

Assessing the future water potential of Istanbul and the need for inter-basin water transfer and the trade-offs for water allocation

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ABSTRACT

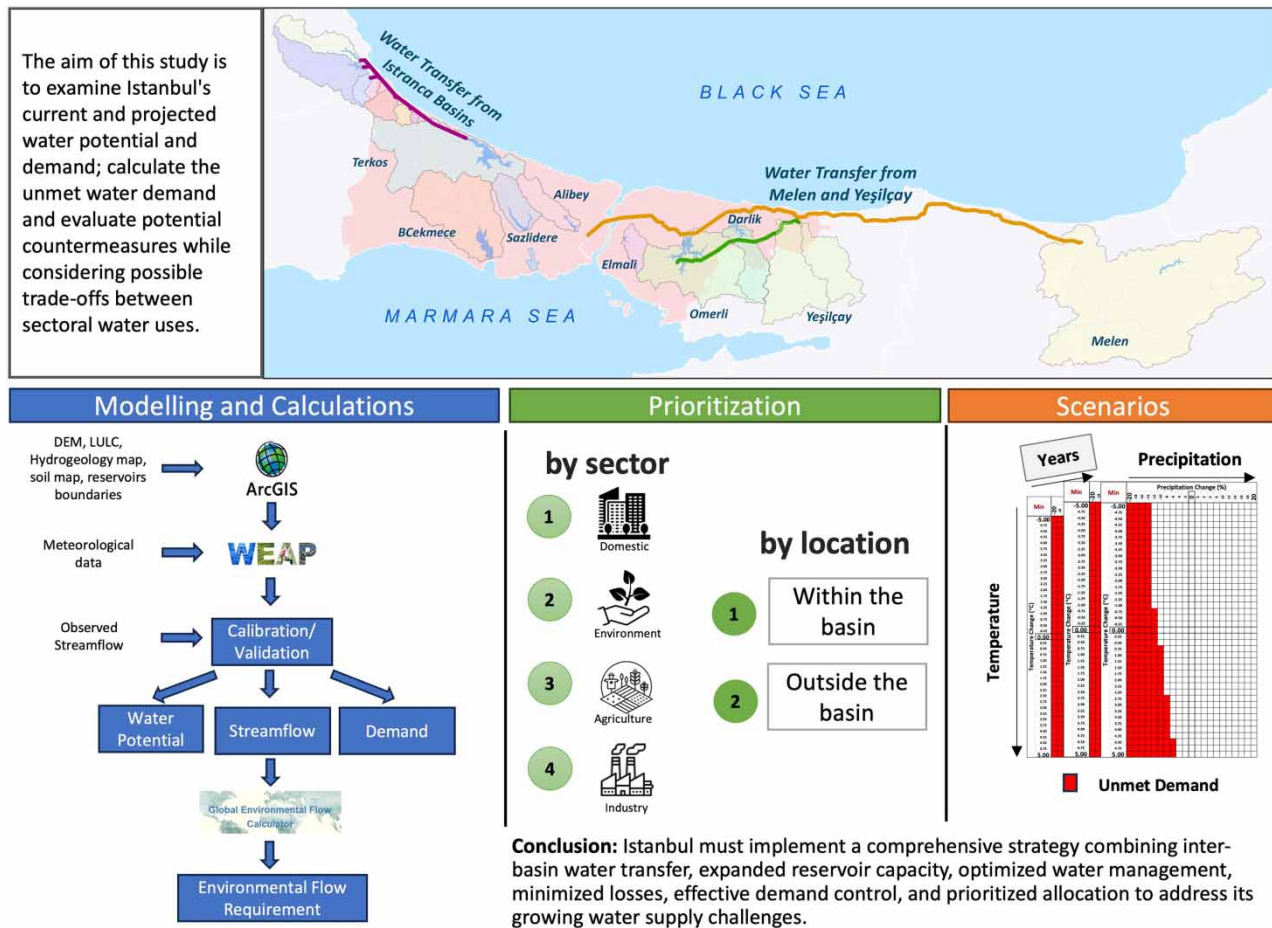
Istanbul faces significant water supply challenges due to limited resources and increasing demand. It has always been very challenging throughout history to supply water to the city and it is expected that the future demand will increase due to population growth, economic development, urbanization, and climate change. This study examines Istanbul's current and projected water potential and demand, calculates the unmet water demand, and evaluates the potential countermeasures while considering possible trade-offs between sectoral water use. A hydrological system has been modelled to calculate water potential and develop scenarios to identify critical tipping points. Also, the unmet demand for different water potential scenarios has been calculated. By analysing these scenarios, it is revealed that the unmet demand will intensify due to population growth and drought conditions. Inter-basin water and additional water resources will increase the resilience of the system but to address Istanbul's water challenges, multiple factors must be optimized together as no single solution can satisfy all needs or eliminate all risks. As providing sufficient potable water is the first priority, the following key factors should be considered: expanding reservoir capacity, optimizing water transfer and reservoir management, minimizing water losses, implementing effective demand management, and prioritizing water allocation.

Key words: megacities, unmet demand, water availability, Water Evaluation and Planning (WEAP), water supply prioritization

HIGHLIGHTS

- With 16 million residents and limited resources, Istanbul faces major water management challenges.
- Water Evaluation and Planning (WEAP) modelling is used to analyse water potential scenarios and system tipping points.
- Population growth and droughts will increase the unmet water demand.
- While inter-basin transfer is the primary action, multiple factors must be optimized together, as no single solution can satisfy all needs.

GRAPHICAL ABSTRACT



INTRODUCTION

The water always makes us live close to a water body since human beings passed from a nomadic way of life to a more settled one. After the dramatic rise of population acceleration due to urbanization, the pressure on water resources has increased continuously. This challenge is particularly acute for megacities, which concentrate large populations in relatively small areas, exacerbating water resource pressures. Istanbul, New York, Beijing, Tokyo, Madrid, Ankara, and Shanghai are facing similar challenges such as high population, limited or far water resources, climate change, and deterioration of quality. To address these challenges, many cities have adopted inter-basin water transfer projects, which are crucial for redistributing water from regions of surplus to regions of scarcity.

New York, with a flexible combined system by interconnections (Water Science and Technology Board Commission on Geosciences 2000), supplies water from three different water basins with a complex infrastructure of reservoirs, aqueducts, and tunnel systems. Ninety percent of the demand comes from the Catskill and Delaware watersheds which are located more than 160 km north of the city (Hanlon 2017). This complex system provides over 3.8 million m³ of water per day to 8.5 million residents, 1 million residents of close neighbourhoods, and millions of commuters and tourists (National Academies of Sciences 2020).

Beijing, located in the semi-arid and semi-humid climate zones, copes with water scarcity and meets increasing water demand by water transfers from additional basins utilizing the South-North Water Transfer Project, the Grand Aqueduct, about 1,264 km long, developed to carry water from the upper reaches of Han River (a tributary of Yangtze River) to Beijing (Wang *et al.* 2017; Liu *et al.* 2018).

Tokyo is the most crowded city in Japan with a population of approximately 14 million residents as of 2023 and the water demand has increased due to population rise and socio-economic change (Takizawa *et al.* 2005). Tokyo relies on three rivers: Tama, Arakawa, and Tone. Daily water supply capacity is 6.8 million m³ and 1.6 billion m³ of water delivered to the city in 2021 with a supply system that consists of 17 reservoirs (the farthest being over 150 km away), six intake weirs, and five transfer channels and treatment facilities (Bureau of Waterworks Tokyo Metropolitan Government 2022).

Madrid's water supply system of the Canal de Isabel II consists of 14 reservoirs with a capacity of 1 billion m³, groundwater collection facilities, treatment plants, and a large distribution network (Navalpötro *et al.* 2013; Community of Madrid 2023). It is one of the most complex systems in Europe.

