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Technical Note

Development of an Urban Water Scarcity Index (Case Study: Tehran City)

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Abstract

In this study, the Urban Water Scarcity Index (UWSI), a hydrology-demography based-index, was developed to assess the intensity of water scarcity in urban areas. The UWSI index is presented to show the difference between hydrological drought (in terms of standardized streamflow index) and the water-crowding index. For the application of the developed index, the city of Tehran was considered as a case study in which about 72% of the domestic water demands are supplied from the surface water sources in the surrounding catchments. The time series of the monthly data of surface water flow entering five reservoirs around Tehran during a period of 21 years (1998-2018) and the annual changes in Tehran's population were the input data to this study. The results showed that the annual value of the UWSI index in the three time periods of 1998-2007, 2007-2009, and 2009-2018 has negative, nearly zero, and positive values, respectively. During the first period, hydrological drought dominated the water stress in Tehran. But in the third period, the water stress is much higher than hydrological drought. The positive trend of UWSI during the recent decade reveals that water stress threatens the sustainability in providing the city's water needs. Therefore, strict strategies are needed to manage and overcome the water shortage. The UWSI index developed in this study incorporates both blue water resources (i.e., the river flows) and population size for Tehran city and can be served as an initial water scarcity assessment tool in other urban areas.

Keywords: Water Scarcity Index, Sustainability of Water Resources, Hydrological Drought, Streamflow, Tehran's Water Demand, Population Growth.

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توسعه یک شاخص کمبود آب شهری (مطالعه موردی: شهر تهران)

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چکیده

در این مطالعه، شاخص درک کمبود آب شهری (UWSPI) به منظور پایش شدت کمبود آب در مناطق شهری که در آب‌های سطحی منبع غالب تأمین نیاز آب خانگی است، توسعه داده شده است. شاخص UWSPI که می‌توان شکل اصلاح شده شاخص فالکن‌مارک درنظر گرفت، برای نشان دادن تفاوت بین خشکسالی هیدرولوژیکی و خشکسالی که جامعه به دلیل کمبود سرانه آب شرب در طول زمان درک می‌کند، ارائه شده است. برای اعمال شاخص توسعه یافته، شهر تهران که منبع مهم تأمین نیاز خانوارهای خود را از منابع آب سطحی حوضه‌های آبریز اطراف (حدود ۷۲ درصد) تأمین می‌کند، به عنوان مطالعه موردی درنظر گرفته شد. سری‌های زمانی داده‌های ماهانه جریان آب‌های سطحی ورودی به پنج مخزن اطراف شهر تهران در بازه زمانی ۲۱ ساله (۱۳۷۷-۱۳۹۷) و مقدار جمعیت سالانه شهر تهران به‌عنوان داده‌های اولیه انتخاب شدند. نتایج نشان داد که مقادیر سالانه شاخص UWSPIدر سه دوره زمانی ۲۰۰۷-۱۹۹۸، ۲۰۰۹-۲۰۰۷ و ۲۰۱۸-۲۰۰۹ به ترتیب دارای مقادیر منفی، نزدیک به صفر و مثبت است. در دوره اول (UWSPI>0)، خشکسالی هیدرولوژیکی حاکم است و درک شهروندان شهر تهران از کمبود آب کم است. اما در دوره سوم که UWSPI<0 است، درک جامعه از کمبود آب بسیار بیشتر از خشکسالی هیدرولوژیکی است. این بدان معناست که خشکسالی هیدرولوژیکی پایداری تأمین آب مورد نیاز شهر را تهدید می‌کند. بنابراین برای مدیریت خشکسالی نیاز به راهکارهای سختگیرانه است. همچنین، نتایج نشان داد که علیرغم عدم تغییر در حجم ورودی به سدها، رشد سریع جمعیت تهران عامل اصلی درک کمبود آب در دوره اخیر بوده است.

کلمات کلیدی: شاخص کمبود آب، پایداری منابع آب، خشکسالی هیدرولوژیکی، نیاز آبی تهران، رشد جمعیت.

