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Assessment of potential of intraregional conflicts by developing a transferability index for inter-basin water transfers, and their impacts on the water resources

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Abstract Rapid population growth, rising water demands, inefficient management, and various distributions of water are the major causes of increased pressure on water resources and the consequent increased water-based conflicts especially in arid and semi-arid regions in Iran being a case in point. Iran is the second largest country in the Middle East. The country-wide average annual precipitation is about 250 mm, which is about one third of the world's average. Therefore, Iran is one of the driest countries in the world. The water supply for human activities in Iran's provinces has become an increasingly complex task. One of the conventional methods to supply water to these regions is through inter-basin water transfers, from water-endowed regions to water-scarce regions. For such projects, it is necessary but also difficult and expensive to estimate the total water storage of every province with traditional methods. This study employs the GRACE satellite data for 2002–2016 are used and develops a method to assess the linkage between water scarcity and conflicts in Iran's provinces. In addition, a transferability index is formulated based on population and conveyable water parameters demonstrating the conditions of the provinces in inter-basin water transfer for reaching equitable compromises. This index leads to an evaluation of the possibility of conflicts arising from inter-basin water transfer projects in Iran. This work's results show that the Bushehr region has a significant amount of conveyable water and low population and hence is suitable to be one of the water-exporting provinces in the inter-basin water projects. The results of this work also demonstrate that the western provinces are likely to experience serious depletion of water resources, and conflicts may arise in the western and central basins due to the changes in water quantity exacerbated by the inter-basin transfer projects.

Keywords Inter-basin water transfer · Water resources · Water conflicts · Transferability index

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Introduction

There are several reasons behind water conflicts, most of which are related to decreased water quantity, deteriorated water quality, and changes in the timing of water availability (Petersen-Perlman and Wolf 2017; Jury and Vaux 2007). The likelihood of a water conflict rises as the rate of such changes within a basin exceeds the institutional capacity to absorb the changes (Wolf et al. 2003). Low hydro-political resilience may also lead to a conflict. Unilateral construction of large water infrastructures, for instance, can cause low infrastructure resilience. However, measures for building institutional capacity, such as creating river basin organizations (RBOs), can reduce the probability of the conflict occurrence. Inequitable water service management by governments may also raise potential conflicts over water between regions. Social and political power equities between provinces also play a central role in regional and inter-regional water management.

Increasing demands for water in some regions have given rise to the need for inter-basin water transfer (IBWT) projects that require the construction and operation of reservoirs, aqueducts, pumping stations, and managed aquifer recharge sites, among other features. Some of the largest water transfers take place from Northern California to Southern California (Getches 2005) and from Southern China to Northern China (Zhang et al. 2015). Such transfers are not free from controversy due to losses of water resources from the source areas and the adverse impacts of such transfers on aquatic ecosystems and other aspects of water resources systems. Nevertheless, economic priorities and political alliances have commonly prevailed and inter-basin water transfers are common worldwide.

The environmental and socioeconomic impacts of IBWT projects have been assessed. For example, Bhattarai et al. (2005) evaluated the economic and hydrologic impacts of the Melamchi IBWT project in Nepal and found that the compensation scheme covered local public goods and local farmers but did not adequately consider third-party stakeholders, such as water mill owners. Karamouz et al. (2010) introduced an optimization model with the objective of maximizing the benefits from the Karoon IBWT projects by considering environmental impacts. Karakaya et al. (2014) investigated the socioeconomic effects of the IBWT projects in Turkey. Zhang et al. (2015) provided a comprehensive bibliometric review of the IBWT-related studies. Zhuang (2016) assessed the positive and negative effects of IBWT projects on water-supplying and water-receiving basins in Northern China and provided alternatives to the IBWT projects. Also, Zhou et al. (2017) analyzed the Hanjiang River's inter-basin water transfers, assessed their impacts on the water allocation and hydropower generation of water supplying basins, and suggested optimal solutions under different scenarios for the water allocations. The latter authors concluded that optimization methods provided a solution for balancing the uneven distribution of water with acceptable negative impacts on the environmental and socioeconomic systems of the water-supplying basins.

The planning of IBWT projects requires knowledge of province's total water storage for deciding how much water can be transferred to other provinces. Traditionally, this is done with in situ measurements of water table for groundwater, river discharge, snow depth, etc., which are the most accurate available data (Biancamaria et al. 2019). In the last decades, remote sensing technologies have proven their capabilities of providing high-resolution data. The Gravity Recovery and Climate Experiment (GRACE) satellite mission has been applied to measure the variations of total water storage at a coarse spatial resolution and a monthly time scale. Many studies have been conducted relying on the GRACE data. Abdelmalik and Abdelmohsen (2019) implemented the GRACE and TRMM to monitor spatiotemporal changes in the total water mass in the Nile basin in 2003–2016. Biancamaria et al. (2019) analyzed water variations in the Garonne basin in France and assessed the 2003–2010 GRACE data of total water storage anomalies (TWSA), and compared with the simulations from the Soil and Water Assessment Tool (SWAT) and SAFARAN-ISBA_MODCOU (SIM). Their results showed good agreement between the GRACE data and the simulations from both models. Also, their analyses showed that the TWSA in the basin was mainly induced by the water stored in shallow aquifers and the first dozen meters of soil depth as well as surface waters. They also found that deep aquifers had a negligible impact on the TWSA.

This work presents a new method to predict the potential of water conflicts between neighboring regions based on the TWSA data of GRACE. Both positive and negative effects of IBWT projects on the water resources in the Iranian river basins are evaluated. The transferability index relies on population and conveyable water parameters and the conditions of all provinces involved in inter-basin water transfer for reaching equitable agreements between water-exporting and water-importing basins in Iran. The conflict-possibility scores of IBWT projects in Iran are further evaluated with the transferability index.

Materials and methods

Potential water conflicts between Iran's provinces

Many conflicts over water between provinces in Iran have been reported in recent years stemming from water scarcity, most of which occurred between the western and central provinces. The eastern and central basins receive less than 200 mm of rain a year, and they endure sporadic droughts. In these provinces, the scarcity of water for agricultural use has caused economic losses and a drinking water crisis.

The characterization of potential conflicts between provinces due to the changes in water quantity requires a regional water balance analysis. Water scarcity is controlled by the availability of water in the hydrologic cycle. The general water balance equation for a hydrologic system is expressed as follows (Kane and Yang 2004):

$$P - \mathrm{ET} - R \pm \Delta S_{\mathrm{sur}} \pm \Delta S_{\mathrm{sub}} \pm \Delta S_{\mathrm{vad}} \pm \Delta S_{\mathrm{glac}} \pm \Delta S_{\mathrm{snow}} = \eta \tag{1}$$

where P is the precipitation, including rainfall and snowfall; ET is the evapotranspiration; R is the surface and subsurface runoff; ΔS_{sur} is the change in surface storage (such as reservoirs, open channels, and lakes); ΔS_{sub} is the change in subsurface storage (saturated); ΔS_{vad} is the change in vadose zone storage (unsaturated); ΔS_{glac} is the change in glacier storage; ΔS_{snow} is the change in snowpack storage; and η is a closure error. All the water volumes in Eq. (1) occur over the same period of time.

It is difficult to directly measure all the water mass balance terms in Eq. (1) (Young and Woo 2004). This difficulty is exacerbated for large basins (e.g., regional scales), which inevitably increases the error term. To circumvent this challenge, this work relies on remotely sensed data from the GRACE to estimate the total water storage depletions and the depletion rates in Iran's provinces. The ratio of the total water storage depletion rates for each pair of neighboring provinces is given by

$$Q = \frac{R_{\mathrm{A}}}{R_{\mathrm{B}}} \text{ for } R_{\mathrm{A}} < R_{\mathrm{B}} \tag{2}$$

where Q is the potential conflict factor and R_{A} and R_{B} are the water depletion rates for provinces A and B, respectively. If Q is close to 1 (i.e., the two provinces have similar changes in water quantity), there is a less potential for the two provinces to experience conflicts over water. Thus, the potential water conflicts among countries, states, or provinces are determined by evaluating their Q values.

Overview of the IBWT projects in Iran

IBWTs are an example of unilaterally constructed water infrastructures which convey water from one basin to another. From the legal viewpoints, IBWTs can be complex, since riparian rights are seriously affected. The environmental impact of such projects is also another concern that must be taken into account. IBWT projects, however, in many instances, simply postpone water shortages and conflicts while the underlying problems remain unsolved (Hernández-Mora et al. 2014). Water scarcity within a basin can be mitigated through imports of external water from other basins. However, such water transfer may raise new conflicts between basins (Jain et al. 2007). Thus, IBWTs may be viewed as "threat multipliers" of water conflicts.