Shanghai, the largest megacity in China, had been supplied approximately 70% of water demand from the Taihu Lake via the Huangpu River until 2010. Then, due to the severe pollution in the Taihu Lake, the Yangtze River became the main water resource for Shanghai and three reservoirs have recently been built to store water (Zhao *et al.* 2016).

Ankara, the capital of the Republic of Türkiye, with a population of 5.8 million, receives water from seven dam lakes. Six of them are located in the Sakarya Basin, at distances ranging from 25 to 90 km. One of them is in the neighbouring basin, Kızılırmak, and water is brought from 128 km away (ASKI 2023).

As discussed above, many megacities around the world are not self-sufficient in terms of water resources and must rely on water to be transferred from other basins. Similar to these megacities, Istanbul employs water transfer systems from adjacent basins and has a complex water supply and distribution system to cope with the allocation of scarce sources of water to the sprawling city.

Istanbul is located on the natural boundary between Europe and Asia (Figure 1). The Bosphorus, a waterway between the Sea of Marmara and the Black Sea, lies down between two continents. The city is not only the most crowded city in Türkiye but also a historical and economic centre. However, the water supply to Istanbul has always been a hard task throughout the city's history (Altınbilek 2006; Saatci 2013). This challenge is also the reason that there are many examples of water-related historical heritage (Aydin *et al.* 2013; Uyumaz & Dabanlı 2013) such as aqueducts, reservoirs, wells, waterways, and fountains. Terkos and Elmalı dams built in the Ottoman period are still in use. After the Republic of Türkiye founded, initial service was given by some private corporations which were then transferred to public institutions. Today, the Istanbul Water and Sewerage Administration (ISKI – Turkish abbreviation of 'İstanbul Su ve Kanalizasyon İdaresi') is mostly responsible for the management, distribution, and sales of water, while the State Hydraulic Works (DSİ – Turkish abbreviation of



Figure 1 | Istanbul's location map.

‘Devlet Su İşleri’), which was founded in 1954, is responsible for major dam constructions and operations (Yıldız 2003). The city’s supply system consists of 14 reservoirs, a water transfer project, and a flexible distribution system. The average supplied water is 3,023,759 m³ water per day in 2022 (ISKI 2023).

The escalation of water demand, especially after the 1980s, made the water supply a vital issue. The population, which was 1.9 million in 1960, has increased to approximately 15.9 million in 2022 (TURKSTAT 2023) due to industrialization and urbanization. Also, the water resources are at risk of illegal settlements within the watershed zones which brings pollution as another problem for these resources (Saatci 2013). All these pressures on the system have caused troubles, especially in the years of drought. The drought in 1993–1994 marks a milestone in Istanbul’s water supply. This drought caused dreadful shortages which led ISKI to renovate existing facilities and develop new water supply resources (Saatci 2013). The main measures carried out at that time were decreasing water loss from the distribution system, bringing water from the Istranca creeks, approximately 120 km away from Istanbul in the north-west direction between 1995 and 2000, and building new water conduits between Yeşilçay and Melen rivers, which are 60 and 187 km, respectively, east of Istanbul (ISKI 2023). Besides, the distribution network has been expanded and diversified to ensure that it supplies each demand site from more than one reservoir. So, the water distribution network has become more flexible.

Even with all these supply measures, the drought that happened in 2014 was another hard time for the city. There were no shortages but it has to be withdrawn water from a river with poor water quality to meet the demand. No doubt that even more water will be needed in the future to meet the demand in the conditions of a rapidly growing population, changing lifestyles, urbanization, and climate change. Even though 65% of the population lives in the European side, 60% of water is supplied from the Asian side of the City. This means that an enormous amount of water is transferred every day under the Bosphorus.

There are some studies in the literature about the hydrological analysis of some of the water basins as a single system. Coskun & Alpaslan (2009) investigated the temporal assessment of the land use change in the Ömerli Basin and water quality in the reservoir by using remote sensing (RS) and geographic information system (GIS), while Gulbaz & Kazezyilmaz-Alhan (2013) focused on the urbanization effects on the Sazlidere Watershed. Cuceloglu & Erturk (2014) employed the Water Evaluation and Planning (WEAP) model to analyse the water budget of the Darlik Basin. Gulbaz *et al.* (2017) investigated the implementation scenarios of low-impact development management practices in the Alibeyköy Basin to reduce the adverse impacts of urbanization. Another study analysed the impact of land use changes on hydrological processes in the Büyükçekmece Basin (Sertel *et al.* 2019). Some other studies discussed Istanbul’s water problems, challenges, and management strategies. Yuksel *et al.* (2004) summarized the situation of water and wastewater management and discussed future strategies for sustaining enough water for increasing populations with suitable quality. Altinbilek (2006) laid out the general picture of water management in Istanbul. Çodur *et al.* (2007) assessed the basin management studies in the context of the EU’s Water Framework Directive. Saatci (2013) revealed the pressures on water quality due to the rapid growth of population and urbanization and gave some examples of solutions. Çetinkaya *et al.* (2022) examined three long-term scenarios for water availability: (1) current supply sources; (2) including new water resources; and (3) relying only on local resources. Only a few studies holistically investigated Istanbul’s water resources (Cuceloglu *et al.* 2017; Çetinkaya *et al.* 2022). However, allocation priorities for sectoral use have not been emphasized in previous studies.

The main purpose of this study is to calculate the water potential of Istanbul under future climate possibilities given certain temperature and precipitation ranges and discuss if planned supply countermeasures will meet the future domestic water demand as it is the number one priority. In addition to that, allocation priorities for sectoral use are to be investigated for the worst-case scenario. To achieve this, an analytical hydrological model was built based on historical data and calibrated, and it provided a necessary understanding of the hydrological system. Water potential has been simulated by inputting new temperature and precipitation values and demands were calculated. Finally, the unmet demand was discussed primarily for domestic use and prioritization was taken into account for minimum water potential cases where trade-off between sectors could be included as a countermeasure.

METHODS

Study area

Istanbul, which extends both to Europe and Asia, is the most crowded city in the Republic of Türkiye, with a total area of 5,343 km². Istanbul’s water supply system consists of 14 reservoirs, wells, and three regulators which withdraw water from

rivers (Figure 2). Approximately 98% of annual capacity originates from surface water resources. Only half of the supply capacity comes from the reservoirs located in Istanbul. These reservoirs are Elmalı, Ömerli, and Darlık on the Asian side and Terkos, Alibeyköy, Büyükçekmece, and Sazlıdere Reservoirs on the European side. The other half of the capacity is transferred from Kırklareli (Istranca Rivers (Düzdere, Kuzuludere, Büyükdere, Sultanbahçedere, and Elmalıdere), Kazandere and Pabuçdere Reservoirs), Düzce (Melen System), and Sakarya (Sakarya Regulators) Provinces.

Istanbul has a transitional climate between the Black Sea and Mediterranean climate characteristics. So, the Black Sea coastal region (rural) in the north has different climate characteristics from the Marmara Sea coastal region (urban) lay on the southern part. In summer, the weather in Istanbul is hot and humid, with the temperature in July and August averaging 24.6 °C. During winter, it is cold, wet, and sometimes snowy, with the temperature in January and February averaging 6.8 °C. Spring and autumn are mild but are unpredictable and often wet, and can range from chilly to warm; however, the nights are chilly (MGM 2023).

The land use data (CORINE – 1990–2018) shows that some of the basins are dominated by forested and natural areas, while others are largely modified by human activities. In particular, basins such as Büyükçekmece, Sazlıdere, and Alibey, which are within the provincial borders of Istanbul, are significantly under the influence of urbanization. On the other hand, Melen and Yeşilçay basins, where water is transferred to Istanbul, have wide agricultural areas (detailed land use change graphs for each basin are given in Supplementary Appendix B).

