation in the northern and northwestern parts of the country (shown in Fig. 13) has resulted in a higher demand for groundwater. The greatest increase in the number of wells was seen in b5 (2740%) in the hyper-arid regions, followed by b25 (1826%) in the overlapped regions and b21 (1716%) in the arid regions.

Table 1 Mean annual precipitation (mm) in Iran and for each climatic region

Year	Humid/sub-humid	Semi-arid	Arid	Hyper-arid	Iran
1984	640	452	247	101	220
1985	555	410	206	70	182
1986	551	446	316	151	273
1987	530	436	228	75	197
1988	598	461	269	111	235
1989	552	351	226	95	195
1990	620	378	183	98	176
1991	557	436	307	162	271
1992	711	473	313	143	273
1993	636	503	310	108	261
1994	557	481	281	98	239
1995	452	350	229	160	219
1996	553	396	290	145	252
1997	542	382	256	160	237
1998	562	378	249	106	214
1999	516	343	235	122	208
2000	569	356	221	74	186
2001	537	349	190	61	164
2002	552	431	241	78	205
2003	627	438	257	87	219
2004	661	426	279	94	232
2005	544	406	241	113	215
2006	490	396	253	89	211
2007	539	388	239	110	211
2008	557	308	140	80	139
2009	550	389	258	131	229
2010	423	359	169	73	156

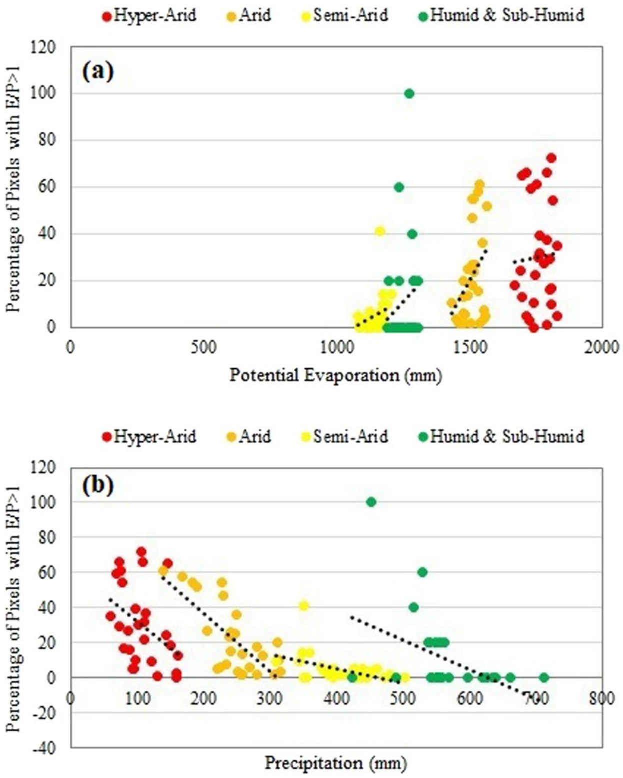


Fig. 7 Relationship between percentage of pixels with $E/P > 1$ and **a** potential evaporation, **b** precipitation for each climatic region

Although the number of wells and depletion increased in 2010 compared to 1984 in all basins, the trend analysis implies that the increasing rate is different for each basin (see Figs. 11, 12, and 13). The results show that the number of wells has been increasing in 17 basins, among which eight basins experience a significant increasing trend (b5, b18, b19, b20, b21, b22, b23, and b25). The basins with significant increasing trends locate in the west and northwest, where the highest rate of precipitation is received, and the most population of the country is settled. However, there is no significant increasing trend in depletion in these basins; some even have a decreasing trend (e.g., b19 in Fig. 13). The only basins with significant positive trends in both depletion and the number of wells are b23 and b25. It should be mentioned that from 2001 to 2010, the number of wells and the amount of depletion in most basins have decreased considerably. The decrease during 2001–2010 may have impacted the trend during the whole study period (1984–2010), leading to decreasing trend in these basins. The non-significant (positive and negative) trends in TWSC also confirm this. The results also reveal that the western and northwestern basins have significant negative trends in precipitation, which could be the main reason for digging more wells in these regions. However, the amount of precipitation in the wet months is enough to compensate for the less precipitation in the dry months (growing season). Hence, despite increasing trends in the number of wells and more groundwater extraction in dry months, depletion is not considerably increasing in these areas. It is worth noting that in the basins located in the north and west, the soil moisture content and surface water may not be negligible, and their contribution to the TWSC