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بحث و مناظره (Discussion) در مورد این مقاله تا پایان تابستان ۱۴۰۲ امکانپذیر است.

1. Introduction

Rapid urbanization, industrialization, and socioeconomic growth increase the demand for water resources (Dai et al., 2019). In urban areas, there is usually more water stress on the surrounding environment of the city (due to the transfer of water from adjacent basins) than on the geographical area of the city itself (Veldkamp et al., 2015). The inter-basin water transfer restricts and challenges the sustainability of water resources in the long term and therefore, increases the water footprint (Fan et al., 2017; Hosseini et al., 2019). Water scarcity in urban areas where there is an imbalance between available water and water demand is a global challenge and a major limitation to socio-economic development (Li et al., 2020). During the years 1950 to 2020, the world's population living in cities has increased from 0.8 billion (29.6%) to 4.4 billion (56.2%) and it is predicted to reach 6.7 billion (68.4%) by 2050 (UN, 2015). Globally, 933 million (32.5%) urban population was living in water-scarce areas in 2016, of which respectively 359 million (12.5%) and 573 million (20.0%) were facing permanent and seasonal water-deficits. Lack of water in urban areas directly affects the health and welfare of urban residents as well as the quality of the urban environment (He et al., 2021). Understanding water scarcity in urban areas is crucial for formulating policies at different scales (Nguyen et al., 2019). Since the late 1980s many indices have been developed across the globe to simplify the water scarcity assessment.

The Falkenmark indicator (Falkenmark and Lindh, 1976) is perhaps the most widely used measure of water stress. It is defined as the fraction of the total annual runoff available for human use. This indicator assesses the blue water scarcity index with two indicators; water shortage and water stress. It needs the number of people living in a geographical area and the volume of renewable freshwater available within the study area. McNally et al. (2019) used the modified version of Falenmark's water scarcity index as the ratio of surface water flow to the population for the period of 1990-2015 on a monthly scale and in Africa. The ratio of Allocated Water to water availability ratio developed by Alcamo and Henrichs (2002) is another widely used index to assess the water scarcity status. In terms of incorporated indicators in developing water scarcity index, Chang and Kleopa (1991) used a comprehensive study on the effective hydrologic indicators. They used streamflow, precipitation, groundwater, temperature, and lake elevation to monitor the severity of drought in central Ohio region.

Despite the extensive research on the development of water scarcity indices at watershed to regional scales, such as the basic human water needs index (Gleick, 1996), social water stress index (Ohlsson and Appelgren, 1998), Water Crowding Index (Gosling and Arnel, 2013), Water Poverty Index (Sullivan et al., 2006), blue-green water scarcity indices (Gerten et al., 2011), and water scarcity based on water footprint (e.g., Hoekstra et al., 2016), the need to develop an index that consider the relationship between water supply, population and water demand is yet sensed aiming at a deep understanding of the dynamics of water shortage in urban areas. In this study, a socio-hydrological index entitled "Urban Water Scarcity Index" was developed for assessing the water shortage in Tehran city. The temporal variation in the population of the city has been used as the proxy variable to incorporate the amount of water demand. Also, the standardized amount of the river inflows to the five dams that supply ~72% of water to the city (i.e., Taleqan, Amirkabir (Karaj), Lar, Latian, and Mamlou) have been used to address the hydrological aspect of the desired index.

2. Materials and Methods

2.1. Urban Water Scarcity Index (UWSI)

Urban Water Scarcity Index (UWSI) is defined as the difference between the standardized streamflow (or hydrological) index and the water crowding index:

$$\mathrm{UWSI_i = SSI_i - SSC_i} \quad (1)$$

$$\mathrm{SSI_i = \frac{SF_i - SF_{avg}}{SF_{sd}}} \quad (2)$$

$$\mathrm{SSC_i = \frac{SC_i - SC_{avg}}{SC_{sd}}} \quad (3)$$

$$\mathrm{SC_i = \frac{SF_i}{Pop_i}} \quad (4)$$

i= 1, 2, …, N

where SSI_i is the standardized streamflow index in period i; SF_i is streamflow volume in period i, SF_{avg} and SF_{sd} are respectively the mean and standard deviation of streamflow volume data; SSC_i is the standardized streamflow volume (SF_i) per capita (Pop_i) in period i; and N is the number of data in time-series. SC_i also also called the water crowding index or Falkenmark's water stress in the literature depends on population size and available water resources (i.e., streamflow) and indicates temporal variation. The use of the average and standard deviation of SC_i in Eq. 3 is for easy calculations.

The negative values of UWSI (SSI<SSC) mean that hydrological (i.e., streamflow) stress prevails and the water stress in the city is not significant and there is still enough water to consume and meet the demands with high reliability (i.e., SF/Pop is high). In such situations, it is possible to overcome the period of water stress by

implementing some strategies (for example, saving water by citizens). A positive UWSI value (SSI>SSC) indicates that the water stress is much greater than hydrological drought (i.e., SF/Pop is small). This means that the water stress threatens the sustainability of the community's water supply to one extent or another. As UWSI moves towards more positive values, the water scarcity is expected to occur shortly after a hydrological drought. Therefore, for more effective management of water shortage in the city, severe strategies are required. A value of UWSI close to zero in a period indicates the threshold of water scarcity in that period. The UWSI can be used on seasonal to annual time scales based on the data availability.

2.2. RAPS Index

To highlight the long-term trend in the time series of Tehran's population and the inflow to reservoirs, the rescaled adjusted partial sums ($RAPS$) introduced by Garbrecht and Fernandez (1994) was used as follows:

$$\mathrm{RAPS_X(k)} = \sum_{t=1}^{k\leq N} \frac{X_i - \bar{X}}{S_X} \quad (5)$$

where X is the considered variable (population or streamflow), k is the counter limit of the current summation, and $\bar{X}$ and S_X are the average and the standard deviation of the data, respectively. Any decreasing (increasing) trend in the *RAPS* is the result of below-average (above-average) values of X (Geravand et al., 2022).

2.3. Study Area and Dataset

Currently, the domestic water need of Tehran is 1.25 to 1.50 MCM/day (~450-550 MCM/year) and about 72% of the demand for domestic use is supplied from the surface water stored behind the five reservoirs of Taleqan, Amirkabir (Karaj), Lar, Latian, and Mamlou (Tehran Province Water and Wastewater Co., 2021). Figure 1 shows the location of the five reservoirs and the location of the hydrometric stations in the catchment of the reservoirs. Though the five dams have been put into operation at different times (Mamlou in 2006, Taleqan in 2006, Lar in 1982, Latian in 1967, and Karaj in 1961), the study period in this study was considered as 1999-2018. The streamflow data of Taleqan and Mamlou were entered into the analysis from their operation dates. This issue does not create a problem for calculating the index and performing the analysis because the index is needed for the streamflow entering the reservoirs, which participate in providing the drinking water of Tehran. Before, the construction of the Taleqan and Mamlou dams, no flow was transferred from these rivers to Tehran's City. Except for Mamlou and Latian catchments, no residential area are located upstream the reservoirs.

The trend of the annual population of Tehran city and the percentage of its annual changes during the period of 1950-2035 published by the United Nations (UN) are shown in Fig. 2. In 2022, the population of Tehran is about 9.4 million people and the annual population increase rate is about 1.35%. According to the UN projection, by 2035, the population of Tehran will be 10.7 million and the rate of annual change will be below 1.0% (https://population.un.org/wpp/).

The trend analysis of time series of monthly inflow to the five studied reservoirs from 1998 to 2018 indicated a positive slope. The trend slopes ranged from 0.0001 million cubic meters per month for Letian and Mamlo reservoirs (or 100 cubic meters per month) to 0.0007 million cubic meters per month for Karaj Dam (or 700 cubic meters per month). Even though the inflows to the reservoirs which supply the water demands of Tehran do not show a decreasing trend, the slope of population growth changes and therefore the demand for water are considerable according to Fig. 2.