Water allocation in the Republic of Türkiye and for Istanbul

In the Republic of Türkiye, the State Hydraulic Works (DSI) is responsible for water resources development. DSI published a regulation on water resources allocation in the Official Gazette issue 30947 (10/12/2019) stating that the water allocation shall be performed in the following priority order based on the quantity and quality of water:

1. potable domestic water supply for people,
2. environmental flows,
3. water supply for irrigation and aquaculture,
4. water supply for the energy sector and industry, and
5. water supply for commerce, tourism, and other businesses.

According to this regulation, water allocation is prioritized for the water needs within the watershed where the water resource is located. This is important for inter-basin water transfer, which is also the case for Istanbul's water supply (Figure 3).

The State Hydraulic Works is an institution under the 'roof' of the central government. On the other hand, local governments are responsible for water supply. Therefore, water supply is managed on the provincial level, not at the watershed level. This is either conducted by province special administrations for smaller provinces or by water and sewage administrations for provinces the municipalities of which are defined as metropolitan municipalities. However, the provinces are administrated by governorships which are the extensions of the central government.

The management of the municipal water supply by local authorities at the city level may lead to problems in water allocation, especially for different provinces located within the same sub-basin, that need to be solved by specially assigned commissions responsible for the watershed. In the case of Istanbul, all of the catchments except the Melen Watershed are located in the Marmara Watershed, distributed over the territories of four provinces. These four provinces are within the same watershed so officially no priorities are defined for any of the provinces. The Melen Watershed is a different watershed with three provinces in its territory; however, there is a special protocol for the water transfer from the Melen Watershed to Istanbul.

Considering all of these facts, the prioritization given in Table 1 is suggested for water allocation scenarios covering the possible unmet water demand of Istanbul considering the following facts:

- Potable domestic water supply for any province cannot be used to cover the unmet water demand for Istanbul.
- Any other sector's water demand in any province should not be disturbed as far as possible. Here, it is considered that any province farther from Istanbul should be supplied less water to cover Istanbul's unmet demand than the closer provinces to Istanbul.
- All of the water supply necessary for other sectors is gathered into one water demand. This is justified by the situation that in these provinces, the water demand in the other sectors, which are industrial, nature needs, commerce, and businesses, are

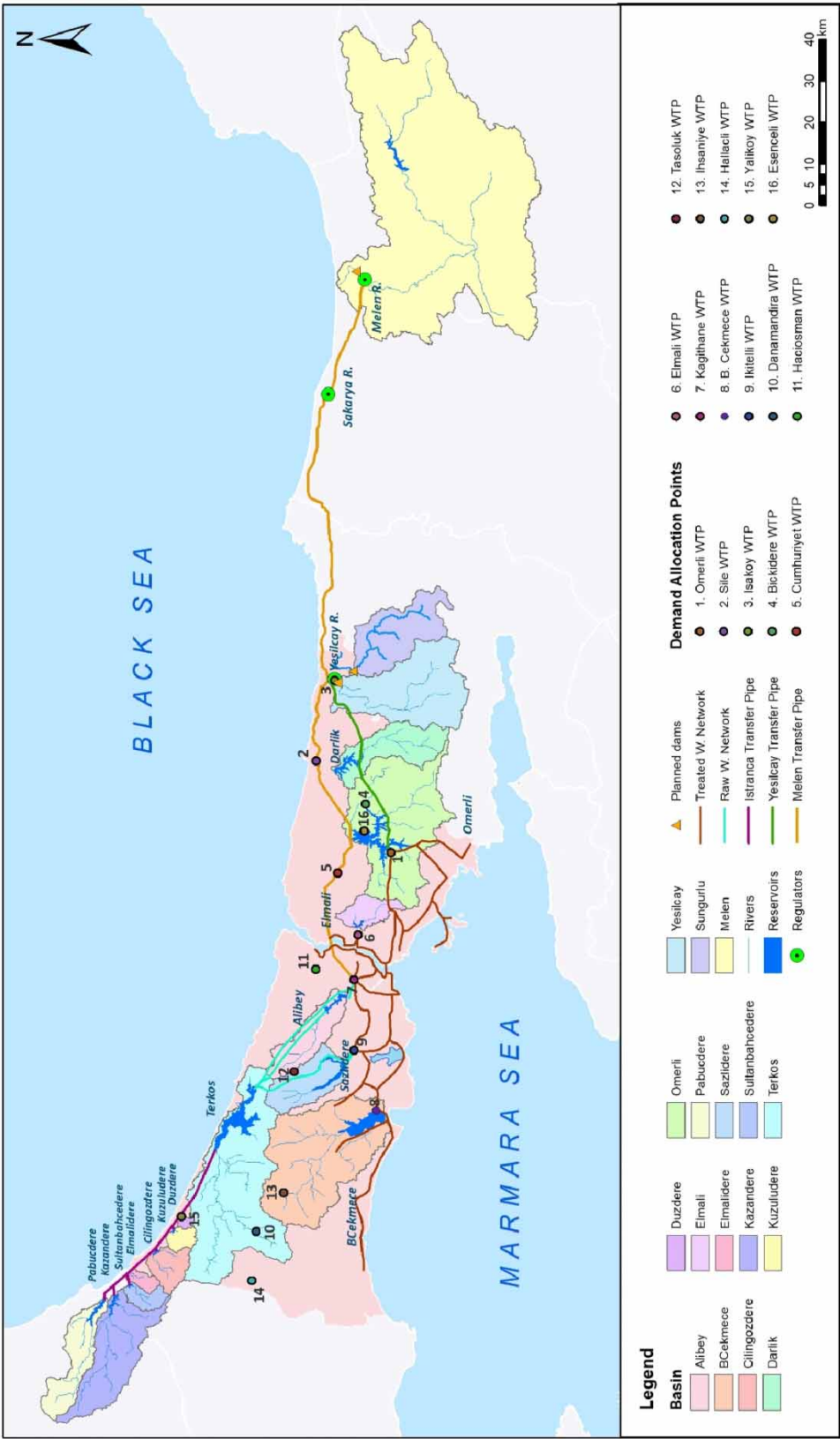


Figure 2 | Istanbul’s water resources and supply system.

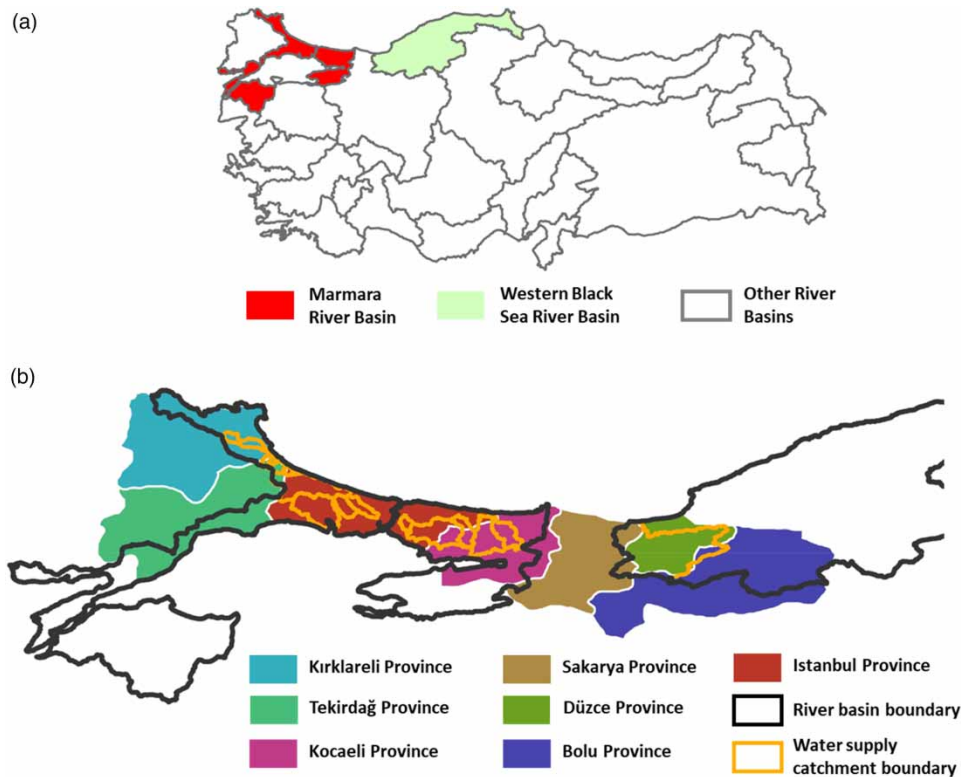


Figure 3 | Watersheds and provinces related to the water supply of Istanbul.