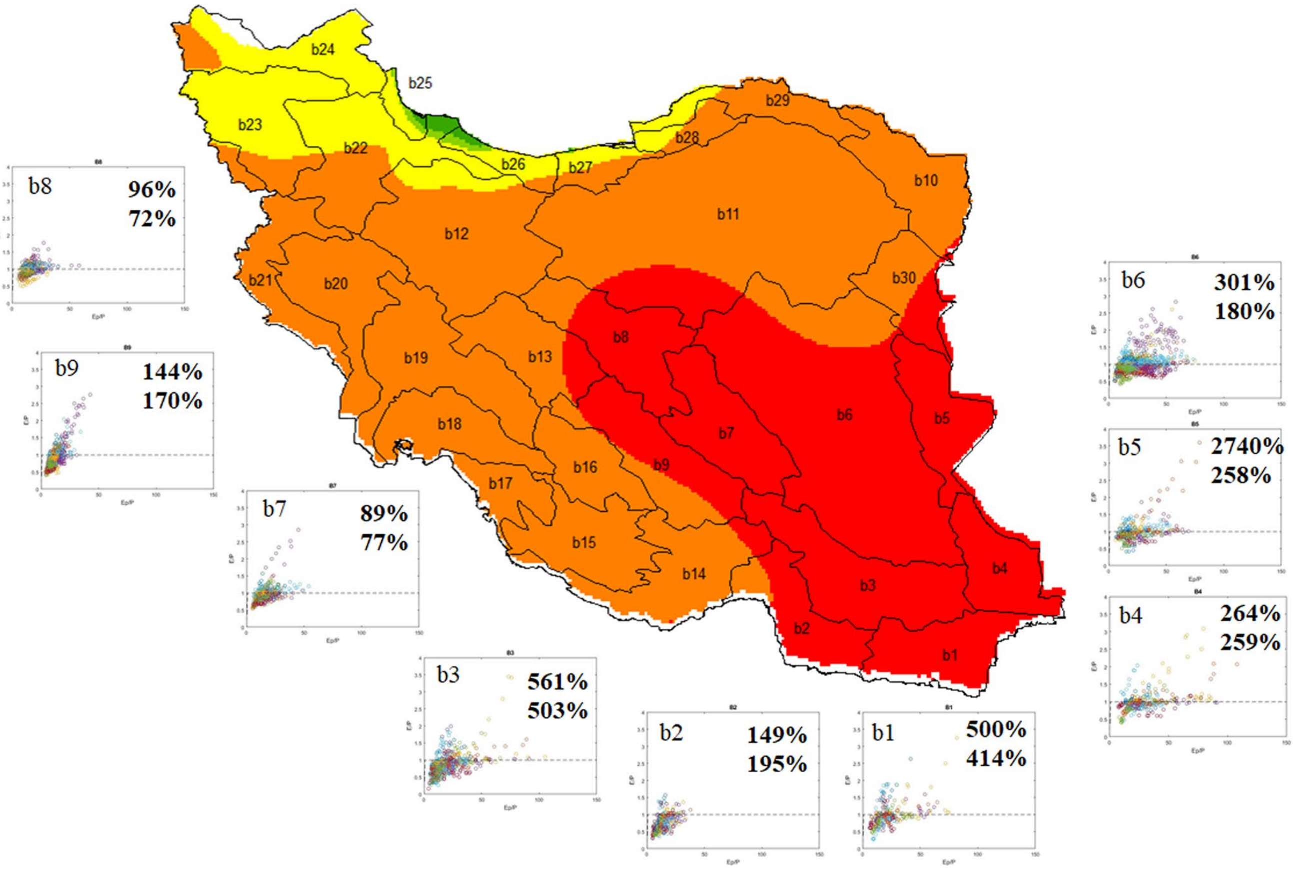


Fig. 8 Evaporation ratio in terms of aridity index through the Budyko Framework during 1984–2010 for each basin located in the hyper-arid regions. The numbers with % show the percentage of change in the number of wells (up) and extraction from the aquifers (bottom) in 2010 compared to 1984 for each basin

should be considered. Nevertheless, groundwater storage change is the dominant part of the TWSC in most basins in Iran (Saemian et al. 2022).

In the west and northwest, evaporation is also decreasing, but the significant negative trend in precipitation and insignificant negative trend in evaporation have led to a significant positive trend in evaporation ratio. Negative trends in evaporation in the basins with decreasing precipitation and increasing depletion indicate that precipitation contributes more to evaporation than depletion (see, for example, b5, b18, b20, b21, b22, b23, b25, and b28).

In the humid areas (west and northwest), evaporation ratio does not commonly exceed unity and it follows the Budyko framework. The results indicate that even though there is an increasing trend in the evaporation ratio in these regions, it still remains under the water-limited line in the Budyko framework (see Fig. 2). This also implies that the water extraction in dry months is replenished during the wet months, meaning the regions are still under steady-state conditions. It indicates the critical role of natural recharge in maintaining groundwater storage in humid areas.

In areas where the evaporation ratio is usually greater than 1, a decrease in rainfall, the number of wells, and depletion has caused a major drop in evaporation. It is more evident for b2, b6, and b8. It is worth noting that decreasing trend in depletion does not necessarily reflect good governance and wise management, but implies that there is not enough groundwater in the aquifers to be extracted (Ashraf et al. 2021; Noori et al. 2021).

Trend analysis of the runoff illustrates the connection between precipitation and runoff, as in the areas with decreasing precipitation trends, runoff also shows a negative trend. It shows that the surface water resources have

