MODELING WATER SUPPLY AND DEMAND BALANCE OF ISTANBUL UNDER FUTURE CLIMATE AND SOCIO-ECONOMIC CHANGE SCENARIOS

by

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ABSTRACT

MODELING WATER SUPPLY AND DEMAND BALANCE OF ISTANBUL UNDER FUTURE CLIMATE AND SOCIO-ECONOMIC CHANGE SCENARIOS

Population growth creates an increased freshwater demand with the subsequent developments due to urbanization and industrialization in the metropolis Istanbul, Turkey. Climate change has additional serious impacts on water resources. Therefore, sustainable water management practices are required to cope with the dynamic socio-economic change and climate change on water demand and supply balance in Istanbul. In this study, Water Evaluation and Planning Systems (WEAP) modeling program, as an Integrated Water Resources Management (IWRM) tool, is used to understand the impacts of climate change and socio-economic changes such as population growth and water use on water demand and supply balance and to know what awaits Istanbul until 2100. The model is analyzed under different scenarios of socio-economic and climate change. The physical and spatial properties of the watershed basin and catchment hydrology data appropriate with Rainfall Runoff (Simplified Coefficient) Method of WEAP are used in the baseline scenario construction and scenario analysis. Regarding the results, the city is expected to experience the negative impacts of climate change much more after 2030 while the impacts will get more dispersed and unpredictable after 2040. The high dependency on the external water resources, especially on Melen River, is increasing the water insecurity of the city especially with the pressure created by increased total water demand of the city. To achieve a water-smart society under the increasing pressures of climate change and socio-economic changes; technological improvements, policy changes and educational activities to increase environmental awareness are needed with the joint contributions of all stakeholders.

ÖZET

İKLİM VE SOSYO-EKONOMİK DEĞİŞİM SENARYOLARI ALTINDA ISTANBUL'UN SU ARZ VE TALEP DENGESİNİN MODELLENMESİ

Nüfus artışı, şehirleşme ve endüstrileşmedeki gelişmeler ile birlikte, Istanbul büyükşehrinin içmesuyu talebinde artışa sebep oluyor. Ayrıca, iklim değişikliği de su kaynakları üzerinde ciddi etkilere sahip. Bu sebeplerden dolayı, Istanbul'daki sosyo-ekonomik değişim ve iklim değişikliğinin su arz talep dengesi üzerinde yarattığı etkilerle baş edebilmek için sürdürülebilir su yönetimi uygulamaları gereklidir. Bu çalışmada, Entegre Su Kaynakları Yönetimi (IWRM) araçlarından biri olan Water Evaluation and Planning Systems (WEAP) modelleme programı, nüfus artışı ve su tüketimi gibi sosyo-ekonomik değişimlerle birlikte iklim değişikliğinin su arz talep dengesi üzerindeki etkilerini ve Istanbul'un gelecekteki (2100 yılına kadar) denge durumunu incelemek amacıyla kullanılmıştır. Model farklı sosyo-ekonomik ve iklim değişikliği senaryoları altında incelenmiştir. Senaryo oluşumu ve analizi sırasında, Yağış-Akış Metod'una uygun olarak havzanın fiziksel ve hidrolik yapısına dair veriler kullanılmıştır. Sonuçlara göre, şehir iklim değişikliğinin olumsuz etkilerini 2030 yılından sonra daha çok hissedecek ve 2040 yılından sonra bu etkiler daha tahmin edilemez düzeyde gerçekleşecek. Şehrin dış su kaynaklarına, özellikle Melen Nehri'ne, olan bağımlılığı ise artan su talebiyle birlikte şehrin içme suyu yönetimini daha riskli kılmaktadır. Iklim ve sosyo-ekonomik değişikliklerin yarattığı etkiler altındayken, suyu akıllıca yöneten bir topluma erişebilmek için, tüm paydaşların katılımıyla desteklenen teknolojik gelişmeler, politik düzenlemeler ve çevre bilincini arttıracak eğitsel çalışmalar gereklidir.