Table 1 | Prioritization suggested for the scenario (excluding potable domestic water supply for people as it is the first priority)

Water supply item	Priority
Environmental flow in the catchments of Bolu province supplying water to Istanbul	1
Environmental flow in the catchments of Düzce province supplying water to Istanbul	2
Environmental flow in the catchments of Sakarya province supplying water to Istanbul	3
Environmental flow in the catchments of Tekirdağ province	4
Environmental flow in the catchments of Kırklareli province	5
Environmental flow in the catchments of Kocaeli province	6
Environmental flow in the catchments of Istanbul province	7
Water supply for irrigation and aquaculture in the catchments of Bolu province supplying water to Istanbul	8
Water supply for irrigation and aquaculture in the catchments of Düzce province supplying water to Istanbul	9
Water supply for irrigation and aquaculture in the catchments of Sakarya province supplying water to Istanbul	10
Water supply for irrigation and aquaculture in the catchments of Tekirdağ province supplying water to Istanbul	11
Water supply for irrigation and aquaculture in the catchments of Kırklareli province supplying water to Istanbul	12
Water supply for irrigation and aquaculture in the catchments of Kocaeli province supplying water to Istanbul	13
Water supply for irrigation and aquaculture in the catchments of Istanbul province	14
Water supply for other sectors in the catchments of Bolu, Düzce, and Sakarya provinces supplying water to Istanbul	15
Water supply for other sectors in the catchments of Kocaeli province supplying water to Istanbul	16
Water supply for other sectors in the catchments of Istanbul province	17

covered by domestic water supply. Tourism is negligible with the exception of Istanbul, where its water demand is also covered by domestic water supply.

Water demand

Potable domestic water demand in this study has been projected using three main variables which are population, water loss, and water use per capita (Equation (1)). ISKI supplied approximately 3 million m³/day of drinking water to the city in 2022 (ISKI 2023). ISKI is the only water supplier to the city. The network reaches 100% of the city.

$$\text{Water demand (WD)} = N(t) \cdot \text{WL}(t) \cdot \text{WU(YAT)} \quad (1)$$

where N is the population, WL is the water loss ratio, WU is the water use per capita per day, t is the time in year, and YAT is the yearly average temperature. Details of the calculations are given in Supplementary Appendix A.

The following seven cities (as seen in Figure 3) have been considered for industrial and agricultural water use: Istanbul, Kocaeli, Düzce, Sakarya, Bolu, Kırklareli, and Tekirdağ and details are given in Supplementary Appendix A. Annual industrial water consumption related to the study area is 29.77 hm³. In the WEAP model, irrigated areas are taken from the CORINE land use maps, and agricultural water use is calculated by assigning thresholds within the city boundaries. The annual average agricultural water use related to the study area is 849.80 hm³.

Environmental flow

The International Union for Conservation of Nature (IUCN) describes the environmental flow as ‘the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated’ (Dyson *et al.* 2008).

In this study, the environmental flow requirements have been calculated for each sub-basin by using the Global Environmental Flow Calculator (GEFC) software developed by the International Water Management Institute (IWMI) (Smakhtin *et al.* 2007). It is an user-friendly environmental flow analysis tool based on the flow duration curve (FDC) concept (Yifru *et al.* 2024). GEFC is used to calculate environmental flows in many studies (Salik *et al.* 2016; Hassanjabbar *et al.* 2018; Kumar *et al.* 2021; Mummidivarapu *et al.* 2023; Ranjan & Roshni 2023).

This software uses the streamflow data as input which is taken from the WEAP model in this study and calculates the environmental flow requirements according to different environmental management classes (EMCs) as given in Table 2.

In each basin, supplying water to Istanbul, EMCs are decided by checking the situation (land use activities like agriculture and industry, etc.) in the basin. Also, sub-basins and cities’ boundaries are overlapped and environmental flow calculations have been done city based.

Model

Modelling is a useful tool to simulate variability in climate, water availability, unmet demand, and various water management scenarios to understand a complex water supply and system. In this study, the WEAP model has been used to model Istanbul’s water resources (details of the model selection are given in Supplementary Appendix C). The WEAP, developed by the Stockholm Environment Institute, is an integrated water resource management tool for examining alternative water resources development and management strategies (Yates *et al.* 2005). The WEAP can analyse both the demand side – water use patterns, allocation priorities, equipment efficiencies, re-use, prices, etc., and also the supply side – streamflow, water availability, groundwater, reservoirs, and water transfers on an equal basis. It is also a comprehensive tool for policy analysis. There are many recent studies that WEAP was used to analyse both demand and supply under future challenges such as Gemechu *et al.* (2024) used the WEAP model to explore surface water allocation under current and future climate conditions, considering various sectoral water use and environmental flow in Awash River basin; Sitotaw Takele *et al.* (2024) analyses both demand and supply under future water development and climate change scenarios in the upper Blue Nile basin; and Yao *et al.* (2024) employed WEAP to investigate water management under different climate change scenarios and anthropogenic pressure in the upper Bandama.

The WEAP model can be automated through an extensive set of Application Programming Interface (API). The WEAP-APIs can be called internally within the WEAP via scripting or externally from other client programs such as Microsoft

Table 2 | GEFC – environmental management classes

EMC type	Definition
A	Natural rivers with minor modification of instream and riparian habitat
B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications
C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present
D	Large changes in natural habitat, biota, and basic ecosystem functions have occurred. A clearly lower-than-expected species richness. Much lowered presence of intolerant species. Alien species prevail
E	Habitat diversity and availability have declined. A strikingly lower-than-expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem
F	Modifications have reached a critical level and the ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible

Excel or Mathworks MATrix LABoratory (MATLAB), which contain additional algorithms not present in hydrological models such as advanced data analysis, comprehensive data reporting, and highly developed optimization algorithms that can aid decision-making (such as cost optimization) or modelling steps (such as uncertainty analysis). These qualities are important for further use of the model and integrating it into more advanced hydroinformatic systems for future studies that are beyond the aims of this study. The user interface of WEAP helps to schematize a study area easily thus supporting the model-building process. By 14 July 2021, Version 2021.0 of WEAP, parallel calculation became possible, so run time has been reduced dramatically for complex systems such as the Istanbul case ([Stockholm Environment Institute 2023](#)).

WEAP comprises five calculation methods to simulate the precipitation and runoff relationship: (1) Irrigation demands only the method of the FAO crop requirement approach, (2) the rainfall-runoff method, (3) the soil moisture method (two bucket model), (4) the MABIA method of FAO Irrigation and Drainage Paper No. 56, and (5) the plant growth (daily; CO₂, water, and temperature stress effects) method. It is considered that the soil moisture method is the most efficient one for hydrological cycle simulation ([Ougougdal et al. 2020](#)). So the soil moisture method was used to calculate runoff in this study (details of the soil moisture method are given in Supplementary Appendix C).