IBWT projects have a long history in Iran, where the first such project, proposed in 1619, involved water transfer from the Karoon region to the Zayande-Rud region. That project progressed very slowly due to various factors until the early 1900s. The project, named Koohrang-I, came into operation in 1953. Table 1 lists the most important IBWT projects in Iran, including the operational projects, as well as the projects under construction or in the reconnaissance or feasibility study phases. These IBWT facilities supply water to major cities in the arid areas of Central Iran. Transferring water from the Zayandeh-Rud River for Yazd and Kashan caused water shortage for the Isfahan farmers. The farmers attempted to block the project by destroying pipelines and conveyance structures (Bozorgmehr 2014). In this case, the IBWTs acted as threat multipliers by increasing the potential of water conflict in the central regions of Iran.

Analysis of water storage in Iran

The total water storage (TWS) in a region is the sum of surface water (streams, lakes, wetlands), groundwater, soil water (in the vadose zone), snow, and glaciers. It is difficult to obtain TWS from measurements due to spatial and temporal variations of water storage and the paucity of measurement stations in a region. TWS variations, on the other hand, can be estimated for a region with the water balance equation relating the change of TWS to precipitation, runoff, and

Table 1 Major IBWT projects in Iran (Abrishamchi and Tajrishi 2005)

Project	Source basin/region	Recipient basin/region	Length (km)	Volume (Mm^3/year)	Purpose	Status
Behesht abad	Chaharmahal and Bakhtiari	Isfahan, Yazd, Kerman	65	800	D, A	Halted
Tabriz	Miandoab	Tabriz	23	200	D	1999
Chaloos	Gilan	Mazandaran	111	280	A	UC
Cheshme-Langan	Dez	Zayandeh-Rood	15	200	D, I, A	2005
Zahedan	Hirmand	Zahedan	10	450	D	UC
Soleghan	Karoon	Rafsanjan	438	200	A	UI
Taleghan	Sefid-Rood	Tehran and Qazvin	180	150	D, A	UC
Ghomrood	Dez	Ghomrood	230	340	D	2011
Kashan	Zayandeh-Rood	Kashan	195	42	D	UC
Koohrang-I	Karoon	Zayandeh-Rood	2.8	300	D, I, A	1953
Koohrang-II	Karoon	Zayandeh-Rood	2.8	160	D, I, A	1965
Koohrang-III	Karoon	Zayandeh-Rood	23.4	260	D, I, A	UC
Lar	Haraz	Tehran	200	30	D	1964
Mazandaran	Mazandaran	Golestan	450	950	A	UI
Moharram	Karoon	Southern cities	744	182	D	UC
Halil Rood	Halil Rood	Kerman	95	75	D	UC
Yazd	Zayandeh-Rood	Yazd	335	90	D	1999

A agricultural, *D* drinking, *I* industrial, *UC* under construction, *UI* under investigation

evapotranspiration. In this manner, a general understanding of TWS trends for a region is possible provided the key water fluxes are measured or estimated accurately. Such measurements or estimates are not always available (Young and Woo 2004). Instead, this study relies on the GRACE satellite measurements of the Earth's gravitational field to estimate TWS variations in Iran's basins. The aim of analyzing TWS variations is to assess the sustainability of past and current uses of water resources.

GRACE satellite data

The GRACE mission consists of twin satellites launched in March 2002 to make precise monthly measurements of the Earth's gravitational field. The observed changes in the gravity field are directly proportional to the changes in mass near the surface of the Earth, which are caused by the changes in TWS. Variations of the Earth's gravity field are caused mainly by the redistribution of water. Therefore, GRACE-based estimates are provided as TWS at a monthly time scale. The TWS so estimated is equal to the sum of all water mass variations in the soil and on the continents (i.e., the sum of surface water, snow water equivalent, soil water, and groundwater; Chen et al. 2016).

The GRACE data represent the sum of all forms of water in the upper Earth's crust expressed as a depth of water in centimeters. In some cases, TWS changes may be due to large earthquakes, instead of the variations in the gravitational field. Such phenomena must be taken into account. Several studies have verified the accuracy of the GRACE satellite–derived measurements of TWS over large areas. For instance, the GRACE data have been applied to monitor hydrologic systems (Ramillien et al. 2008) and to determine evapotranspiration (Ramillien et al. 2006; Rodell et al. 2007). Swenson et al. (2006) compared the GRACE data with in situ measurements in Illinois, showing that the GRACE exhibited good correlation with the in situ measurements.

Overview of the water resources in Iran

Iran is located in an arid area of the Middle East with an area of 1,648,195 km^2 and a population of about 80 million. Iran is divided into 31 provinces, six main river basins, and 30 sub-basins. The main basins and provinces in Iran are shown in Fig. 1. Iran's climate is mainly arid and semi-arid, with a nationwide average annual precipitation of 250 mm (Afshar and Fahmi 2019),

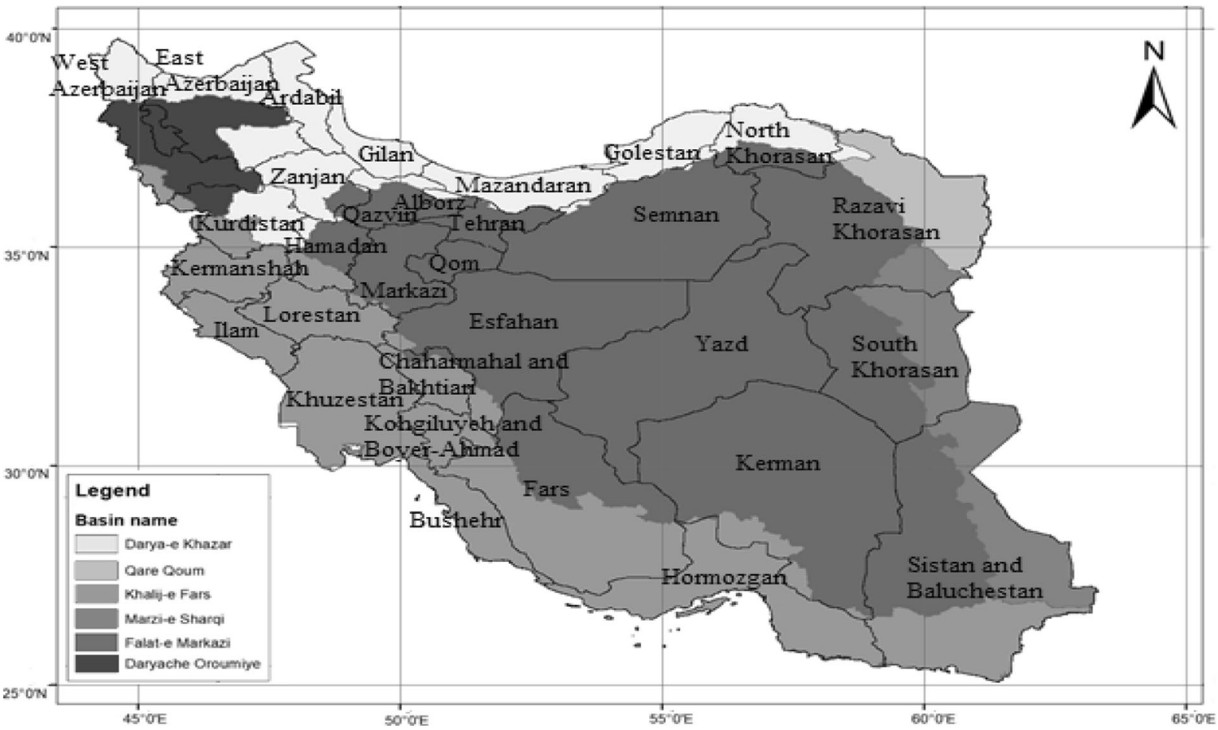


Fig. 1 Six main river basins and provinces of Iran

which is about one third of the world's average annual precipitation.

Iran's precipitation varies across its regions. Rasht, for instance, a provincial capital, has an average annual precipitation of 1360 mm, while Yazd, another provincial capital, has an average annual precipitation of 60 mm. In most regions of Iran, the average annual precipitation is less than 250 mm. Thus, water scarcity is a serious problem Iran must cope with. Falat-e-Markazi and Marzi-e-Sharqi are the driest basins in Iran, featuring an average annual precipitation of about 200 mm. Darya-e-Khazar, on the other hand, is the main basin with the highest average annual precipitation in Iran, which is about 420 mm. The recipients of the majority of the IBWT projects are the urban areas located in the Falat-e-Markazi and Marzi-e-Sharqi basins. The average annual precipitation values obtained from 48-year data (1968 through 2016) for all provinces are shown in Fig. 2.