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LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
BAU	Business as Usual
DSİ	Government Water Affairs
ETref	Reference Evapotranspiration
GIS	Geographic Information Systems
GWP	Global Water Partnership
HT	High Technology
HT-LP	High Technology with Low Population
IWRM	Integrated Water Resources Management
İKLİMBU	Boğaziçi University Climate Change and Politics Application and Research Center
İSKİ	Istanbul Water and Sewerage Administration
Kc	Crop Coefficiency
LT	Low Technology
LT-HP	Low Technology with High Population
MGM	General Directorate of Meteorology
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
Pe	Effective Precipitation
R^2	The Coefficient of Determination
RCP	Representative Concentration Pathways
RSR	The Standard Deviation Ratio
TUİK	Turkish Statistics Institute
WEAP	Water Evaluation and Planning Programme
WTP	Water Treatment Plant

1. INTRODUCTION

The population of the world had tripled in the 20th century and is expected to reach 9.1 billion in 2100 while it was 6.5 billion in 2005 (UN Estimates, 2005). This rapid increase in population coupled with industrialization and urbanization has increased the water demand. The extensive use of water resources harms ecosystems (World Water Council, 2000). Therefore, the unsustainable use of the existing water resources would create a water crisis with detrimental impacts on the ecosystem.

In smaller scale, populous cities are highly vulnerable in terms of their water management practices since their water demand is already high and increasing more rapidly due to urbanization. Istanbul is the largest and most populous city in Turkey with a population of 14.8 million (2016) and 18.5 % of the country lives in Istanbul (TUİK, 2017). Since the mid 1990s, Istanbul's economy has been one of the fastest growing Organisation for Economic Co-operation and Development (OECD) areas (OECD, 2008). While the population growth rate of Istanbul was 0.98% in 2008, it was 1.95% in 2015 (TUİK, 2017). In addition to this rapid increase in its population, Istanbul has 40% of the country's industry (Eroglu et al., 2001). Industrialization and urbanization enhance the socio-economic activities in the city and living standards of the citizens. Yet, increasing urbanization has detrimental impacts on the natural resources, creates pollution, increases rates of deforestation, and degrades fresh water resource quality (McDaniel, 2017). Furthermore, population increase, urbanization, and ameliorated lifestyles often lead to consuming natural resources more and consequently increasing water demand of the individuals (McDaniel, 2017). Istanbul's population is expected to reach 17.6 million people in the year 2025 according to the assessment of the Turkish Statistical Institute (TUİK, 2018). Thus, with the increasing pressures of population increase and urbanization, Istanbul needs a more sustainable water resource management schema.

With climate change, the average temperature of the world has increased due to anthropogenic facilities such as burning fossil fuels and industrial activities. As temperature increases, evaporation also increases and it creates a reinforcing effect on the temperature rise at the global scale. The water resources are decreasing and temperature rise enhances the depletion of water resources by affecting the climate patterns through changes in the water cycle such as precipitation and evaporation. Thus, climate change has a significant effect on water resources, which should be seriously taken into account.

Water scarcity has been exacerbated with climate change. The best indicator of water scarcity is the level of renewable freshwater amount per person. Water scarcity is defined as having insufficient amount of available water resources to meet water need over a region and the level of water stress is decided regarding the renewable freshwater amount per person (FAO, 2012). When the annual freshwater amount is below 500 m^3 per person over a region, it is counted as absolute water scarcity. When annual freshwater supplies of a country or region is between 1000 and 1700 m^3 per person, the population faces regular water stress (FAO, 2012). Thus, Istanbul is a water-stressed metropolis based on its annual freshwater amount per person, 1.519 m^3/ pers.yr (DSİ, 2017).

Projected climate change and urbanization will further impact the existing water resources, which will exacerbate the water stress of the metropolis and jeopardize water security in the near future. Additionally, according to the United Nations Development Programme (2006), poor management of water resources is mostly the cause of water scarcity. The water demand of Istanbul becomes an important parameter in preparing a sustainable development plan for the city with increasing population, changing lifestyle patterns, rapid urbanization and changing climatic conditions. Therefore, sustainable water management practices are needed to achieve water security. In the scope of this purpose, WEAP (Water Evaluation and Planning Systems) modeling program is used as a tool to understand the water demand and supply balance in Istanbul until 2100 and evaluate the temporal change in water security.