Model schematization and data collection

All water resources and structures, including 14 reservoirs and their catchments, two water transfer regulators, 12 water treatment plants and demand distribution pipelines, have been defined in the WEAP model ([Figure 4](#)) by using GIS tools.

The model needs a wide range of historical data. Precipitation, temperature, humidity, wind speed, and cloudiness data were obtained from the Turkish State Meteorological Service (MGM – Turkish abbreviation of ‘Meteoroloji Genel Müdürlüğü’). Streamflow records from 1985 to 2014 were provided by DSI, and reservoir operation data was provided by ISKI. For demand projection, population records from 1960 to 2022 were taken from the Turkish Statistical Institute ([TURKSTAT 2023](#)). Land use maps were obtained from the CORINE Database 1990, 2000, 2006, 2012, and 2018 ([CORINE 2023](#)).

For groundwater calculations, the Istanbul hydrogeology map ([ÖZTAŞ 2007](#)) was used.

Calibration and validation

Calibration is a crucial step of modelling as it shows how reliable the model is. In this study, calibration has been conducted by adjusting observed and simulated streamflow data. To examine the calibration performance, some statistical measures were checked.

The Nash–Sutcliffe efficiency (NSE) (Equation (2)) is commonly used in hydrologic modelling to evaluate how well-modelled values match the observed. $NSE = 1.0$ indicates a perfect match, while 0.0 value of it shows the estimates are as good as the mean value of observations ([Nash & Sutcliffe 1970](#)). NSE values between 0.0 and 1.0 generally seem as acceptable levels of performance ([Moriassi et al. 2007](#)). NSE is the common method used in many studies with the WEAP model ([Yates et al.](#)

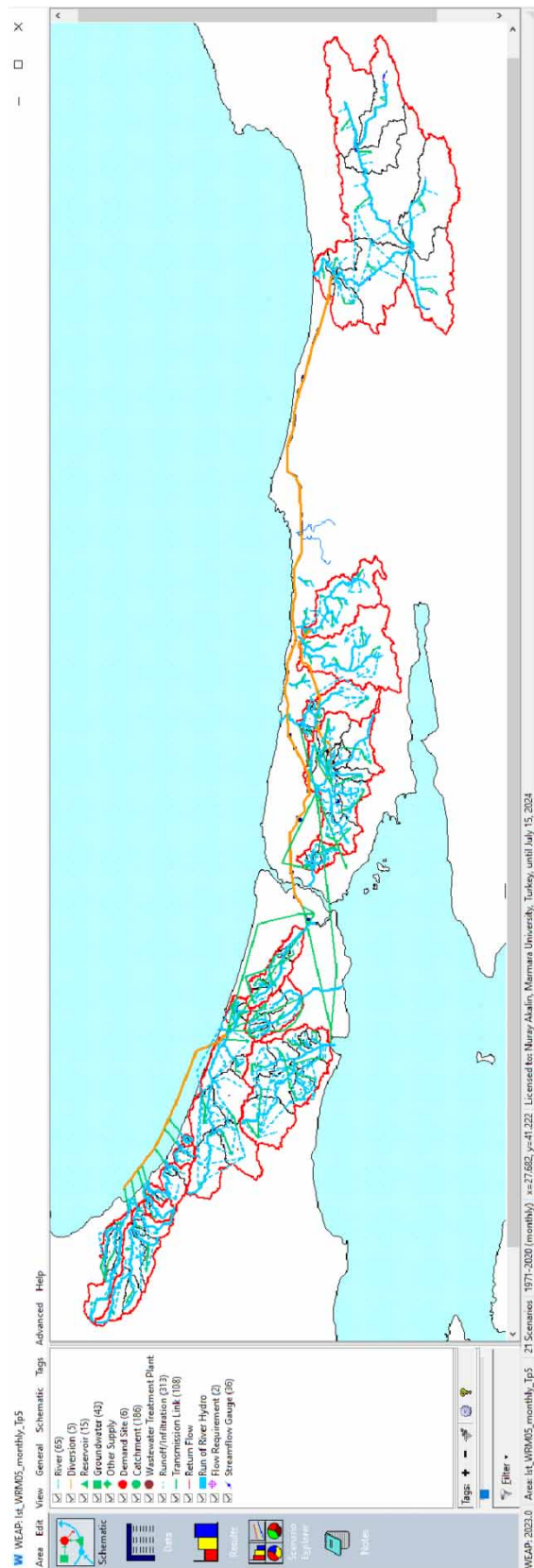


Figure 4 | Model schematization.

2005; Blanco-Gutiérrez *et al.* 2013; Bhawe *et al.* 2014).

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{\text{obs}} - Y_i^{\text{sim}})^2}{\sum_{i=1}^n (Y_i^{\text{obs}} - Y^{\text{mean}})^2} \quad (2)$$

Percent bias (PBIAS) (Equation (3)) is another calibration statistic method that indicates how well the model matches the total flow. For a perfect match of simulated and observed, PBIAS is 0.0. Positive values show an underestimation bias, while negative values indicate overestimation (Gupta *et al.* 1999).

$$PBIAS = 100 \times \frac{\sum_{i=1}^n Y_i^{\text{obs}} - Y_i^{\text{sim}}}{\sum_{i=1}^n Y_i^{\text{obs}}} \quad (3)$$

The coefficient of determination (R^2) indicates the degree of collinearity between model results and observed flow (Moriasi *et al.* 2007). Moriasi *et al.* (2007) assessed a model as ‘satisfactory’ if $NSE > 0.5$ and $PBIAS \pm 25\%$ for streamflow.

A monthly time step has been used for calibration. Monthly streamflow measurements between the 1970s and today (each gauge has a different time period) have been compared with modelled streamflow data. The calibration performance assessments of some gauges are summarized in Table 3. Also, the graphs of observed and simulated values are given in Supplementary Appendix D.

Climate change projections

Istanbul has a transitional climate between the Mediterranean and Black Sea regions. The average surface mean temperature is 12 °C, and total precipitation is 391 mm/year (MGM 2023).

The outcomes of four climate change projections have been examined for this study. One out of four is a global outlook from the IPCC’s 6th Assessment Report, and the other three are downscaled projections applicable to Istanbul.

The IPCC’s 6th Assessment Report shows that mean surface temperature will increase (high confidence), mean precipitation will decrease (high confidence), snow amount will decrease (high confidence), and hydrological drought will increase (high confidence) in the European Mediterranean region (Gutiérrez *et al.* 2021; Iturbide *et al.* 2021), and Istanbul falls into this region.