Transferability index and conflict possibility

The inter-basin water transfer projects affect the water balances of the source and destination basins involved in water exchange. A transferability index is herein developed based on two parameters: conveyable water and population. Conveyable water determines the amount of water a province must either export or import (Table 2) in order for the country to achieve a balanced distribution of water resources. Conveyable water is not the only determinant of a basin's water balance concerning inter-basin water transfer projects because the population of each province and its water demands are also important factors to be considered. The larger the population of a province, the greater the amount of water needed to meet its demands. We propose a scoring system, whereby exporting of water from a province receives a negative score. The scoring is performed by means of a statistical sieve applied to the provinces producing their sorting based on the ratio of their relative populations to the total population of the country from high to low, and then assigned scores from 1 to 10 points. In addition, based on the values of the conveyable water parameter, the provinces were arranged in a decreasing order (i.e., from positive to negative). Note that a negative value means exporting water and a positive value means importing water. This parameter also scored from 1 to 10. These scoring results are shown in Fig. 3. Finally, by multiplying these scores, the transferability index (or overall score) for

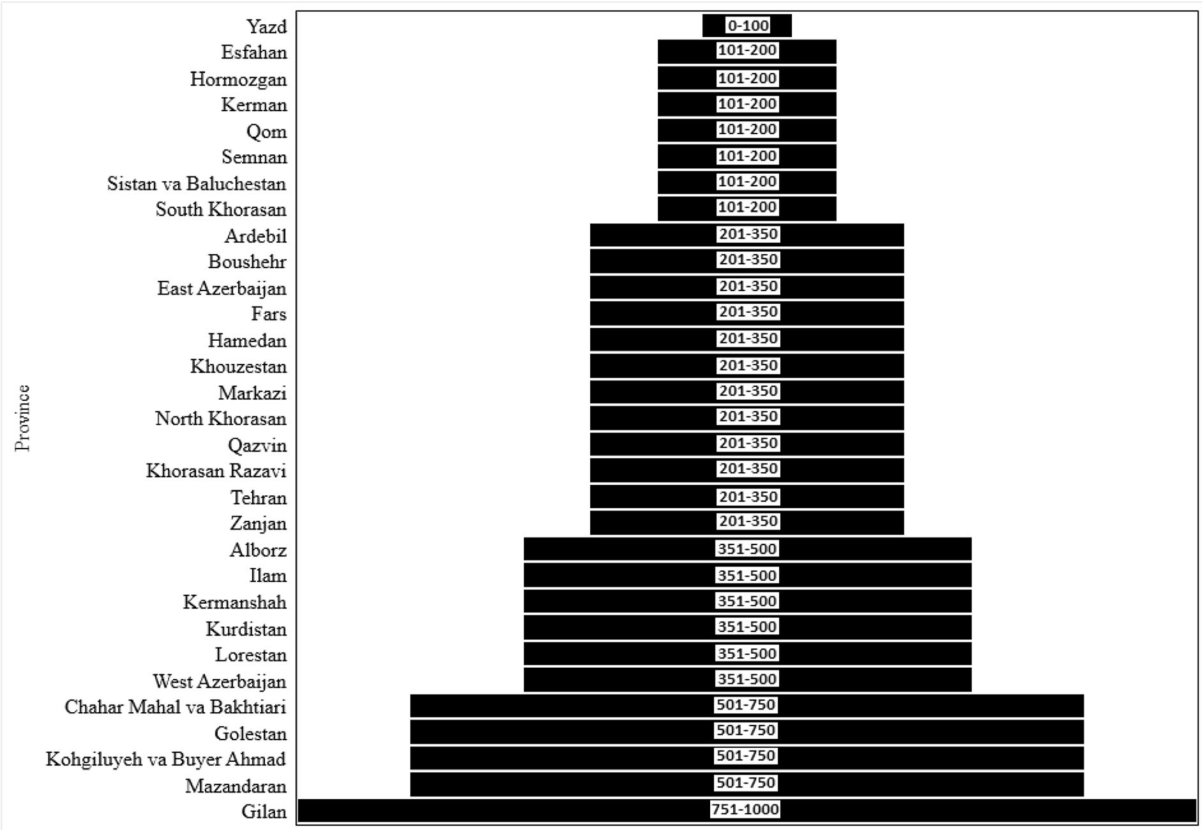


Fig. 2 Average annual precipitation (mm) of Iran's provinces

each province was calculated. It ranges from 1 to 10 (Fig. 4). An index equal to 1 indicates severe need for water, while a value of 10 indicates a high ability to export water. Comparing the transferability index values of the source and recipient basins or provinces produced a conflict possibility scored from 1 to 10 (Fig. 5). A conflict possibility equal to 1 indicates that there is a low possibility of conflict, and a value equal to 10 implies that there is a high possibility of conflict between the source and recipient basins.

Results and discussion

Prediction of potential of water conflicts between Iran's provinces

The monthly changes in the total available water were estimated for Iran's provinces in 2002–2016 with the GRACE data. The monthly grid average was calculated for each province, and the trend in water storage was analyzed. The annual total water storage depletion rate was obtained for each province. It is found from this study that there will be potential conflicts between the western and central provinces and also between the northern and northwestern provinces since their Q ratio values are less than 1. This is consistent with the history of water disputes and conflicts in these regions. Numerous conflicts associated with the water-sharing systems in Urmia (Zadl et al. 2012), Karkheh (Roozbahani et al.), Ghezel-Ozan (Madani et al. 2014), and Zayandeh-Rud (Mohajeri et al. 2016) occurred in recent years. These basins are all located in the central and western provinces in Iran. Potential future conflicts may be predicted by calculating the trend of the total water depletion. Note that the depletion rate was determined for each province by calculating the slope of the trend line, which is also employed for prediction of future conflicts. The potential of conflicts increases over time if the depletion rate persists because the change in water quantity increases.

Table 2 Water transfers by IBWTs

Province	Conveyable water (10^6 m^3/year)	TWS change (cm/year)
Alborz	37.7	− 1.6
Ardebil	202.1	− 1.6
Bushehr	− 119.6	− 1.7
Chahar Mahal va Bakhtiari	162.3	− 1.7
East Azerbaijan	− 74.0	− 1.0
Esfahan	102.3	− 0.3
Fars	− 191.1	− 1.7
Gilan	− 27.3	− 1.6
Golestan	74.4	− 1.6
Hamedan	254.8	− 1.6
Hormozgan	− 91.0	− 1.7
Ilam	6.9	− 1.7
Kerman	− 44.0	− 0.3
Kermanshah	323.6	− 1.7
Khouzestan	− 48.6	− 1.7
Kohgiluyeh va Buyer Ahmad	147.9	− 1.7
Kurdistan	153.1	− 1.6
Lorestan	309.6	− 1.7
Markazi	214.2	− 1.6
Mazandaran	− 227.6	− 1.6
North Khorasan	− 26.9	− 1.6
Qazvin	58.4	− 1.6
Qom	12.2	− 0.3
Khorasan Razavi	173.1	− 0.3
Semnan	181.0	− 0.3
Sistan va Baluchestan	− 207.9	− 0.3
South Khorasan	− 4.2	− 0.3
Tehran	− 82.8	− 1.6
West Azerbaijan	74.0	− 1.0
Yazd	− 21.5	− 0.3
Zanjan	− 33.7	− 1.6
–	–	–

minus = water export; plus = water import

Although there are many other factors that influence water conflicts, the change in water quantity is a main driver of the related calamity.

Impacts of IBWTs on Iran's basins and provinces

The monthly GRACE satellite–derived estimates of TWS from 2003 through 2007 were obtained for Iran. The average change in TWS over this 5-year period is the reference for comparing the TWS variations in other years. The difference between the TWS change in any year and the average TWS change in the reference period is referred to as water equivalent anomaly (WEA). A WEA map for Iran's basins is shown in Fig. 6, from which it can be observed that during 2002–2016, the Khalij-e-Fars and Daryaya-e-Omman main basins endured pronounced TWS depletions. Note that most water source areas for IBWT in Iran are located within these two basins.

The rate of TWS variation was calculated for three periods: 2002–2004 (first 3 years of GRACE operations), 2014–2016 (most recent 3 years of GRACE operations), and 2002–2016 (the entire duration of GRACE operation). The results corresponding to these three periods are shown in Figs. 7a and b and 8.

