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Abstract

This study examined changes in Iran's river flows by applying regression and analysis of variance methods to long-term ground-truth data. Evaluations were performed for the country's data-rich rivers, covering almost 97% of all rivers and including more than 35 years of measurements. The results showed that about 56% of Iran's rivers have experienced a negative trend in mean annual flow that is approximately 2.5 times greater than that reported for world's rivers, leading to a shift from perennial to intermittent for about 20% of rivers in Iran's sub-basins. This reflects surface freshwater shortages in Iran caused by natural and, more importantly, anthropogenic disturbances. It may even indicate the development of new hydrological regimes which can have significant implications for future surface water storage in Iran. This research improves understanding of changes in Iran's river flows and provides beneficial information for sustainable water resources management in the country.

Keywords: Anthropogenic disturbance; River discharge; Climate change; Iran.

Introduction

Iran's river flow regimes have experienced a number of extremes in spatiotemporal conditions, such as unprecedented flood and drought events, in the past few decades¹. For example, destructive floods occurred during winter and spring 2019, causing a national emergency to be announced in 40% of the country and resulting in 76 casualties. At the other extreme, a 50% reduction in precipitation in 2017 created a severe hydrological drought that negatively affected about 90% of Iran².

In recent decades, changes in Iran's river flows have been detected and have been attributed to climate change^{3,4} and, in particular, to extensive changes in land-use patterns and agricultural water use⁵⁻⁷. Water use patterns have changed as a result of large-scale dam

construction, with 647 dams currently in operation and 146 dams under construction⁸. Construction of an additional 537 dams across the country is planned. Therefore, Iran's river flows are now strongly regulated, with the aim of enhancing regional economies and securing national self-sufficiency in food production.

The severity and frequency of extreme flood and drought events are expected to increase as a consequence of climate variability and water and land-use changes in Iran, but the impacts are expected to be unequally distributed across the country⁹. Therefore, a good understanding of both the patterns and changes in Iran's river flow regimes is needed to mitigate the severe pressures on Iran's surface water resources and to help plan water management strategies, particularly with respect to hydropower production and water supply.

Some recent studies have investigated potential river flow trends in individual sub-basins in Iran^{4,10,11}. However, generalisation of findings from these studies to national scale is difficult, as the studies include regional differences and cover different periods. To our knowledge, trends in river flow at national scale in Iran remain largely unclear, despite good coverage of river flow at multiple monitoring stations. In order to address this knowledge gap, in the present study trends in Iran's river flows during recent decades were analysed. Knowledge of river flow changes is imperative, since surface water supplies around five billion cubic metres (km³) of water to around three million hectares of wetlands in Iran, meeting 44% of the water needs in urban areas and the agricultural sector and recharging up to 10 km³ of subsurface resources in Iran¹². The analysis was based on monthly streamflow measurements in all 30 sub-basins in Iran, obtained at 139 stream gauging stations that mostly have more than 35 years of records (Fig. 1). Spatiotemporal trend analyses were performed on monthly, seasonal and annual time scales, to determine past streamflow variations across the country. The overall aim of the study was to picture out changes in Iran's river flows for sustainable water resources management in Iran.

Figure 1: Location of the 139 selected hydrometric stations (orange triangles) in Iran, main land-use and sub-basins with population distribution across Iran.

Results and Discussion

Decline in annual discharge. Figure 2 shows mean, maximum and minimum annual stream flow, and indicates how their coefficient of variation (CV) varied across Iran (the greater the diameter of a circle, the higher value of the index). The south-western rivers flowing into the Persian Gulf and the western rivers flowing into the Caspian Sea were found to have the highest annual discharge among all the rivers in Iran. These regions include most of Iran's perennial rivers. Likewise, the lowest annual river discharge, equal to or near zero, was observed in the southern and eastern sub-basins, indicating the dominant location of intermittent rivers in the country. These intermittent rivers play an important role in human life and ecosystem sustainability by recharging aquifers and nourishing lakes, wetlands, marshes and dam reservoirs in the arid regions¹³. The lowest CV was observed for annual river flows in the Caspian Sea region, where a Mediterranean climate prevails. For example, stations 19051 and

18106 in this region had CV of 21% and 22%, respectively (Table S1). The highest values of CV, representing high internal variability, were found in the east, north-east and central parts of Iran, where the climate is classified as arid and semi-arid. Stations 41243 and 16079 in this region had CV of 586% and 254%, respectively (Table S1).