Table 3 | Calibration performance of flowrate stations

Station name	Basin	Period	Calibration			Period	Validation		
			NSE	PBIAS	R^2		NSE	PBIAS	R^2
Kızılağaç	Pabuçdere	1991–2005	0.46	2.36	0.46	2006–2020	0.45	−10.56	0.53
Balkaya	Kazandere	2006–2014	0.47	−10.2	0.49	2015–2020	0.23	7.34	0.26
Karamandere	Terkos	2002–2012	0.60	−0.16	0.62	2013–2020	0.44	−3.29	0.47
İzzettin	B. Çekmece	1998–2009	0.53	10.13	0.63	2010–2020	0.60	−0.67	0.60
Ahmediye	B. Çekmece	1996–2008	0.78	−0.21	0.78	2009–2020	0.65	2.48	0.66
Prinçciköy	Alibey	2001–2008	0.72	0.85	0.74	2010–2020	0.61	0.13	0.66
Göçbeyli	Ömerli	1980–2000	0.80	6.25	0.82	2001–2020	0.80	8.37	0.86
Darlık Reservoir	Darlık	1995–2004	0.63	−1.63	0.67	2005–2014	0.66	−5.61	0.68
Göksu	Yeşilçay	1968–2000	0.74	0.15	0.74	2001–2015	0.70	0.46	0.72
Geredeli	Yeşilçay	1968–1984	0.71	−2.13	0.72	1987–2001	0.76	−1.92	0.76
Uğurluköy	Melen	1999–2009	0.72	2.43	0.73	2010–2018	0.76	2.56	0.76

The other three downscaled projections are:

1. [SYGM \(2016\)](#) conducted regional downscaled climate projections based on HadGEM2-ES, MPI-ESM-MR, and CNRM-CM5.1 global models between 2015 and 2100 for Türkiye's basins including the Marmara and Western Black Sea River basins where water resources of Istanbul located. Increase in temperature 1.8–3.1 °C and 3.6–5.3 °C for RCP4.5 and RCP8.5 scenarios, respectively. It is projected that the Marmara Basin will have more precipitation in general but the southern part will have less. Only one basin (Büyükçekmece) falls into the southern region of Marmara region, whereas all the others are located on the northern coast of Marmara ([SYGM 2016](#)).
2. [Akçakaya et al. \(2015\)](#) conducted regional downscaled climate projections based on HadGEM2-ES, MPI-ESM-MR, and GFDL-ESM2M global models, and the results show an increase of up to 4–4.5 °C (relatively RCP4.5 and RCP8.5) for the Marmara and Western Black Sea River basins until the end of the century. Based on the RCP4.5 scenario, there is an increase of precipitation between 5 and 15% in the Marmara Basin until the end of the century and a decrease of precipitation by 5% until 2070 and then an increase of 10% in the Western Black Sea until the end of the century. Looking into the RCP8.5 scenario, an increase in precipitation in both the Marmara and Western Black Sea basins is expected ([Akçakaya et al. 2015](#)).
3. The last of the downscaled projections are from İstanbul Municipality which focuses solely on İstanbul rather than the Marmara region. İstanbul Municipality's Climate Change Adaptation Plan (2021) shows an increase in average surface temperatures of 1.5 (RCP2.6)–4.8 (RCP8.5)°C until the end of the century. At the end of the century, the daily maximum temperatures will also increase and it is expected to have a higher acceleration in temperature rise in the summer months vs. winter. It is also expected that 1 or 2° of this increase will be due to the city heat island effect. Other findings also reveal that the amount of snowfall and the time for the snow to melt down will be reduced.

On the contrary to the other downscaled projections based on the RCP8.5 scenario, there will be a reduction in total precipitation by 12% and a 30% reduction in the summer months. Also, an increase in the deviation of the number of days of precipitation combined with the effects of evaporation would lead to an increase in the days of drought from 45 to 57 days ([IBB 2021](#)).

Calculations of water potential

All projections have some results in common which are the increase in temperatures, and the increase in the number and severity of drought and flood events; at the same time, there are differing results for precipitation. These results show that the uncertainty in the water resources availability may increase in the future in İstanbul. Regardless of the trends based on the climate prediction models, it can be said that extreme events may occur in different years. What is certain is the uncertainty with regard to the timing or severity of these events. Based on this, this study will focus on a wide range of possibilities and not on a single climate change projection.

To calculate the future water availability with an analytical hydrological model based on historical data, temperature and precipitation have been chosen as two main parameters. A matrix of water potential will be created with a wide range of possible precipitation and temperature values ([Figure 5](#)).

As mentioned earlier, there are 14 reservoirs and multiple rivers collecting, storing, and supplying water to İstanbul. There is no storage capability on the Melen and Yeşilçay rivers but the water is being transferred through water intake regulators. The existing water potential of these rivers for İstanbul is hence limited by the capacity of the intake structures, pumps, and pipelines. This limited capacity per year is 575 and 145 hm³, respectively.

Total water potential has been calculated with the hydrological model based on the selected parameters, for the existing reservoirs and rivers separately and as a whole considering these limitations on the rivers. There are also plans for the construction of dams on Melen (Melen Reservoir) and Yeşilçay (Osmangazi and Sungurlu reservoirs) rivers. The water potential for this scenario is also calculated.

Total water potential matrices have been created for the following three water supply options:

- a. Total water potential of existing water reservoirs (14 reservoirs).
- b. Total water potential of existing water reservoirs plus the amount of water that is transferable from Melen and Yeşilçay regulators (720 hm³). This represents today's situation.
- c. Future total water potential of the water reservoirs including planned Melen, Osmangazi, and Sungurlu reservoirs (17 reservoirs).

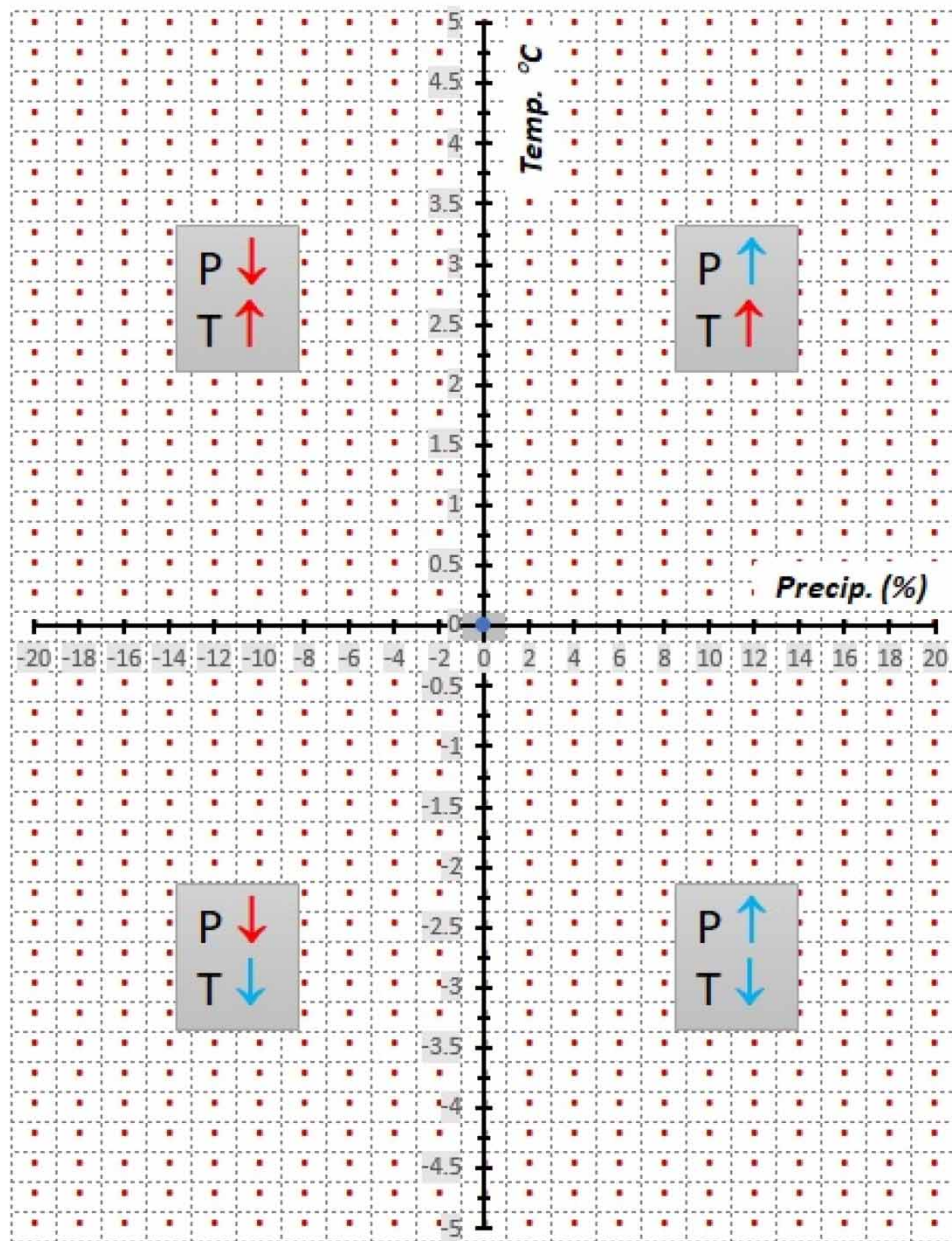


Figure 5 | Schematized boundaries of the selected climate parameters for the matrix (P, precipitation; T, temperature).