It is evident from Fig. 7a that the majority of Iran's provinces had a positive TWS change during 2002–2004, and only three provinces (Chahar Mahal va Bakhtiari, Kurdistan, and East Azerbaijan) had a negative change, which was less than 1 cm/year. The western provinces had a relatively positive TWS change. Kermanshah, Hamedan, Lorestan, Ilam, and Khouzestan provinces had a TWS change of + 2 cm/year. The central and eastern provinces, which are mostly located within the Falat-e-Markazi and Marzi-e-Sharqi basins, also had a positive change, which was less than 1 cm/year.

The situation of Iran's water resources during 2014 through 2016 was quite different. As shown in Fig. 7b , all of Iran's provinces endured a negative TWS change. Kermanshah, Lorestan, Hamedan, and Khouzestan provinces, which had a positive TWS change during 2002 through 2004, exhibited a negative change. Generally, the provinces located within the Khalij-e-Fars and Darya-e-Omman basins faced a TWS decline. These two basins received the largest depths of precipitation in Iran.

It is seen in Fig. 7b that the depletion of water resources in the western and northern provinces is more severe than that in the southern and eastern provinces, indicating that the northern and western provinces, which have more water than the eastern and southern provinces in Iran, have more significant depletion in their water resources than others. Thus, the inter-basin water transfers from the northern and western provinces could put a greater pressure on their water resources and consequently make it difficult for them to meet their needs.

The trend of the change of the TWS time series in Iran's provinces was calculated for Yazd and Kurdistan

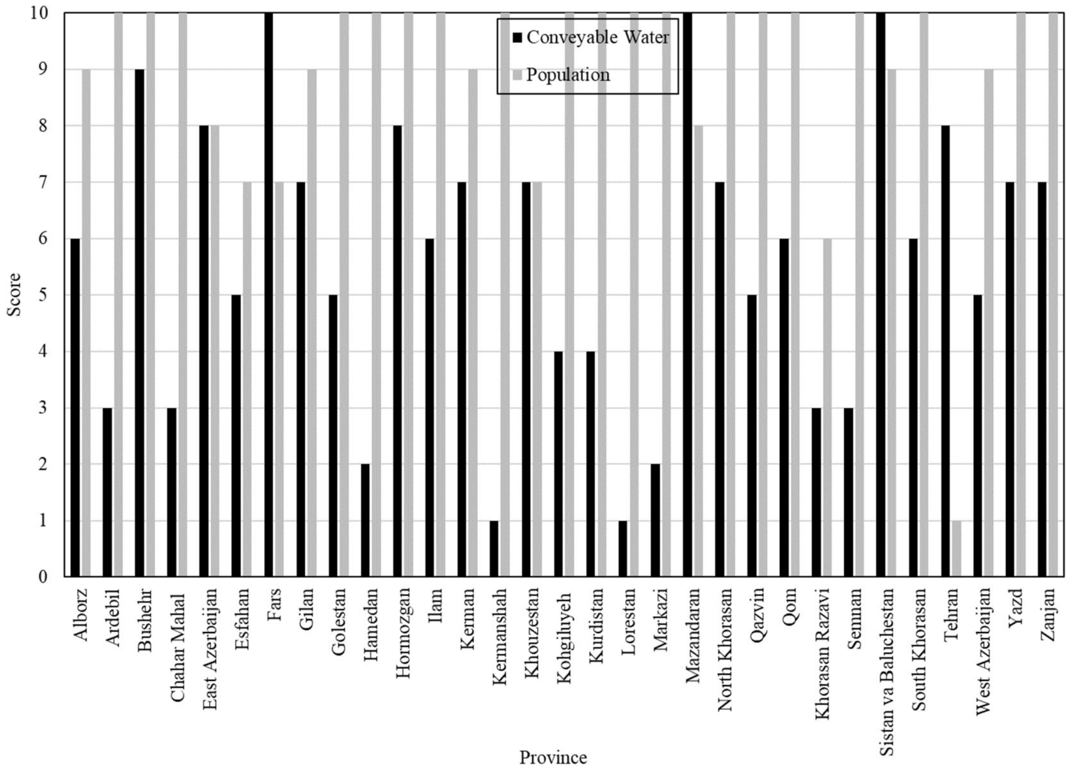
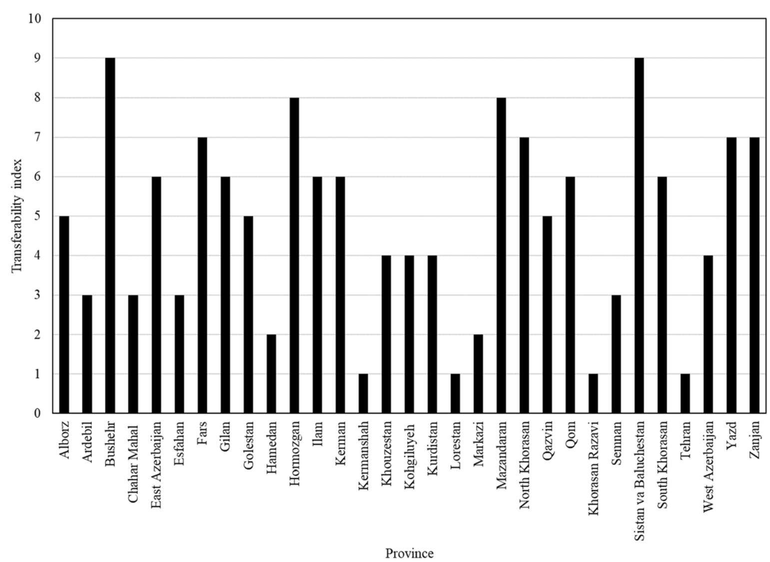


Fig. 3 Scores of conveyable water and population of Iran's provinces

provinces, which had the largest and smallest TWS changes, respectively. Figure 9 shows that Kurdistan, a region with plentiful precipitation, had a TWS change larger than that of Yazd province. This result demonstrates that this province is depleting its non-renewable water resources (such as deep groundwater resources). Yazd province has depleted almost all of its own water resources and is using the imported water. Therefore, the TWS change in Yazd is negligible and the slope of the trend is lower than that in Kurdistan and Iran as a whole.