Figure 2: Mean, maximum and minimum annual stream flow, and coefficient of variation (CV) at the selected hydrometric stations across Iran. Increasing circle diameter indicates higher variability.

Figure 3 shows the trend obtained on analysing the stream flow data at annual scale. The result revealed negative trends for annual river discharge at 78 of the stream gauging stations investigated (56%), positive trends at 12 stations (9%) and null trends at 49 stations (35%) (p -value < 0.1). On global scale, around 22% of the world's rivers are reported to be

showing significant decreasing trends in annual discharge and 9% are showing increasing trends¹⁴. Thus, the number of rivers showing a decreasing trend in annual discharge is 2.5 times greater in Iran than in the rest of the world¹⁴. Although both natural and anthropogenic driving forces have led to the severe decline in Iran's surface water resources¹⁵, anthropogenic forces dominate¹⁶. According to the Deputy Director of Planning for Water and Water Resources at the Iranian Ministry of Energy, Hedayat Fahmi, by 2018 about 20% of Iran's perennial rivers, such as the Zayandeh-Rud and Simineh-Rud rivers, had transformed into intermittent (seasonal) rivers and most former seasonal rivers had dried up or become narrow streams. This is a result of Iran's unsustainable development plans, which aim to grow the economy, infrastructure and the agriculture sector, regardless of the country's renewable water and environment-ecosystem resilience^{12,16}.

In the present analysis, the greatest change in annual discharge was seen at station 21237 (+2.87 m³/s/yr) and the smallest change at station 21191 (-1.53 m³/s/yr) (Table S1). A decreasing trend in annual discharge was observed in rivers located in the central part of Iran, highlighting the overall decline in the streamflow availability in this region. Man-made impacts of development, such as extensive inter/trans-basin water diversion policies, are the main reason from the decline in river flows in central Iran¹². There was also a decreasing trend in annual discharge of rivers that are the main source of Iranian inland lakes (Lakes Urmia, Zarivar, Parishan, Shadegan, Namak, Bakhtegan, and Maharlu), all of which are suffering from a continuous decline in their water level^{9,17,18}. Therefore, our findings confirm that Iranian lakes/wetlands are drying up, which is an alarming finding for Iran's water resources authorities. The greatest negative change in annual discharge was observed in rivers located in the north-west, near the Caspian Sea, and in the south-west, near the Persian Gulf, which constitute the main stream flow into these water bodies (Fig. 3). This can add to environmental problems in these regions, as river waters play an important role in balancing water salinity

and transporting organic matter. This eco-hydraulic condition will reduce the amount of land-based nutrients in surface sediments of these water bodies and will affect the land-based component of aquatic zones¹⁹. Large dams and reservoirs impounded along perennial rivers have contributed dramatically to the negative change in annual discharge in these regions²⁰. Simultaneously, climate change impacts in terms of decreasing precipitation in western Iran²¹ have reduced annual discharge to the Caspian Sea and Persian Gulf^{4,22,23}.

Figure 3: Spatial map of annual river discharge trends. Triangles show stations with a statistically significant trend (p -value < 0.1), with blue and red triangles indicating increasing and decreasing rates, respectively, and triangle size indicating rate magnitude. Black rectangles represent stations with no significant trend (p -value ≥ 0.1).