In order to calculate the total water potential, the following steps have been used:

- Calculate the monthly water potential of each reservoir with the calibrated analytical model. The evaporation from the reservoir surface is extracted from the potential. Use the monthly historical input temperature and precipitation observed between 1980 and 2020.

This produces 40 years*12 months = 480 data points for each resource.

- Sum the monthly results to find out the total water potential for each year.
- Calculate the 40-year average water potential.
- Add this point on the matrix as [0,0] point.
- Repeat this calculation for each point on the matrix changing the historical input temperature and precipitation by increments shown in Figure 5. This yields an additional 860 points on the matrix.

f. Create contour plots for the data matrix.

Three matrices and contour plots have been created to present the results of each of the four supply options:

1. Average: Employs the 40 years' monthly historical temperature and precipitation values and iterations of each monthly data to create the matrix and the contour.
2. Min: The year with the minimum water potential is selected and results are presented for that year.
3. Max: The year with the maximum water potential is selected and results are presented for that year.

RESULTS AND DISCUSSION

Domestic water demand

Water demand has been calculated as a function of population, water loss, and water use per capita (Equation (1)). Water use per capita projection takes into consideration the effects of the same temperature change assumptions described in water potential calculations (Supplementary Appendix Equation (A.5)).

Water demand increased every decade until the 2050s due to the increase in population. Assumptions of water loss reduction actions to be taken by the municipality show that water demand will be balanced out after the 2050s as water loss has a significant effect on water demand. Water demand estimations are given in Figure 6.

Water potential

Water potential results calculated by the WEAP model are presented in Figure 7.

The average water potential of existing water reservoirs (14 reservoirs) differs between 659 and 1,294 million m^3/year . When the amount of water that is transferable from the Melen and Yeşilçay regulators (720 hm^3) is added to this value, the potential changes are between 1,379 and 2,014 million m^3/year in an average climate year. If the planned reservoirs have been built, the average water potential differs between 1,832 and 3,380 million m^3/year (Table 4).

Unmet demand

The unmet demand for different scenarios of hypothetical minimum, average, and maximum water potential based on historical climate data (1980–2020) has been calculated for Istanbul. Three supply options described in Calculations of water

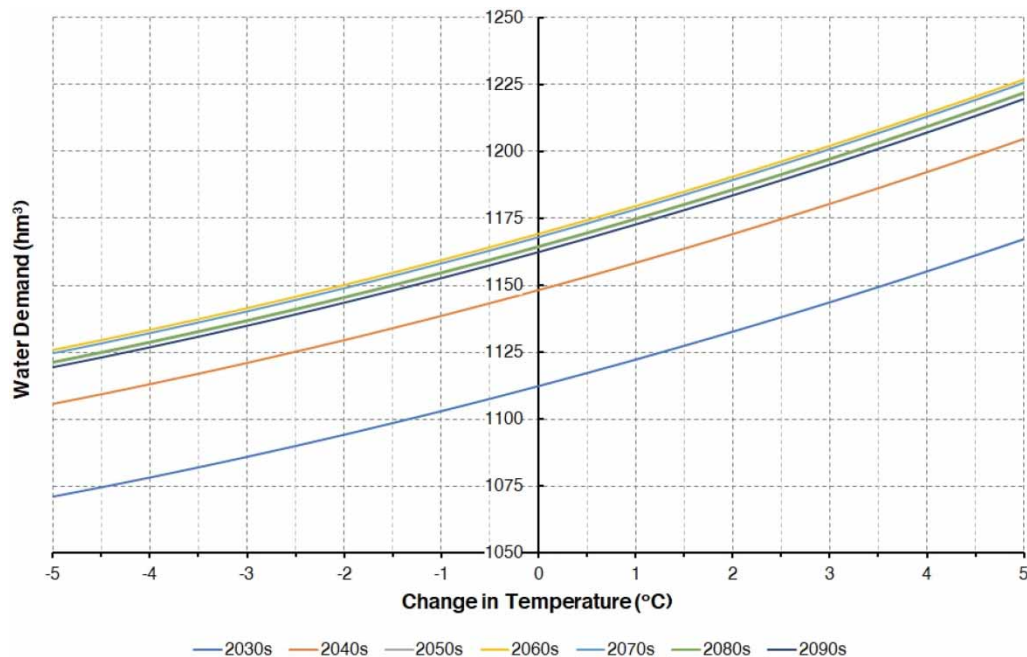


Figure 6 | Water demand projections for different decades (million m^3).