Fig. 4 Transferability index values of Iran's provinces



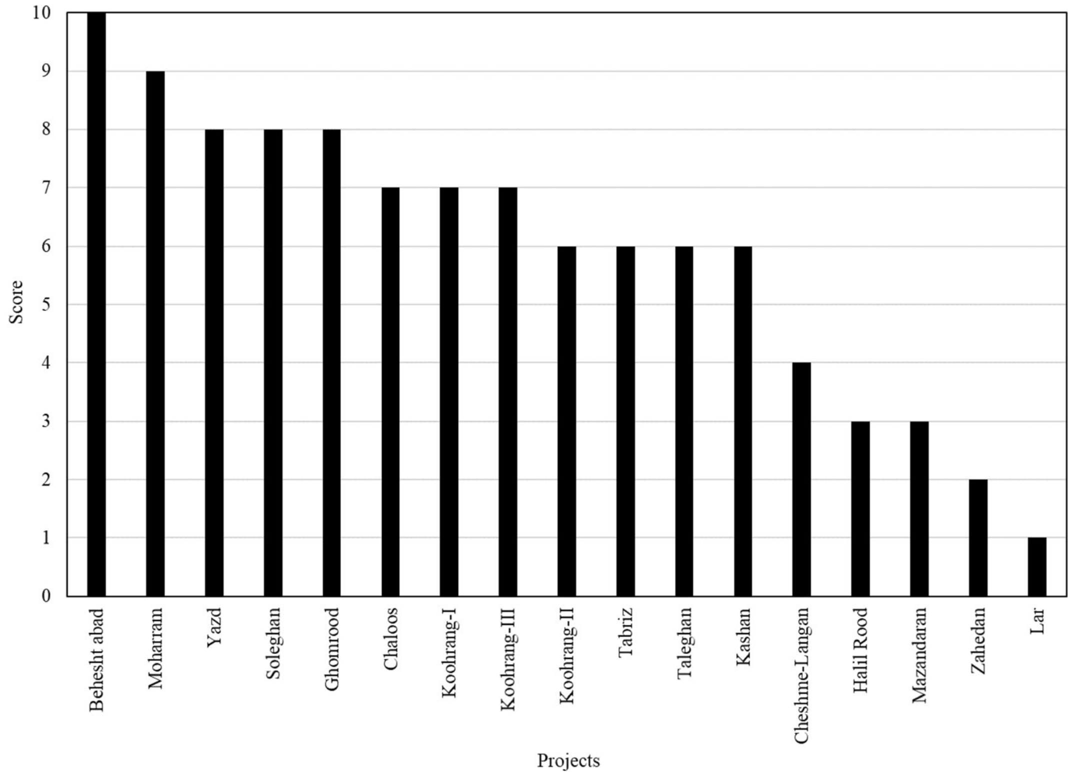


Fig. 5 Conflict possibility scores of Iran's IBWT projects

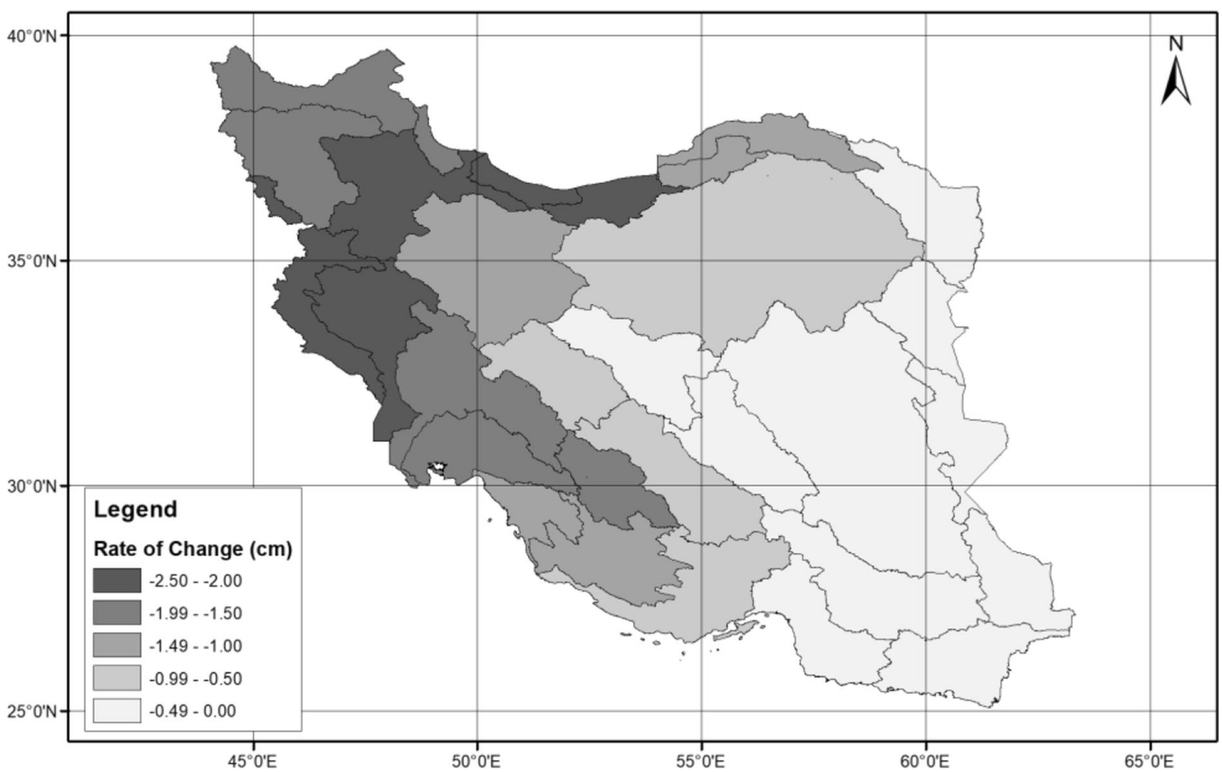
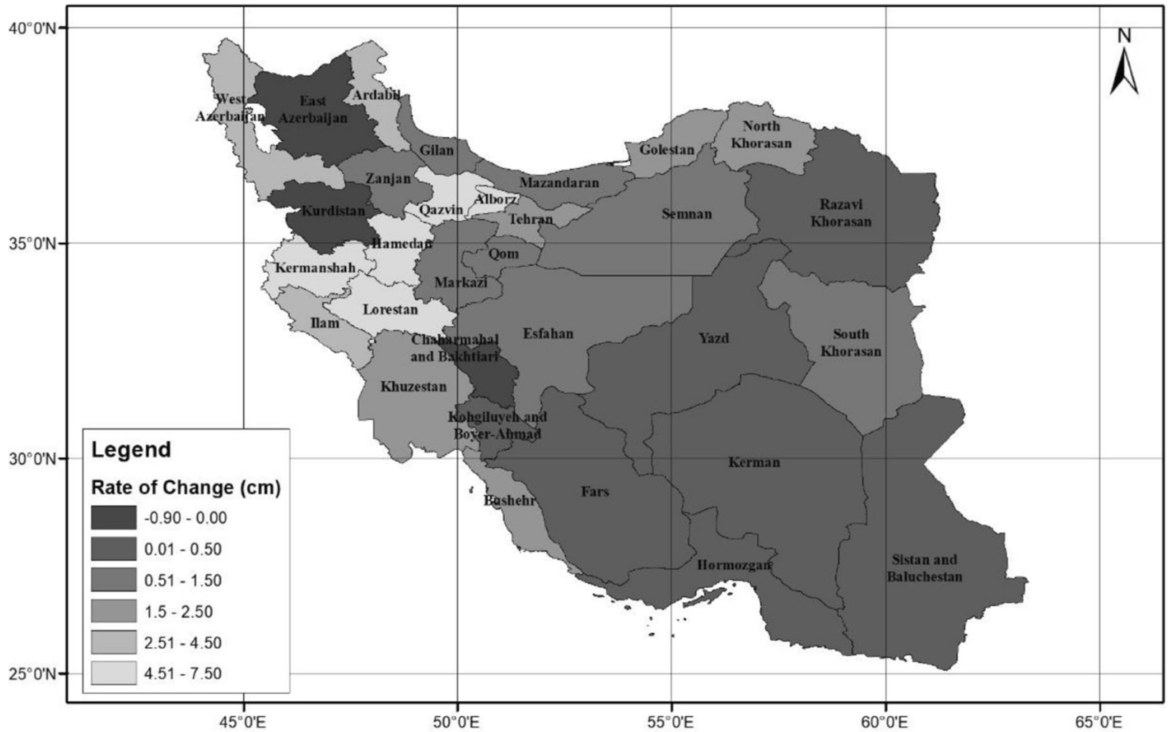
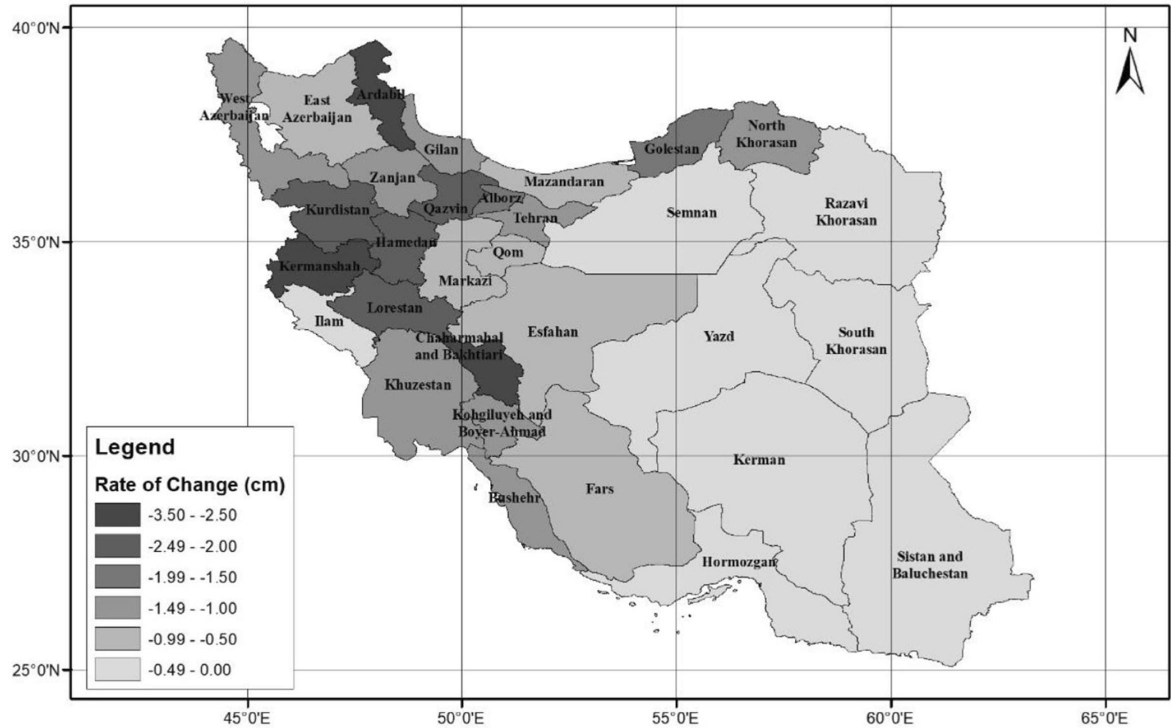