Most eastern and south-eastern trans-boundary rivers were also found to show a negative trend in annual discharge (except for station 53013 – Table S1). In addition to climate change impacts, harnessing of rivers in neighbouring countries (Afghanistan) for agriculture and hydropower to enhance economic development is also influencing inflow from the trans-

boundary rivers to Iran, and this impact might even outstrip those of climate change in the region²⁴. The decline in annual discharge in the eastern and south-eastern trans-boundary rivers has reduced crop yields²⁵, increased inland migration²⁶, lowered the water level in Lake Hamun²⁷ and, more importantly, exacerbated international disputes between Iran and Afghanistan²⁸. In north-east Iran, which is one of the country's main agricultural hubs, a negative trend in river discharge has increased groundwater abstraction for agricultural development. This could be the reason for the high rate of groundwater loss in these areas reported by Ahmadi et al.²⁸. Future flow manipulation in the Harirud river in Afghanistan would add to the negative trend in annual discharge in north-east Iran. In north-west Iran (Lake Urmia and Aras sub-basins), all hydrometric stations investigated showed a negative or no trend in annual river discharge. According to a study by Ashraf et al.¹⁵, the Lake Urmia sub-basin has experienced the greatest rate of decline in water storage in Iran, an effect dominated by anthropogenic activities. Therefore, impacts of human interventions and climate change are contributing to severe negative trends in river discharge in these regions^{30,31}. In the west of the country, where the rivers mostly flow out of Iran (Fig. 4), a negative trend in river annual discharge was observed mainly due to river flow regulation, as the region has the highest concentration of dams in Iran. This can pose a threat to downstream terrestrial and aquatic ecosystems and exacerbate the small-scale storms caused by drying up of small wetlands in Iran and Iraq^{4,32}.

Projected change and variability in climate indices using climate models indicate a general decreasing trend in precipitation in Iran in the future^{9,15}. Anthropogenic impacts of development and policies to achieve national self-sufficiency in crop production to provide food for Iran's growing population by harnessing running waters would exacerbate the impacts of climate change on Iran's rivers⁵. Therefore, the increased pressures on Iran's water resources can be expected to continue or even accelerate in the future. Studies by Milly et al.³³ and

Haddeland et al.³⁴ found a decrease in projected runoff in the Middle East region, including Iran. Therefore, a shift toward sustainable water and land management is required to mitigate the negative effects of water shortages across Iran.

Figure 4: Iran's river network with information about surface inflows or outflows in trans-boundary rivers.

Decline in seasonal discharge. Figure 5 shows the results of trend analysis on river discharge in Iran on a seasonal time scale. The results revealed that the seasonal average river flow change in summer was $-0.02 \pm 0.12 \text{ m}^3/\text{s}/\text{yr}$. The highest rate of seasonal discharge in summer was observed at station 42009 ($0.64 \text{ m}^3/\text{s}/\text{yr}$) and the lowest at station 17041 ($-0.32 \text{ m}^3/\text{s}/\text{yr}$). Negative rates of river discharge in summer were observed at 60 stations (43%), positive rates at 10 stations (7%), and no significant change at 69 stations (50%). In autumn, positive trends were seen at 17 stations (12.2%) and negative trends at 52 stations (37.4%). The maximum,

minimum and mean rate of river discharge in autumn was 2.2 (station 21237), -0.6 (station 17043) and $0.001 \pm 0.29 \text{ m}^3/\text{s}/\text{yr}$, respectively. In winter, the calculations showed that the maximum, minimum and mean rate of river discharge was 4.9 (station 21237), -0.2 ± 0.9 and $-2.85 \text{ m}^3/\text{s}/\text{yr}$ (station 22023). In winter, 59 stations (42.4%) showed a significant decrease in river discharge and 12 stations (8.6%) showed an increase.

Figure 5: Spatial map of seasonal discharge trends in rivers in Iran. Triangles show stations with a statistically significant trend (p -value < 0.1), with blue and red triangles indicating increasing and decreasing rates, respectively, and triangle sizes indicating rate magnitude. Black rectangles represent stations with no significant trend (p -value ≥ 0.1).