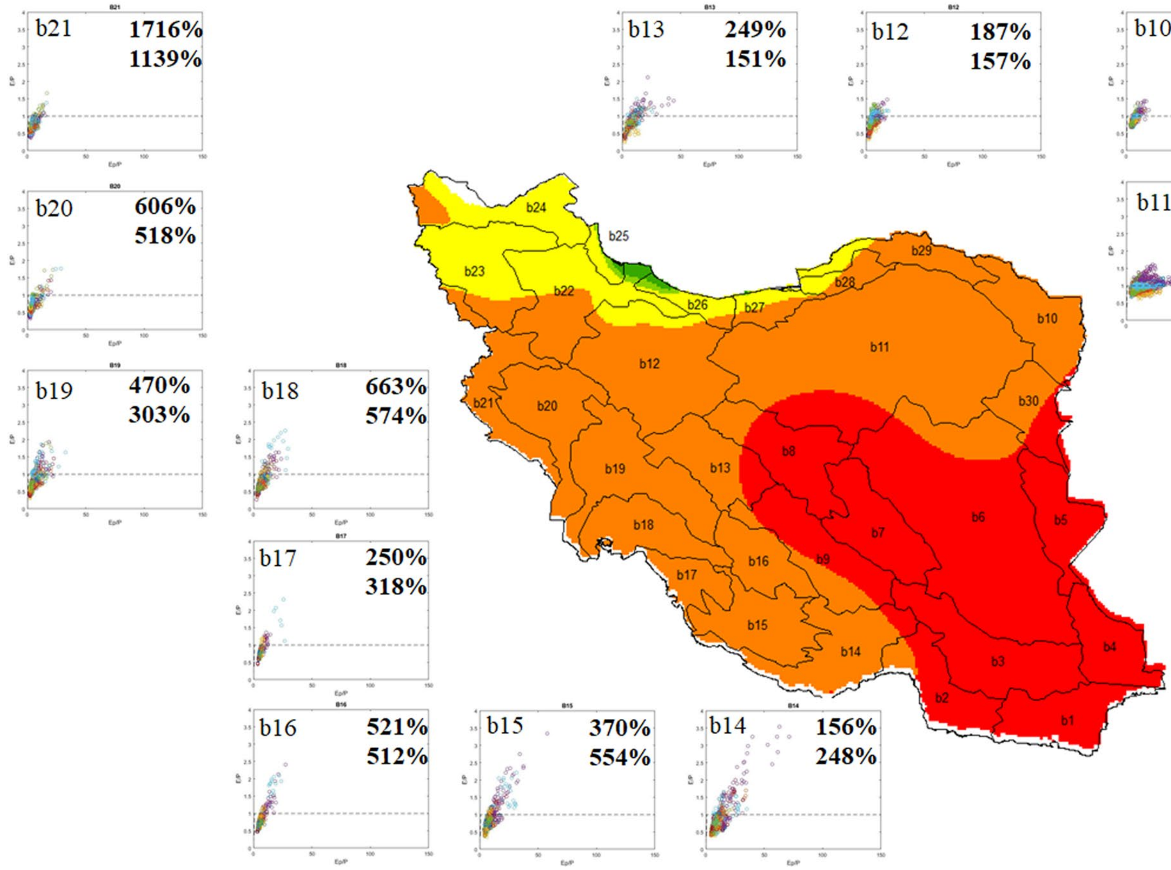


Fig. 9 Evaporation Ratio in terms of aridity index through the Budyko framework during 1984–2010 for each basin located in the arid regions. The numbers with % show the percentage of change in the number of wells (up) and extraction from the aquifers (bottom) in 2010 compared to 1984 for each basin

been decreasing in these areas, leading to more groundwater extraction. Furthermore, it also can justify the decreasing trend in TWSC in these areas. In general, our findings are consistent with the previous studies conducted for different periods using GRACE and in situ data (e.g., Voss et al. 2013; Forootan et al. 2014; Moshir Panahi et al. 2020).

Iran has experienced several long-term droughts, detected in this study through the Budyko framework. These natural/anthropogenic drought events, besides the bad governance and mismanagement, caused many water bodies to dry up and most of the aquifers to depleted in recent decades (AghaKouchak et al. 2015; Ashraf et al. 2017, 2019). These situations resulted in considerable water-related issues in the country (Madani 2014). Despite data and model uncertainty, the results indicate that water storage (mainly groundwater) depletion in Iran is a crucial issue that should be considered by all stakeholders, including local communities, water experts, and decision policymakers. As some other studies illustrated the critical situation of groundwater in Iran in recent years (2002–2019) (Ashraf et al. 2021; Noori