Fig. 6 TWS annual rate of changes in sub-basins of Iran



(a)



(b)

Fig. 7 TWS annual changes in Iran's provinces during **a** 2002–2004 and **b** 2014–2016

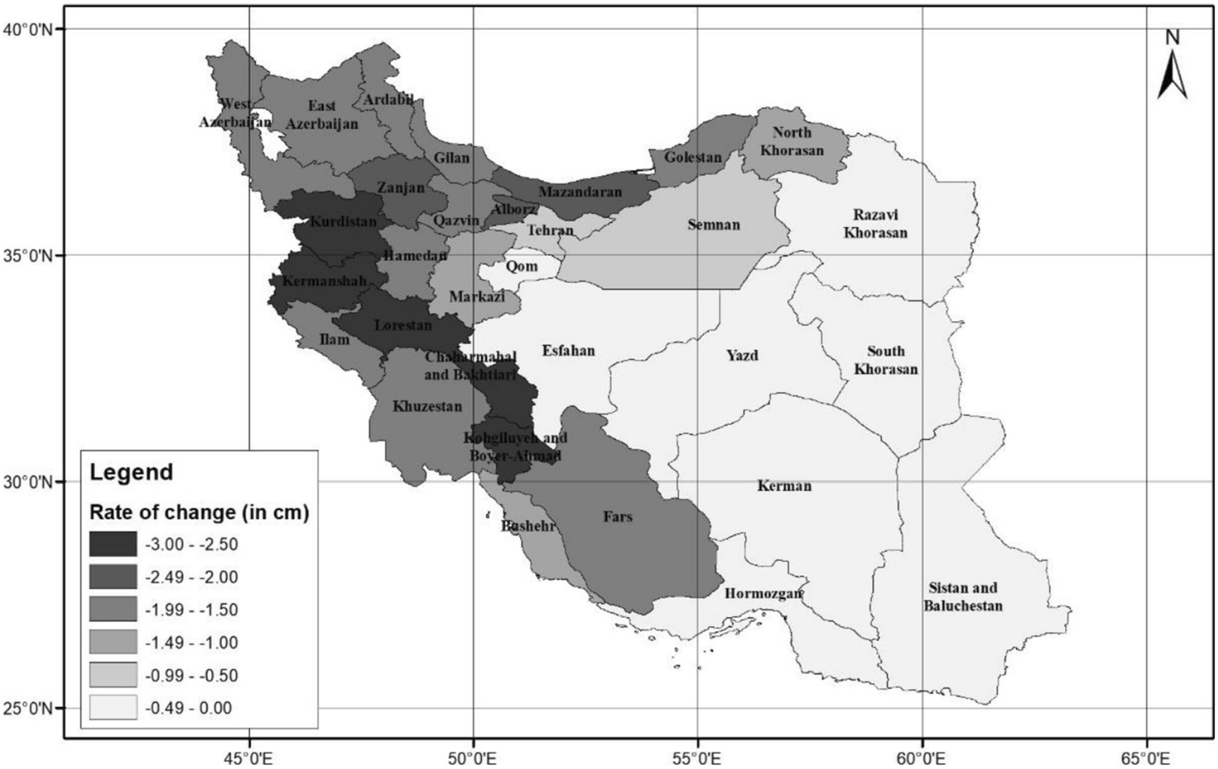


Fig. 8 TWS annual changes in Iran's provinces during 2002–2016

The TWS change time series for Iran was calculated by averaging all grids within the country, leading to a depletion rate of − 0.93 cm/year.

Sustainable water resources use in Iran's provinces

Sustainable use of resources implies their use meets the present and future needs. If Iran's provinces continue to increase their use of renewable water resources, they will begin to deplete non-renewable resources, such as deep groundwater that has a small recharge rate (Maliva and Missimer 2012). The decline of the TWS in Iran's provinces over long periods implies that the renewable water resources are being exploited beyond their rates of replenishment, and non-renewable resources are being mined until extinction. The year when a province begins the unsustainable use of its water resources was obtained by calculating and analyzing the TWS change time series. The results are shown in Fig. 10.

Suitable TWS changes with IBWTs

IBWTs modify the TWSs of the provinces that have geographical proximity. Table 2 shows the calculated water transfers (conveyable water) that would produce a balanced change in TWS across regions. A balanced change in TWS would minimize serious depletion of water storage in the provinces and would distribute water to achieve a relatively uniform and small TWS change across regions.

Transferability of provinces and possible conflicts in IBWT projects in Iran

According to Fig. 4, the transferability index values of Iran's provinces change from 1 to 9. Based on the population and conveyable water, some provinces such as Bushehr, Sistan, and Balouchestan have the highest transferability index values, and so they can export their excess water to the water-scarce regions, while other provinces such as Kermanshah and Khorasan Razavi must have imported water in order to meet their demands. Mazandaran and Hormozgan also have a high capability to be among the water-exporting provinces. The impact of population on transferability is obvious in Tehran. Despite its good score on conveyable water, this province was among those that need the imported water due to its large population (about 13 million).

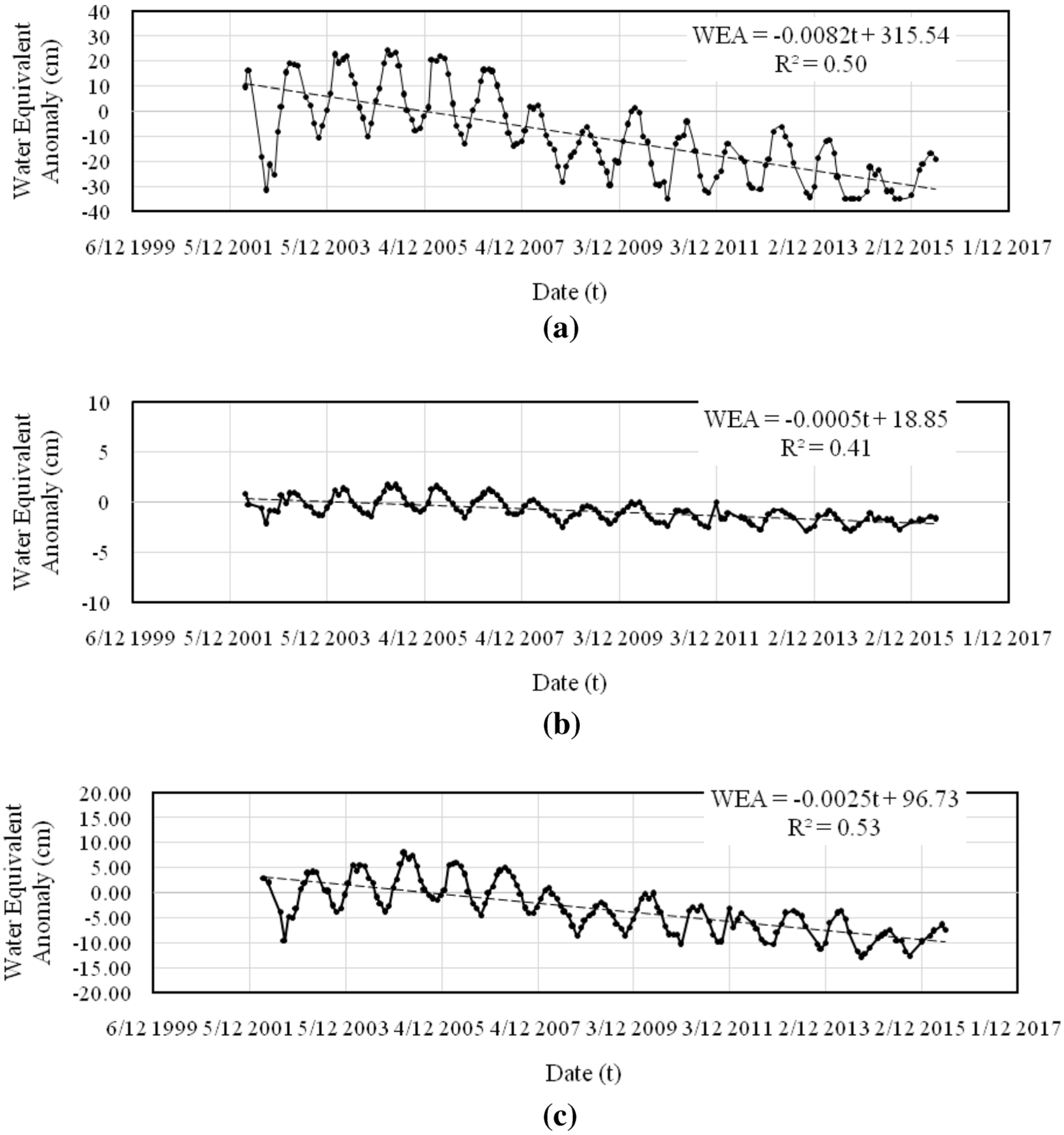


Fig. 9 Water equivalent anomaly time series for **a** Kurdistan, **b** Yazd, and **c** entire Iran

Eventually, most of the northern and western provinces in Iran, which usually had more water than other provinces such as Lorestan, Hamedan, and Golestan, did not get a high transferability index. This can be attributed to their high depletion of water and their large population. Consequently, for supplying their demands, they need to import water from the provinces with a higher transferability index. Thus, this transferability index helps quantify the possibility of conflicts between the source and recipient basins and provinces.