Maximum, minimum and average rates of river flow in winter season are 4 (station 21237), -3.92 (station 21191), and $-0.33 \pm 0.92 \text{ m}^3/\text{s}/\text{yr}$, respectively. During the spring season, the negative and positive rates of river discharge are observed at 53.9% (75 stations) and 4.3%

(6 stations), respectively. The maximum decline in river's discharge in this season took place at the southwest and north of the country, where the climate change has had a profound effect on snowmelt and river discharge capacity³⁵. Maximum, minimum and mean rate of river flow in spring was 4 (station 21237), -3.92 (station 21191), and -0.33 ± 0.92 m³/s/yr, respectively. In spring, negative rates of river discharge were observed at 75 stations (53.9%) and positive rates at 6 stations (4.3%). The greatest decline in river discharge in spring was observed in the southwest and north of the country, where climate change has had a profound effect on snowmelt and river discharge capacity³⁵.

Based on the results, the highest number of stations with a significant positive trend and the lowest number with a significant negative trend occurred in autumn. This may be the result of a positive trend in autumn rainfall in Iran during the past few decades³⁶. More importantly, water needs for agricultural crops, and thus exploitation of surface water resources, are low in autumn. Increasing river discharge in autumn at regional/country scale has also been reported by Lins and Slack³⁷ and Birsan et al.³⁸. The greatest negative trend in river discharge was seen in spring. This is in line with previous findings for different regions of Iran, which show that rivers with snowmelt sources are experiencing a decreasing trend in spring discharge⁴, highlighting climate change impacts in terms of declining snowfall in the country³⁹.

Decline in monthly discharge. Figure 6 shows the results of trend analysis of river discharge on monthly scale. It was found that areas adjacent to the Caspian Sea had the largest number of stations with no significant trend in river discharge in all months. This is consistent with previous findings of a lower impact of climate change on water resources in this region⁴⁰. River flows at stations located in the Lake Urmia basin showed negative or no trends (except for Lighvan station (station 31019) in April, May and September), as a result of dam construction and excessive agriculture development in this area. A study by Hassanzadeh et al.³⁰ found that declining inflow contributed about 65% to the drop in lake volume and water level. Considering

the negligible share of groundwater feed to Lake Urmia (~3%)⁴¹, decreased streamflow would dramatically threaten the lake's ecosystem. In the south-east of Iran (e.g. station 53013), monthly river flow trends were negative or null. Decreasing access to fresh surface water resources has been identified as one of the main reasons for an increasing number of unauthorised wells and inland migration in these areas²⁷. The decrease in river discharge in north-east Iran in the cropping season has increased utilisation of groundwater resources, resulting in the greatest rate of drop in groundwater level in these months^{42,43}.

The number of stations with positive, negative or null trends, together with the rate of river discharge at these stations are given in [Table S1](#). The average rate of river discharge was negative in all months except December. The greatest rate of decline in average discharge was seen in April and May. The highest number of stations with a positive (negative) significant trend in river discharge was seen in September and the lowest in May. The highest number of stations with a negative significant trend in river discharge was seen in June and the lowest in December. The number of stations with no significant trend varied from 53 to 79 stations in different months of the year.

Figure 6: Spatial map of monthly river discharge trends. Triangles show stations with a statistically significant trend (p -value < 0.1), where blue and red triangles indicate increasing and decreasing rates, respectively, and triangle size indicates rate magnitude. Black rectangles represent stations with no significant trend (p -value ≥ 0.1).

Conclusions

Increasing demand for water to secure food and water for Iran's rapidly growing population and extreme climate conditions have placed severe pressures on the availability of surface

water resources in the country. This study investigated changes in river flow in Iran over time and space. The results showed that rivers located in regions with a Mediterranean climate (mainly the Caspian Sea basin) had the lowest variations in inter-annual discharge, while rivers in regions with an arid climate (east and central parts) showed the highest variations. On an annual time scale, around 56% of the 139 hydrometric stations studied showed a decreasing trend in river discharge, with the proportion indicating a decline being 2.5 times the global average (about 22%). Such declines in Iran's river flows pose serious threats to the country's water and food security and its environmental sustainability. In addition, severe declines in river flows and shifts from perennial to intermittent rivers in some sub-basins of Iran may indicate the development of new hydrological regimes, with significant implications for future surface water storage. Considering the general decreasing trend in future precipitation projected for Iran by climate models and the country's ambitious development plans, regardless of renewable water resources, the pressures on Iran's water resources are expected to continue or even increase in the future. Therefore, prompt action should be taken to mitigate the impacts of natural and man-made driving forces on the country's water resources sector.