The long-term average values of monthly inflow to the studied reservoirs are shown in Fig. 3a. The highest and lowest inflow to the reservoirs occur in the months of April-May and September, respectively. The higher volume of inflow to Lar and Karaj dams (Amir Kabir) during the spring and summer seasons indicates the predominance of runoff generated by snow melting in the upstream basins of these reservoirs. The average annual inflow to Taleghan, Lar, Karaj (Amir Kabir), Letian, and Mamlo reservoirs during the period of 1998-2018 is 355.1, 353.6, 371.8, 223.7, and 39.0 million cubic meters, respectively. The long-term flow duration curves for the five studied reservoirs are shown in Fig. 3b.

To quantify the contribution of baseflow to the streamflow of the studies reservoirs, the ratio Q_{90}/Q_{50} was calculated from the flow duration curves shown in Fig. 3b. The Q_{90}/Q_{50} ratios were calculated as 0.16 (Lar), 0.29 (Mamlou), 0.26 (Latian), 0.32 (Karaj), and 0.22 (Taleqan). This indicates that the baseflow contribution to the Karaj and Lar rivers is relatively higher and lower than that of other rivers.

Dependency of Tehran's water demands on surface water, and the immigration issue which resulted in a high population growth in this metropolis, bring up a high concern for supplying the water demands of this city as hydrological drought occurs in the catchment area upstream of these reservoirs. In addition, climate change is effective as an additional factor in reducing the river streamflows which end to the reservoirs. Therefore, monitoring and quantifying the hydrological drought of the reservoir catchments as well as the metropolis's demographic changes over time can help the sustainable management of surface water resources supplying the water demands of Tehran city.