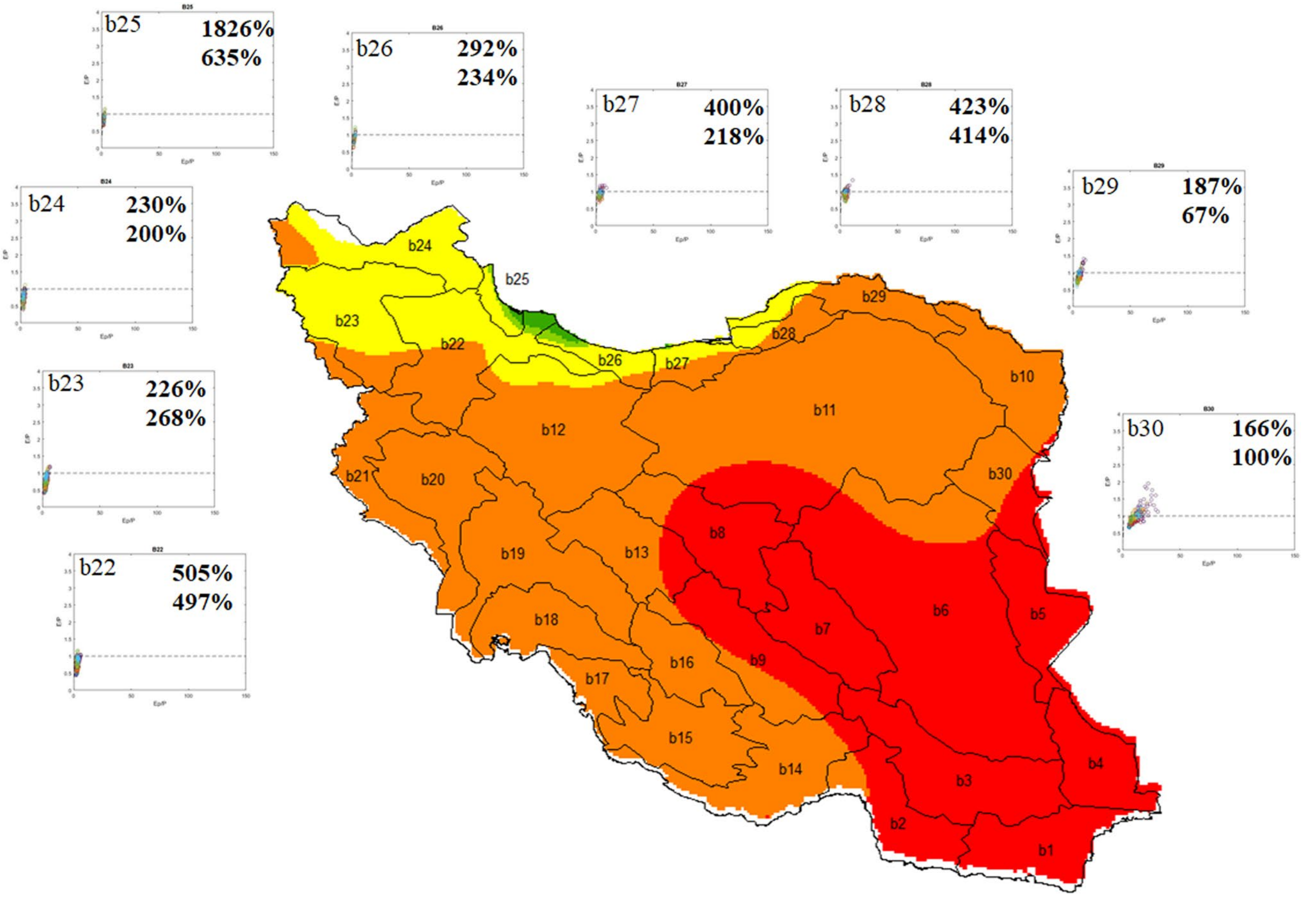


Fig. 10 Evaporation ratio in terms of aridity index through the Budyko framework during 1984–2010 for each basin located in the regions with overlapped climate. The numbers with % show the percentage of change in the number of wells (up) and extraction from the aquifers (bottom) in 2010 compared to 1984 for each basin

et al. 2021; Saemian et al. 2022), it indicates that groundwater management and governance programs in the country have failed (Noori et al. 2021). Groundwater depletion and increasing the number of the “prohibited” and “critical prohibited” plains in Iran would lead to environmental and food security in the country with considerable socioeconomic consequences such as unemployment, conflicts, and mass rural–urban migration (Madani et al. 2016; Mehrparvar et al. 2016; Mianabadi et al. 2021a). According to the results of the current and previous studies, the northern and western basins remain still at steady-state conditions and are categorized as “free plains.” However, in these basins, which contain a large part of the population of the country and have high agricultural production potential, the groundwater