Methods

Study area and data. The study area covered all of Iran's territory. Iran is located in the world's dry belt, with mean annual precipitation of around 250 mm, which is less than one-third of the global average. The overall morphology of the country in western and northern parts consists of numerous mountains, while eastern and central parts consist of low and uniform terrain. The presence of the mountains has led to the formation of diverse climates, so that Iran experiences both an arid climate (east region) and a Mediterranean climate (coast of the Caspian Sea at the north) at the same time of year. These physical conditions have led to an unequal distribution of rainfall in the country, whereby around 70% of Iran's surface area receives only about 31% of total rainfall ([Fig. S1](#)). Annual potential evaporation ranges from 500 mm in the north-west

to 3750 mm in southern basins of the country. Mean annual temperature varies between 0 °C in the north and 28 °C in the south of the country. Mean annual rainfall varies from 50 mm in the centre and east to 1800 mm in the northern regions of Iran (Fig. S2). Mean annual runoff in Iran is about 400 km³, with 270 and 130 km³ of evapotranspiration and renewable water capacity, respectively⁴⁴.

During the last decades, surface water resource planning and management in Iran has been based on political rather than hydrological units. In hydrological terms, the country contains six primary water basins and 30 secondary basins or sub-basins (Fig. S3), equipped with more than 1730 active gauging stations. Iran's water resources monitoring network is stronger than that in other countries in the Middle East. The first hydrometric stations in Iran were established in the 1940s, in the vicinity of the capital city of Tehran and in the south-west of the country. Currently, around 20% of all stations have a service life of more than 40 years (Fig. S4). Approximately 22% of Iran's border with neighbouring countries is made up of 26 major rivers, through which part of surface runoff enters or leaves the country (Fig. 4).

As mentioned, monthly river flow measurements were used in this study. Stream flow data from 1731 stations were obtained from Iran Water Resources Management Company and filtered based on the quantity and quality of measurements. Finally, 139 data-rich hydrometric stations with proven data quality, located in 30 sub-basins across the country, were selected for further analysis. Figure 1 shows the distribution of these 139 hydrometric stations in Iran, while they are listed and their statistical characteristics are presented in Table S2. It is worth mentioning that perennial rivers in Iran are mostly located in the north and west, while intermittent rivers and streams are mostly located in central and eastern parts.

Trend analysis. The trend analysis methodology used in the present study is illustrated in Fig. S5. Linear regression analysis followed by analysis of variance (ANOVA), as suggested by Pinhas et al.⁴⁵, was used to determine trends in river flow, rate of variation and its significance.

The methodology has the advantage of simplicity, while providing the necessary information in terms of slope and variability, making it useful in practice.

To apply this methodology, a code was first assigned to each station and a number to each sub-basin. The entire dataset was then categorised using the Pivot Table in Microsoft Excel software, based on the assigned codes and sub-basin numbers. Linear regression and ANOVA F -test were performed using the analysis Tool Pak in Microsoft Excel. The null hypothesis in this approach is that all coefficients of each estimated regression are equal to zero. Therefore, rejection of the null hypothesis means that the coefficients are not equal to zero, i.e. the estimated regressions are meaningful. This happens when the estimated significance level for the F -statistics < 0.1 (90% confidence level).

Thereafter, river flow time series at each hydrometric station were analysed at monthly, seasonal and annual timescale. Finally, the Xlstat add-in solution was used to prepare classification and regression trees of river discharge change across the sub-basins. Note that no data reconstruction was performed in this study and all analyses were performed on the statistical period of the hydrometric stations. More details about the methods used can be found in Pinhas et al.⁴⁵.

Data availability

The data used in this are publicly available via Data Archive of the Iran Water Resources Management Company <http://wrs.wrm.ir/amar/login.asp>.

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450 **Conflict of interest**

451 The authors declare no conflicts of interest.

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