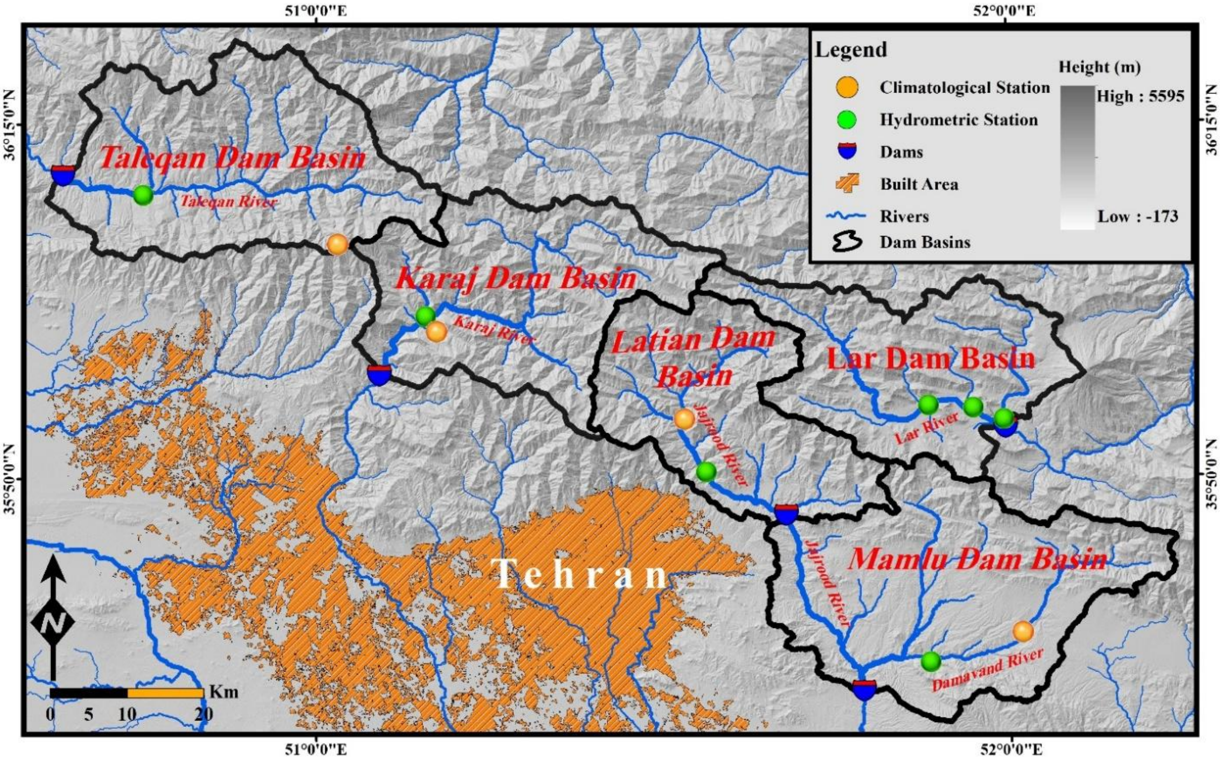

Fig. 1- Location of the five reservoirs and their upstream catchments that supplying the main part of Tehran's domestic water demands

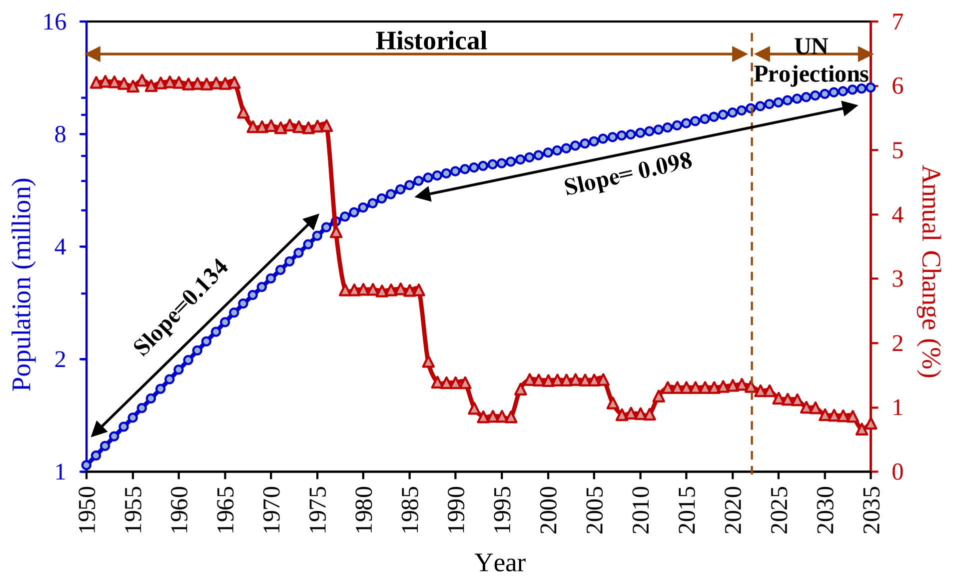

Fig. 2- Trends of Tehran population size and annual change during 1950 to 2035 (Data Source: https://population.un.org/wpp/)