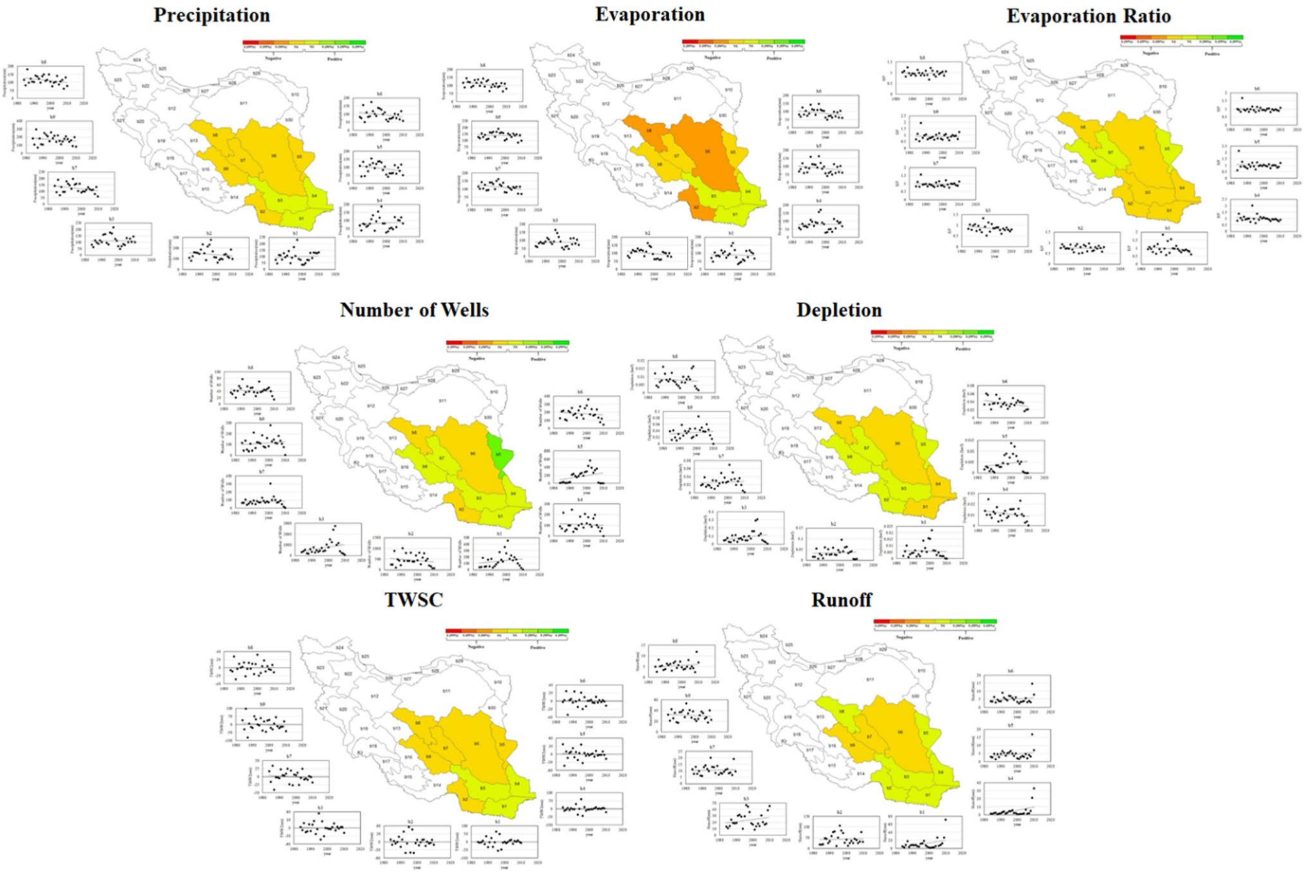
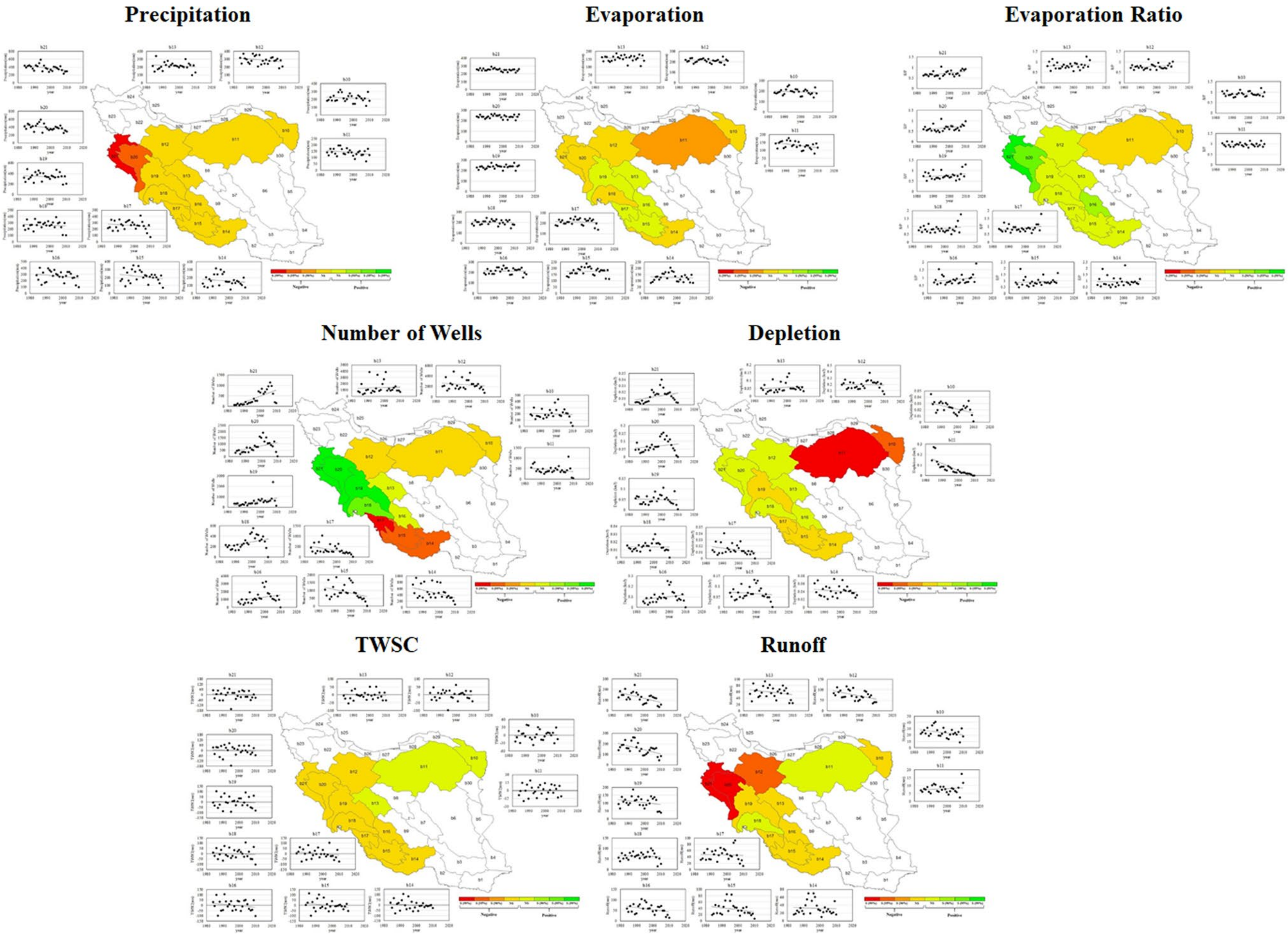