Figure 5 shows there is a high possibility of conflicts in the Beheshtabad inter-basin water transfer project. This is so because the source provinces are Chaharmahal and Bakhtiyari with a transferability index of 3, and the recipient provinces are Esfahan, Yazd, and Kerman with transferability index values of 3, 7, and 6, respectively. This means the source provinces of this project do not have a high transferability index even though the recipient provinces have good transferability index values. The Lar project, in contrast to the Beheshtabad project, has a low conflict possibility score because of its high transferable source region (Haraz in Mazandaran province) and its water-scarce recipient province (Tehran). The conflict possibility scores of the Iran's IBWT projects are shown in Fig. 5.

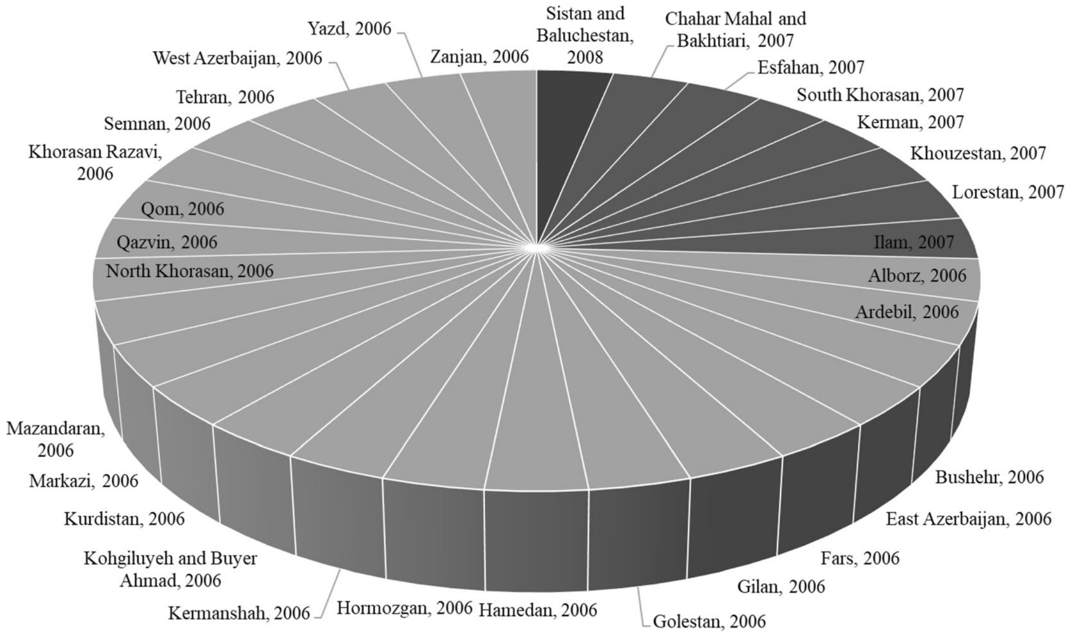


Fig. 10 Provinces and the years in which unsustainable water resources use began

Effects of IBWTs on Iran's water resources

A comparison was made between two IBWT scenarios. It was assumed in the first scenario that there was no IBWT project in Iran (notice that, in reality, several projects listed in Table 1 are in operation). Thus, the conveyed waters to the recipient basins were reallocated to the donor or source basins to evaluate the effects of the reallocation on water resources. In the second scenario, the operation of all the projects listed in Table 1 was assumed. The change in TWS was calculated under each of these two assumptions and the corresponding WEA maps were created and are shown in Fig. 11.

It is shown in Fig. 11a that if all the IBWTs were constructed, the depletion of water resources would shift from the central and eastern provinces to the western and northern ones. Under this scenario, the weighted standard deviation of the TWS changes in the provinces is equal to 2.82. Under the second scenario, the provinces would suffer depletion more equally (Fig. 11b), with a weighted standard deviation of the TWS changes being 0.60, which is much lower than that of the first scenario. Therefore, the first scenario implies that some provinces would benefit while others would have to cope with serious water resources depletion. The provinces would be in a dire situation under the second scenario, and they would have a nearly equal rate of TWS depletion.

Conclusion

Inter-Basin water transfer was assessed in this study as one of the solutions to balance the water distribution in Iran. IBWT can raise conflicts among regions, and therefore, assessing the potential of such conflicts is essential in assessing the worthiness of a IBWT project. For this purpose, by using the GRACE satellite data, the total water storages of all provinces in Iran were first computed. A new method was developed to determine the potential of water conflicts. The analyses of water conflicts for Iran's provinces indicated that the quantity of water was not the only reason for water conflicts. Hydro-political resiliency could also exacerbate the conflicts.

This study also demonstrated that the water resources in the northern, western, and southwestern provinces of Iran, mostly located within the Darya-e-Khazar, Khalij-e-Fars, and Darya-e-Omman main basins, were likely to endure future severe water resources depletion and face severe water shortages. The increased population and future water demand would threaten the Iran's water security. Many IBWT projects are currently operating in provinces such as Lorestan, Chahar Mahal va Bakhtiari, and Khouzestan, which are serving as donors. However, if water transfers continue, these projects would soon fail to meet their functions, and the related provinces may become water recipients of IBWTs.