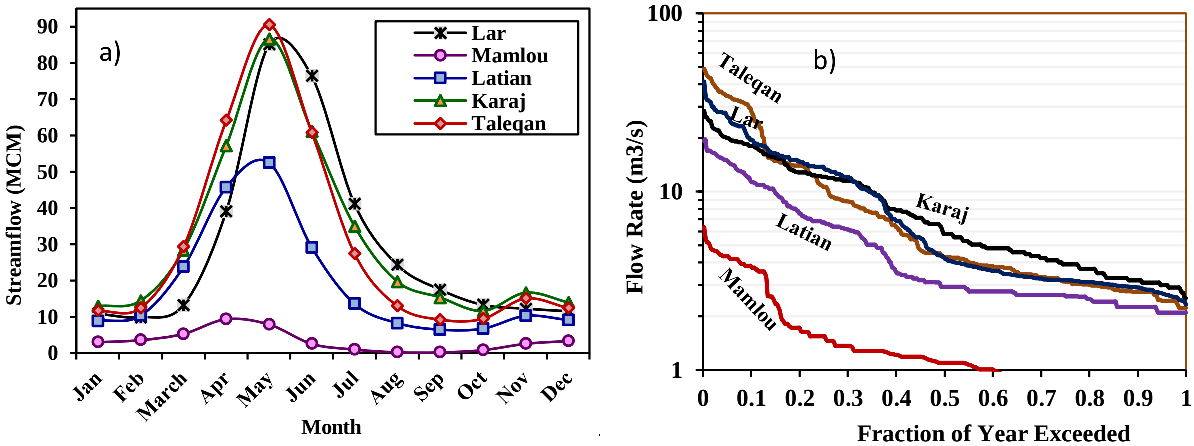

Fig. 3- a) Monthly average (1998-2018) and b) flow duration curve of streamflow to the five reservoirs supplying Tehran domestic water

3. Results and Discussion

Using Eqs. 1 to 4, the values of the UWSI index are calculated on an annual scale and the trend of its changes is shown in Fig. 4. This shows that the value of the UWSI starts from -0.3 in 1998 and increases to zero in 2007 which states that during this period (i.e., UWSI is negative) the streamflow stress (e.g., hydrological drought) relatively prevailed and the water stress in Tehran is not significant. Therefore, the population does not face a significant water shortage and though the catchments upstream of the reservoirs may generate smaller streamflows, there is still enough water to meet the demands with high reliability. During 2007-2009, the value of the UWSI index is around zero which shows that these three years are transitional periods from the dominance of hydrological drought to a new period where the water stress is dominant. From 2009 until now, the value of the UWSI index has reached its maximum value in the last 20 years (around +0.3). During this period, the water stress is higher than hydrological drought. This means that the water crowding (blue water/population) threatens the sustainability of the water supplies of the society. The interpretation of UWSI index values during the new period (from 2009 to now) shows that the socio-hydrological drought occurs in a short period after the hydrological drought in Tehran. Therefore, to effectively manage the water supply, stricter strategies on water demands are needed compared to the previous period.

Further investigation was made on the trend of Tehran's population and the total inflows to the five reservoirs by computing the RAPS index. The annual variations of RAPS for population ($RAPS_{pop}$) and total streamflow to reservoirs ($RAPS_{SF}$) are shown in Fig. 5. According to Fig. 5, although from 2008 onwards, the cumulative changes of the inflow to the reservoirs ($RAPS_{SF}$) do not show a significant trend, this year is considered a turning time for the values of RAPS of the population ($RAPS_{pop}$). The values of $RAPS_{pop}$ show a steep upward trend from 2008 to present. Assuming the constant rate of reservoirs' inflows in the future (based on Fig. 5), it is likely that the growth of the population of Tehran city (and therefore, the increase in water demands) creates a critical situation in this city.

4. Conclusion

Balancing the water supply and water demands according to the sustainable water resources management strategies in the metropolises are among the highest priorities of every government. In this research, a new socio-hydrological water scarcity index has been proposed for the quantitative evaluation of water shortage in Tehran. The results of this research showed that the hydrological drought in the city of Tehran during the years 1999-2007 had a higher impact on the occurrence of socio-hydrological water shortage. Since 2008 however the water scarcity has prevailed over hydrological drought due to the rapid population growth. Considering the insignificant changes in the reservoirs' inflows during the last decade, it can be concluded that the ongoing increase in Tehran's population leads to the occurrence of water stress. Therefore, in order to overcome the water shortage in Tehran, it is necessary to adopt policies with higher efficiency compared to water savings proposed to the citizens.