Fig. 11 Trends in P, E, E/P, number of wells, D, TWSC, and R at basin scales in hyper-arid regions

withdrawal is increasing rapidly, and they may encounter water scarcity in the future. Hence, we suggest that policymakers provide appropriate long-term plans for drought and climate change adaptation with focusing on groundwater management (e.g., Mianabadi et al. 2020b, 2021b). Otherwise, the arising environmental and socioeconomic implications will considerably threaten the security and sustainability of the country as a whole.



Precipitation

Evaporation

Evaporation Ratio

Number of Wells

Depletion

TWSC

Runoff

Fig. 12 Trends in *P*, *E*, *E*/*P*, number of wells, *D*, TWSC, and *R* at basin scales in arid regions

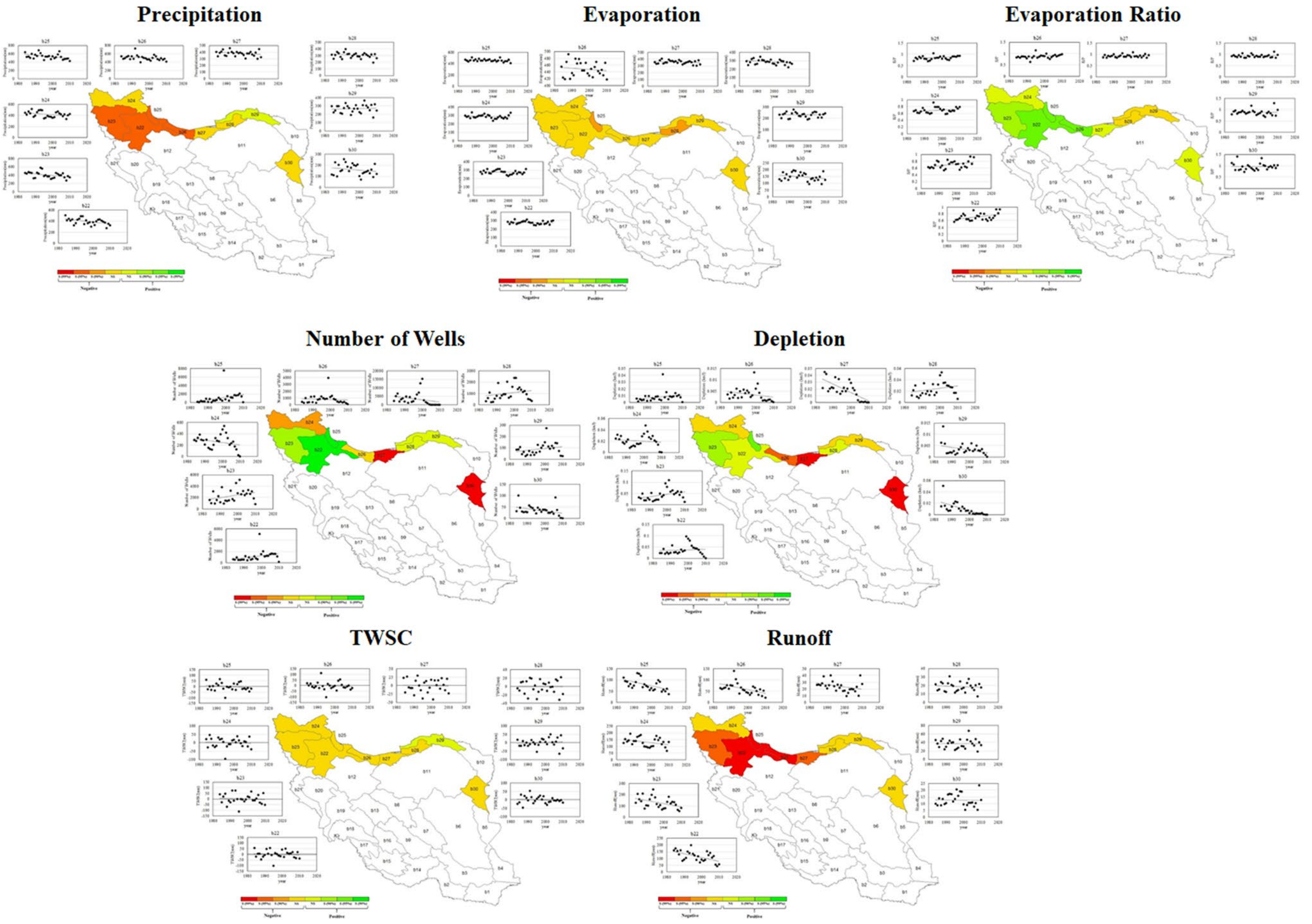


Fig. 13 Trends in *P*, *E*, *E*/*P*, number of wells, *D*, TWSC, and *R* at basin scales in overlapped regions