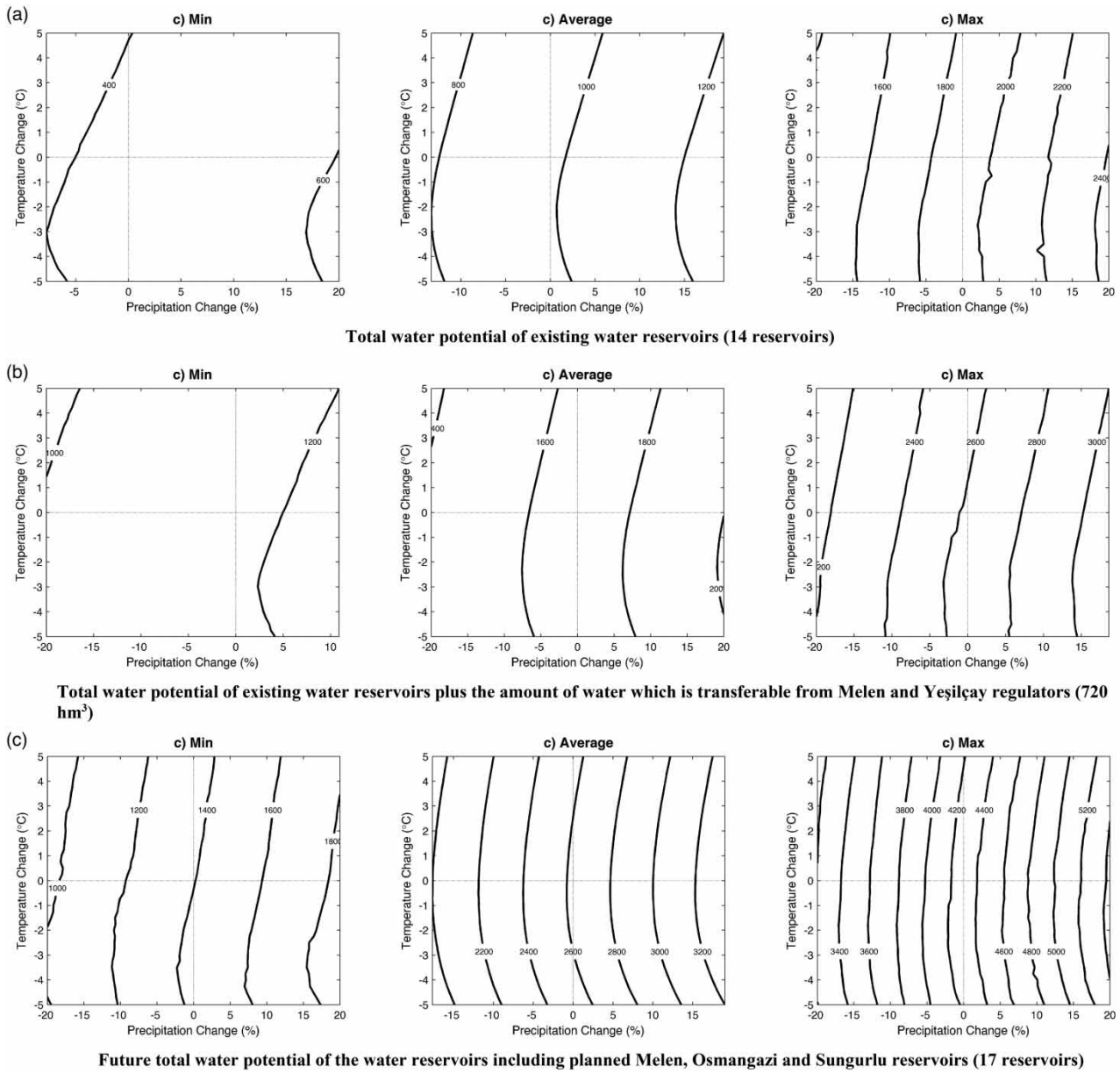


Figure 7 | Average, min, and max water potential for three supply options (million m³/year).

Table 4 | Comparison of water potential for existing and future supply options

Supply options	Water potential (hm ³)		
	Min	Average	Max
(a) Total water potential of existing water reservoirs plus the amount of water that is transferable from the Melen and Yeşilçay regulators (720 hm ³)	993–1,360	1,392–2,026	2,112–3,185
(b) Future total water potential of the water reservoirs including planned Melen, Osmangazi, and Sungurlu reservoirs (17 reservoirs)	921–1,914	1,830–3,370	3,130–5,391

potential have been used for analysis. Detailed results are given in Supplementary Appendix E, whereas their summaries are given in the following paragraphs:

The existing 14 reservoirs supplying water to Istanbul are insufficient in normal and dry periods even in the 2030s without water transfer from the Melen and Yeşilçay regulators located outside the city. Only in the case of max potential reached (a very wet year), the 14 reservoirs can meet demand (Supplementary Appendix Figure E.1(a)).

While the current supply capacity including the 14 reservoirs and transfer from the rivers of Melen and Yeşilçay is sufficient to meet the demand in average conditions, there might be a shortage in dry years depending on how climate change effects will be.

By increasing the water potential to the existing supply system by transferring water from long distances with the planned dams and additional transmission structures, the risk of unmet demand will be significantly reduced and will eliminate all the risks for the years with average water potential.

Although water demand can generally be supplied in the 2040s with existing infrastructure, the severity of unmet demand in dry years increases compared with the 2030s (Supplementary Appendix Figures E.1(b) and E.2(b)). Increasing the potential for transferable water reduces this severity (Supplementary Appendix Figure E.2(b) and E.2(c)).

In this study, it is estimated that the population will be over 20.5 million and water loss will be around 8% in the 2050s. Supplementary Appendix Figure E.3(b) shows that with these assumptions, the existing capacity is not enough to meet the demand under extreme conditions even if the climate change effects are mild. If new water resources investments are made, the severity will not be worse than in the 2040s.

After the 2050s, the severity of unmet demand decreases as the water losses reduce due to technological development (Supplementary Appendix Figure A.4).

No matter what investments are made, it may not be possible to fully meet the projected water demand under some extreme conditions of climate change (such as a further decrease in precipitation in dry years and an increase in temperature). Nevertheless, it should be kept in mind that the unmet demand here does not mean being complete lack of water, but the inability to provide the desired amount of water per capita. This fact points to the solution as well. In the coming decades, technological developments/improvements are expected to have an impact not only on decreasing water losses but also on reducing the net water use of individuals and industries. Obviously, the availability of additional water resources makes it easier to manage the unmet demand in any case and additional water resources will also increase the resilience of this system.

It should be taken into consideration that the entire water potential is employed for domestic water needs in this study. On the other hand, a certain part of this water potential will also be needed to maintain the ecological flow requirement. In this case, the unmet demand will increase as the amount of water that can be supplied to the network will decrease. For this reason, reducing water use per capita has the potential to be an important water governance tool for Istanbul alongside all the efforts to increase the supply capacity.

Allocation priorities and trade-offs

In the previous section, as Istanbul's drinking water demand is the first priority in accordance with the regulation, water potential, and drinking water demand were compared. Even if Melen, Yesilçay, and Sungurlu dams are included in the water supply system, there are climate scenarios where Istanbul's water demand cannot be met. For this reason, industrial water use, which is ranked as the least important in the regulation, was excluded from the water supply. As this amount was not enough to meet the demand, the case of agricultural water use allocation, which is at a higher priority level, was examined. It has been seen that if the water for agriculture and other sectors (industry, etc.) were not supplied, Istanbul's potable domestic water demand could be met to a significant extent even in years of minimum water potential. In the next stage, environmental flows (average yearly flow requirement is 782 hm³), which ranked second in importance, were examined.

Without allocating the needs of agriculture and other sectors, both Istanbul's potable water demand and environmental flows can be substantially met even under the worst-case climate scenarios. Other sectors, such as industry, have a very low impact as their water needs are very small.

Since the regulation states that providing sufficient potable water to Istanbul is the first priority, the trade-off should be between environmental flow and irrigation. The trade-off of meeting environmental water needs is that agricultural water demand may be limited or unmet depending on climatic conditions.

Demand management measures need to be taken as water shortages are inevitable in extreme drought situations (Supplementary Appendix F).

CONCLUSION

The majority of the megacities around the world had to address their water supply problems by transferring water from basins around them. Istanbul also has been employing the same approach since 1995 as its water demand has been always on the rise; mainly driven by increasing population, lifestyle, and socio-economic changes.

In Istanbul, water is supplied and distributed to the citizens by the municipality. As it is a public and non-profit institution, ensuring an uninterrupted supply of water is always a priority; so there have always been plans to create new water resources and a tendency to keep reservoirs as full as possible, instead of optimizing water transfer and cost.

In order to satisfy the increasing water demand of Istanbul, building new water resources is essential but may not be enough by itself considering the effects of climate change. Demand management and optimal use of resources will gradually become more crucial. In addition to demand management and optimizations, water loss improvements are of utmost importance and speeding up the implementation of improvements will bring significant benefits to mitigate unmet demand risk.

It can be concluded that in addressing Istanbul's water demand and supply problem, the following factors need to be considered and optimized as none of them alone satisfies the needs and eliminates all the risks:

1. Additional water reservoirs to the existing system.
2. Optimal control of water transfer and levels of the reservoirs.
3. Reduced water loss.
4. Demand management.
5. Allocation prioritization.

In order to respond to these challenges, the municipality has invested in technology and automation infrastructures to measure and control the water resources, treatment plants, distribution, and pumping network in recent decades. Also, a flexible water supply network has been established to ensure to supply of each demand site from more than one reservoir and connections between reservoirs have been built. All this infrastructure should enable a complex decision-making and execution capability. At this critical point in water management capability, hydrological predictive and optimization models can bring great benefits to the decision-making process. Initially, these predictive models can run in parallel to the conventional decision-making process to better integrate the system.

The model approach developed and calibrated in this study might be a foundation for further studies including optimal allocation of water from reservoirs under uncertainties and challenges of climate change by minimizing pumping energy and treatment chemicals and costs.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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