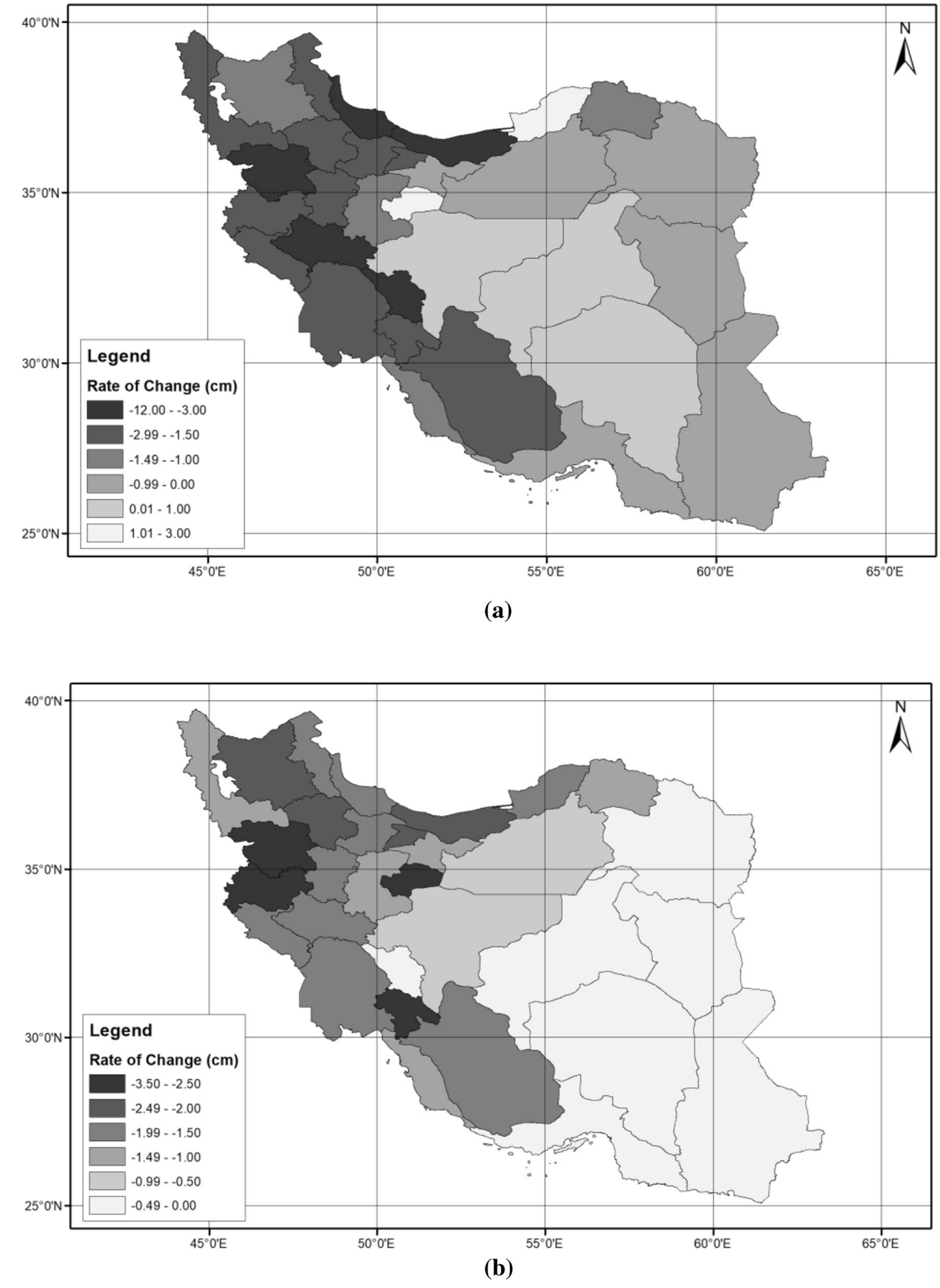


Fig. 11 TWS annual rates of changes in Iran's provinces if **a** all the IBWTs are built and **b** no IBWTs are built

The transferability index was herein introduced based on the conveyable water and population parameters to quantify the capacity of a province to export or import water. Results showed that provinces such as Bushehr, Sistan, and Balouchestan had relatively high transferability index values and they were capable of exporting water, while provinces such as Kermanshah and Khorasan Razavi had to import water for meeting their demands. The results for Tehran province highlighted the importance of considering the population parameter. This province has a high level of conveyable water, yet, due to its large population, its water transferability was at the lowest level. Therefore, Tehran is not in a favorable position to export water. Also, many provinces with plentiful water resources in the past, such as Golestan, Lorestan, and Hamedan, were among those that will have to import water due to their high populations and high water depletion rates. This study relied on the transferability index to calculate the possibilities of conflicts between the source and recipient regions in Iran's IBWT projects. It was found that some projects, such as Beheshtabad and Moharram, had a high conflict occurrence possibility, while the Lar project had a low possibility of water conflict because of its high transferable source region (Haraz) and water-scarce recipient province (Tehran).

Our analyses revealed that the IBWT projects in Iran with a delivery capacity of less than 500 Mm^3/year would be ineffective. Such IBWTs must undergo careful socioeconomic, environmental, and ecological assessments prior to development. Thus, it is necessary to consider other alternative management schemes of water supply in Iran, such as water desalination, water recycling, rain harvesting systems, conservation, and improved agricultural water systems prior to considering new large IBWT projects.

Another characteristic of the IBWTs in Iran is that most water-scarcity provinces are adjacent to other provinces that are currently suffering water shortage and drought. Therefore, increasingly larger and most distant IBWTs would be required to reach a balanced water distribution among the source and recipient provinces. This study demonstrated that these new IBWTs would be temporary solutions that ultimately would generate increasingly complex water scarcity problems.

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Compliance with ethical standards

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

References

Abdelmalik, K. W., & Abdelmohsen, K. (2019). GRACE and TRMM mission: the role of remote sensing techniques for monitoring spatio-temporal change in total water mass, Nile basin. *Journal of African Earth Sciences, 160*.

Abrishamchi, A. and Tajrishi, M. (2005). Interbasin water transfer in Iran. Paper presented at the Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop.

Afshar, N. R., & Fahmi, H. (2019). Impact of climate change on water resources in Iran. *International Journal of Energy and Water Resources, 3*(1), 55–60.

Bhattarai, M., Pant, D., & Molden, D. (2005). Socio-economics and hydrological impacts of melamchi intersectoral and interbasin water transfer project, Nepal. *Water Policy, 7*(2), 163–180.

Biancamaria, S., Mballo, M., Le Moigne, P., Pérez, JMS., Espitalier-Noël, G., Grusson, Y., Cakir, R., Häfliger, V., Barathieu, F., Trasmonte, M., Boone, A., Martin, E., and Sauvage, S. (2019). Total water storage variability from GRACE mission and hydrological models for a 50,000 km^2 temperate watershed: the Garonne River basin (France). Journal of Hydrology: Regional Studies, 24.

Bozorgmehr, N. (2014) Iran: dried out. https://www.ft.com/content/5a5579c6-0205-11e4-ab5b-00144feab7de.

Chen, J., Famigliett, J. S., Scanlon, B. R., & Rodell, M. (2016). Groundwater storage changes: present status from GRACE observations. *Surveys in Geophysics, 37*(2), 397–417.

Getches, D.H. (2005). Interbasin water transfers in the Western United States: issues and lessons. Paper presented at the Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop.

Hernández-Mora, N., del Moral Ituarte, L., La-Roca, F., La Calle, A. and Schmidt, G. (2014) in Globalized water 175–194, Springer.

Jain, S. K., Agarwal, P. K. and Singh, V. P. (2007) in Hydrology and water resources of India 1065–1109, Springer.

Jury, W. A. and Vaux, H. J. (2007) The emerging global water crisis: managing scarcity and conflict between water users. 95, 1–76, doi:https://doi.org/10.1016/s0065-2113(07)95001-4.

Kane, D. L. and Yang, D. (2004). Northern research basins water balance. International Association of Hydrological Sciences.

Karakaya, N., Evrendilek, F., & Gonenc, E. (2014). Interbasin water transfer practices in Turkey. *Journal of Ecosystem and Ecography, 4*(2).

Karamouz, M., Mojahedi, S. A., & Ahmadi, A. (2010). Interbasin water transfer: economic water quality-based model. *Journal of Irrigation and Drainage Engineering, 136*(2), 90–98.

Madani, K., Zarezadeh, M., & Morid, S. (2014). A new framework for resolving conflicts over transboundary rivers using

bankruptcy methods. *Hydrology and Earth System Sciences, 18*, 3055–3068. https://doi.org/10.5194/hess-18-3055-2014.
Maliva, R., & Missimer, T. (2012). *Non-renewable groundwater resources arid lands water evaluation and management*. Berlin: Springer Berlin Heidelberg.
Mohajeri, S. et al. (2016) in Integrated water resources management: concept, research and implementation. 603–627, Springer.
Petersen-Perlman, J. D. and Wolf, A. T. (2017) Water conflicts. The international encyclopedia of geography. 1–10, doi: https://doi.org/10.1002/9781118786352.wbieg0788.
Ramillien, G., Frappart, F., Güntner, A., Ngo-Duc, T., Cazenave, A., & Laval, K. (2006). Time variations of the regional evapotranspiration rate from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry. *Water Resources Research, 42*(10).
Ramillien, G., Famiglietti, J. S., & Wahr, J. (2008). Detection of continental hydrology and glaciology signals from GRACE: a review. *Surveys in Geophysics, 29*, 361–374. https://doi.org/10.1007/s10712-008-9048-9.
Rodell, M., Chen, J., Kato, H., Famiglietti, J. S., Nigro, J., & Wilson, C. R. (2007). Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal, 15*(1), 159–166.
Swenson, S., Yeh, P. J. F., Wahr, J., & Famiglietti, J. (2006). A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois. *Geophysical Research Letters, 33*(16).
Wolf, A. T., Stahl, K., & Macomber, M. F. (2003). Conflict and cooperation within international river basins: the importance of institutional capacity. *Water Resources Update, 125*, 31–40.
Young, K.L. and Woo, M.-K. (2004). Queen Elizabeth Islands: problems associated with water balance research. IAHS Publications-Series of Proceedings and Reports, 290, 237–248.
Zadl, S. O., Ravesteijn, W., Herrnans, L. and van Beek, E. (2012) Managing conflicts in water resources allocation: the case of Urumia Lake Basin, Iran. River Basin Management VII 172, 153.
Zhang, L., Li, S., Loáiciga, H. A., Zhuang, Y., & Du, Y. (2015). Opportunities and challenges of interbasin water transfers: a literature review with bibliometric analysis. *Scientometrics, 105*, 279–294. https://doi.org/10.1007/s11192-015-1656-9.
Zhou, Y., Guo, S., Hong, X., & Chang, F. (2017). Systematic impact assessment on inter-basin water transfer projects of the Hanjiang River basin in China. *Journal of Hydrology, 553*, 584–595.
Zhuang, W. (2016). Eco-environmental impact of inter-basin water transfer projects: a review. *Environmental Science and Pollution Research, 23*(13), 12867–12879.

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