Conclusion

This study focuses on the changes in the water balance components in the 30 major basins in Iran during 1984–2010. The study's findings revealed alarming situations, mainly in the east and center of the country. Due to physical limits to the renewable groundwater in many basins in Iran, water extraction from aquifers decreased from 2001 onward. It indicates the failure in the groundwater management and governance programs in the country. A significant decrease in precipitation in western Iran has led to less amount of surface water and more groundwater depletion. Although the Budyko framework implies that the western basins are still under steady-state conditions, the rapid increase in groundwater extraction may cause severe water challenges in the future in these areas, like what happened in the eastern and central basins. This issue can threaten the environment, water, and food security with considerable socioeconomic consequences. The current water crisis in Iran arises from both natural variabilities and anthropogenic changes. The natural variabilities are not entirely avoidable; thus, policymakers need to focus on the anthropogenic water challenges. Both governments and local people can be involved in water management in Iran. Providing appropriate plans for increasing the coping and adaptive capacity of the communities by the policymakers and establishing the local governance and engagement of the local stakeholders for implementing the provided strategies can mitigate the unpleasant implications of the water challenges in Iran.

Author contribution AM took part in conceptualization, methodology, investigation, formal analysis, visualization, writing—original draft. MP-B involved in conceptualization, methodology, writing—reviewing and editing.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

Ethical approval The manuscript is an original work with its own merit, has not been previously published in whole or in part, and is not considered for publication elsewhere.

Consent to participate The authors have read the final manuscript, approved the submission to the journal, and accepted full responsibilities pertaining to the manuscript's delivery and contents.

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References

AghaKouchak A, Norouzi H, Madani K et al (2015) Aral sea syndrome desiccates Lake Urmia: call for action. J Great Lakes Res 41:307–311. https://doi.org/10.1016/j.jglr.2014.12.007

Alborzi A, Mirchi A, Moftakhari H et al (2018) Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts. Environ Res Lett 13:084010. https://doi.org/10.1088/1748-9326/aad246

Allen R, Pereira L, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrig Drain Pap 56 FAO, Rome, Italy, 300 p

Ashraf B, Aghakouchak A, Alizadeh A et al (2017) Quantifying anthropogenic stress on groundwater resources. Sci Rep 7:1–9. https://doi.org/10.1038/s41598-017-12877-4

Ashraf S, AghaKouchak A, Nazemi A et al (2019) Compounding effects of human activities and climatic changes on surface water availability in Iran. Clim Change 152:379–391. https://doi.org/10.1007/s10584-018-2336-6

Ashraf S, Nazemi A, AghaKouchak A (2021) Anthropogenic drought dominates groundwater depletion in Iran. Sci Rep 11:1–10. https://doi.org/10.1038/s41598-021-88522-y

Budyko MI (1974) Climate and life. Academic Press, Orlando

Chen X, Alimohammadi N, Wang D (2013) Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework. Water Resour Res 49:6067–6078. https://doi.org/10.1002/wrcr.20493

Danaei G, Farzadfar F, Kelishadi R et al (2019) Iran in transition. Lancet 393:1984–2005. https://doi.org/10.1016/S0140-6736(18)33197-0

Degefu MA, Alamirew T, Zeleke G, Bewket W (2019) Detection of trends in hydrological extremes for Ethiopian watersheds, 1975–2010. Reg Environ Change. https://doi.org/10.1007/s10113-019-01510-x

Döll P, Müller Schmied H, Schuh C et al (2014) Global-scale assessment of groundwater depletion and related groundwater abstractions: combining hydrological modeling with information from well observations and GRACE satellites. Water Resour Res 50:5698–5720. https://doi.org/10.1002/2014WR015595

Doulabian S, Golian S, Toosi AS, Murphy C (2021) Evaluating the effects of climate change on precipitation and temperature for Iran using RCP scenarios. J Water Clim Change 12:166–184. https://doi.org/10.2166/wcc.2020.114

Du C, Sun F, Yu J et al (2016) New interpretation of the role of water balance in an extended Budyko hypothesis in arid regions. Hydrol Earth Syst Sci 20:393–409. https://doi.org/10.5194/hess-20-393-2016

Forootan E, Rietbroek R, Kusche J et al (2014) Separation of large scale water storage patterns over Iran using GRACE, altimetry and hydrological data. Remote Sens Environ 140:580–595. https://doi.org/10.1016/j.rse.2013.09.025

Gerrits AMJ, Savenije HHG, Veling EJM, Pfister L (2009) Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model. Water Resour Res 45:W04403. https://doi.org/10.1029/2008WR007308

Gleeson T, Wada Y, Bierkens M, van Beek L (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488:197–200

Gleick PH (1993) Water and conflict: fresh water resources and international security. Int Secur 18:79–112

Greve P, Orlowsky B, Mueller B et al (2014) Global assessment of trends in wetting and drying over land. Nat Geosci 7:716–721. https://doi.org/10.1038/ngeo2247

Huang P, Song J, Wu Q et al (2022) The ecohydrological effects of climate and landscape interactions within the Budyko framework under non-steady state conditions. CATENA 217:106481. https://doi.org/10.1016/j.catena.2022.106481

Istanbulluoglu E, Wang T, Wright OM, Lenters JD (2012) Interpretation of hydrologic trends from a water balance perspective: the role of groundwater storage in the Budyko hypothesis. Water Resour Res 48:W00H16. https://doi.org/10.1029/2010WR010100