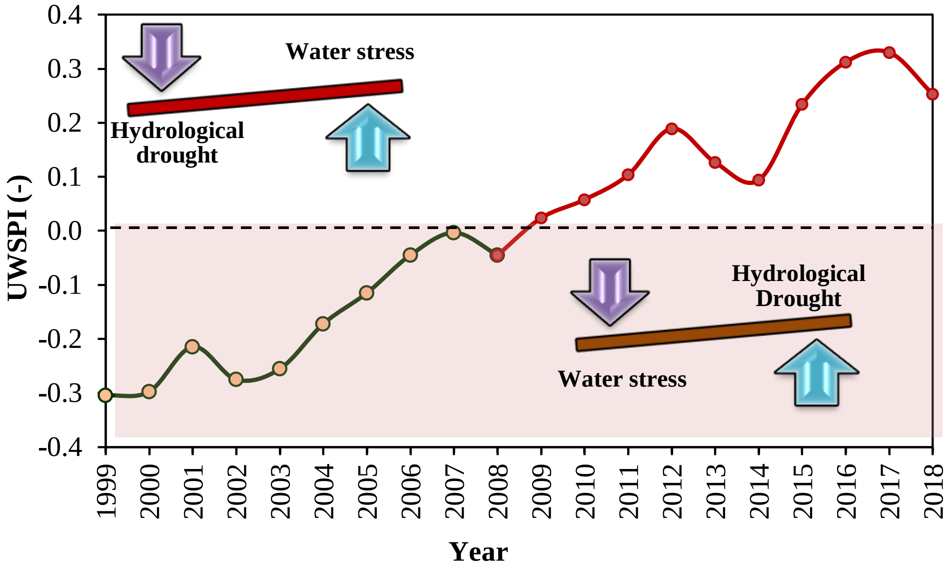

Fig. 4- Annual trend of urban water scarcity index (UWSI) for Tehran city during 1999-2018

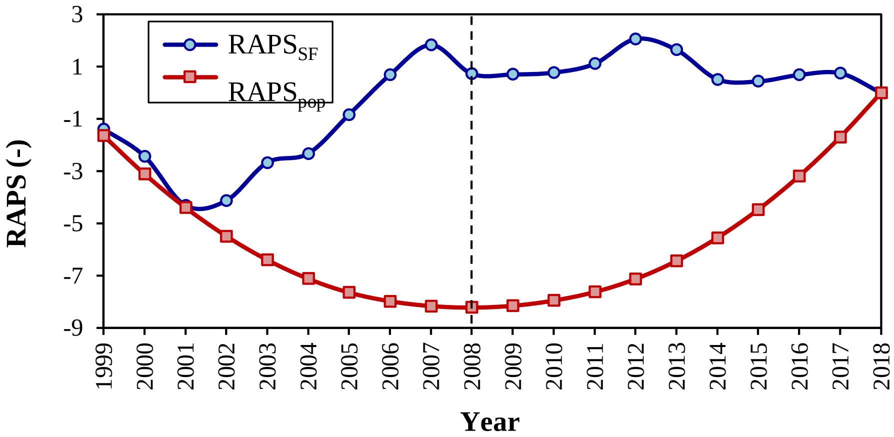

Fig. 5- Annual variations of accumulated Tehran's population ($RAPS_{pop}$) and accumulated total inflows to the Tehran's five reservoirs ($RAPS_{SF}$) during 1999-2018

Among the advantages of the UWSI index, we can point out the simplicity of calculations, incorporating the dimensions effective in the occurrence of water shortage in urban areas (i.e., demographic and hydrological dimensions) and its dynamic nature in time and space. The last feature is due to the use of time changes of the urban population in accordance with the changes in the surface flow entering the reservoirs. It is also possible to implement this index in different spatial scales (catchment to region). Due to the low complexity and the availability of the information needed to calculate the UWSI index, the Iran Water Resources Management Company can use this index to evaluate the socio-hydrological water stress for other cities. By estimating the amount of urban population on a monthly scale based on the monthly population growth rate, one can have more knowledge about how this index changes seasonally in the study area.

Finally, since water scarcity in urban areas has a multi-faceted nature, it requires intensive efforts of hydrologists and environmental and social scientists to integrate important aspects/indicators that intensify water scarcity (e.g., water quality, water footprint, lifestyle of citizens).

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