Jafary F, Bradley C (2018) Groundwater irrigation management and the existing challenges from the farmers' perspective in central Iran. Land 7:1–21. https://doi.org/10.3390/land7010015

Kendall MG (1975) Rank correlation methods. Charles Griffin, London

Madani K (2014) Water management in Iran: What is causing the looming crisis? J Environ Stud Sci 4:315–328. https://doi.org/10.1007/s13412-014-0182-z

Madani K (2021) Have international sanctions impacted Iran's environment? World 2:231–252. https://doi.org/10.3390/world2020015

Madani K, Aghakouchak A, Mirchi A (2016) Iran's socio-economic drought: challenges of a water-bankrupt nation. Iran Stud 49:997–1016

Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259

Mehrparvar M, Ahmadi A, Safavi HR (2016) Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: a case study. Int J River Basin Manag 14:33–45. https://doi.org/10.1080/15715124.2015.1081209

Mianabadi A, Shirazi P, Ghahraman B et al (2019) Assessment of short- and long-term memory in trends of major climatic variables over Iran: 1966–2015. Theor Appl Climatol 135:677–691. https://doi.org/10.1007/s00704-018-2410-z

Mianabadi A, Davary K, Pourreza-Bilondi M, Coenders-Gerrits AMJ (2020a) Budyko framework; towards non-steady state conditions. J Hydrol 588:125089. https://doi.org/10.1016/j.jhydrol.2020.125089

Mianabadi A, Derakhshan H, Davary K et al (2020b) A novel idea for groundwater resource management during megadrought events. Water Resour Manag 34:1743–1755. https://doi.org/10.1007/s11269-020-02525-4

Mianabadi A, Davary K, Kolahi M, Fisher J (2021a) Water/climate nexus environmental rural–urban migration and coping strategies. J Environ Plan Manag. https://doi.org/10.1080/09640568.2021.1915259

Mianabadi A, Hasheminia SM, Davary K et al (2021b) Estimating the aquifer's renewable water to mitigate the challenges of upcoming megadrought events. Water Resour Manag 35:4927–4942. https://doi.org/10.1007/s11269-021-02980-7

Moshir Panahi D, Kalantari Z, Ghajarnia N et al (2020) Variability and change in the hydro-climate and water resources of Iran over a recent 30-year period. Sci Rep 10:1–9. https://doi.org/10.1038/s41598-020-64089-y

Nalley D, Adamowski J, Khalil B, Ozga-Zielinski B (2013) Trend detection in surface air temperature in Ontario and Quebec, Canada during 1967–2006 using the discrete wavelet transform. Atmos Res 132–133:375–398. https://doi.org/10.1016/j.atmosres.2013.06.011

Noori R, Maghrebi M, Mirchi A et al (2021) Anthropogenic depletion of Iran's aquifers. Proc Natl Acad Sci USA 118:1–7. https://doi.org/10.1073/pnas.2024221118

Pingale SM, Khare D, Jat MK, Adamowski J (2014) Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. Atmos Res 138:73–90. https://doi.org/10.1016/j.atmosres.2013.10.024

Richts A, Vrba J (2016) Groundwater resources and hydroclimatic extremes: mapping global groundwater vulnerability to floods and droughts. Environ Earth Sci 75:926. https://doi.org/10.1007/s12665-016-5632-3

Rodell M, Famiglietti JS, Wiese DN et al (2018) Emerging trends in global freshwater availability. Nature 557:651–659. https://doi.org/10.1038/s41586-018-0123-1

Saemian P, Elmi O, Vishwakarma BD et al (2020) Analyzing the Lake Urmia restoration progress using ground-based and spaceborne observations. Sci Total Environ 739:139857. https://doi.org/10.1016/j.scitotenv.2020.139857

Saemian P, Tourian MJ, AghaKouchak A et al (2022) How much water did Iran lose over the last two decades? J Hydrol Reg Stud 41:101095. https://doi.org/10.1016/j.ejrh.2022.101095

Sanjani S, Bannayan M, Kamyabnejad M (2011) Detection of recent climate change using daily temperature extremes in Khorasan Province, Iran. Clim Res 49:247–254. https://doi.org/10.3354/cr01031

Savenije HHG (2004) The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrol Process 18:1507–1511. https://doi.org/10.1002/hyp.5563

Shuttleworth WJ (1993) Evaporation. In: Handbook of hydrology. McGraw-Hill, New York, pp 4.1–4.53

University of East Anglia Climatic Research Unit (2014) CRU TS3.22: Climatic Research Unit (CRU) Time-Series (TS) Version 3.22 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901–Dec. 2013). NCAS Br Atmos Data Cent 24 Septemb. https://doi.org/10.5285/18BE23F8-D252-482D-8AF9-5D6A2D40990C

Voss KA, Famiglietti JS, Lo M et al (2013) Groundwater depletion in the middle east from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. Water Resour Res 49:904–914. https://doi.org/10.1002/wrcr.20078

WMO (2013) The global climate 2001–2010

Zhang Y, Pan M, Sheffield J et al (2018) A climate data record (CDR) for the global terrestrial water budget: 1984–2010. Hydrol Earth Syst Sci 22:241–263. https://doi.org/10.5194/hess-22-241-2018