The design of the WEAP enables the user to construct their own spatial and physical area. With this flexibility over a specific region and the capacity of observing the water balance over an area, WEAP modeling tool is used to model the future water balance of Istanbul. The catchment area is modeled by adding water supply and demand nodes and analyzed under different scenarios to represent the plausible changes in population, lifestyles, technology and climatic conditions until 2100.

While WEAP model is important to provide crucial information about the effects of socio-economic activities and climate change over water resources in Istanbul catchment basin, the results of scenario analysis can guide policymakers to develop sustainable water management strategies while securing water for the future.

2. LITERATURE REVIEW

The use of modeling tools has a crucial role in natural resources management. The models are important to predict and analyze the future outcomes under different scenarios. In water management, models are used for forecasting and therefore preventing possible negative future outcomes resulting from the unsustainable management strategies. To minimize the negative impacts and challenges in water resource management, caused by human activities such as industrial facilities, there has been a need to study the watersheds in a holistic manner caring for social, economic and environmental objectives and providing water security. Thus, Integrated Water Resources Management (IWRM) concept has been developed (GWP, 2013).

To decrease the pressure on water resources created by multiple stressors like climate change, urbanization, population increase, good governance is key to implementation of better water management (UNWWAP, 2006, 2009). Governance should integrate all processes shaping society, economy and environment (Water Initiative, 2011). Furthermore, the sustainable utility from freshwater resources depends on the better managed water storage and allocation processes. From these perspectives, IWRM approach serves as an efficient way for the administrative decisions of the water storage and allocation processes.

2.1. Water Security

Water security is one of the biggest challenges of 21st century as water demand and the pressure of climate change increase (Wagener et al., 2010). Unfortunately, today, almost 80 % of the world’s population is highly threatened by water insecurity (Vorosmarty et al., 2010). The main idea of water security is to balance human and environmental water needs. However, water security is an evolving field (Srinivasan et al., 2017) and there are different definitions with a wide variety of perspectives to water security concept. Definition of water security varies for different subject areas (Table 1.1). For the areas of water resources management and policy, the definitions touch upon the issues of water scarcity, supply security, interdisciplinary linkages, sustainable development, and protection of water systems against floods and droughts (Cook and Bakker, 2012).

Table 1.1. Approaches to water security (adapted from Cook and Baker, 2012).

Subject Area	**Water security focus or definition**
Agriculture	➢ Input to agricultural production and food security
Engineering	➢ Protection against water related hazards ➢ Supply security
Environmental science	➢ Access to water functions and services for humans and the environment ➢ Water availability in terms of quality and quantity ➢ Minimizing impacts of hydrological variability
Fisheries, geology/geosciences, hydrology	➢ Hydrologic (groundwater) variability ➢ Security of the entire hydrological cycle
Public health	➢ Supply security and access to safe water ➢ Prevention and assessment of water contamination in distribution systems
Anthropology, economics, geography, history, law, management, political science	➢ Drinking water infrastructure security ➢ Input to food production and human health ➢ Violent conflict (motivation for occupation or barrier to cooperation) ➢ Minimizing (household) vulnerability to hydrological variability
Policy	➢ Interdisciplinary linkages (food, climate, energy, economy and human security) ➢ Sustainable development ➢ Protection against water-related hazards ➢ Protection of water systems against flood and droughts ➢ Sustainable development of water resources to ensure access to water systems
Water resources	➢ Water scarcity ➢ Supply security (demand management) ➢ “Green” (vs “blue”) water security

Although the focus areas and definitions change, there is a popular definition of water security by the Global Water Partnership: ‘‘Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced" (GWP, 2010). While the early definitions were mainly focusing on human water needs, this recent definition by GWP emerged after realization of how critical ecosystem services and biodiversity are destroyed resulting from the indiscriminate implications (Srinivasan et al., 2017). The GWP definition for water security, which is often used by academic scholars, encompasses seven variables; meeting basic needs, securing the food supply, ecosystem protection, sharing water resources, risk management, valuing water and water governance (Cook and Bakker, 2012).

Although the GWP definition of water security includes a broad range of topics, it misses some crucial points as it is challenging to find an approach bringing all dimensions of water security together (Srinivasan et al., 2017). One challenge is the spatial water insecurity, securing water in one place may lead to insecurity in another place since water is a mobile and shared resource. For example, water security assessment at the national level would not convey local scale water security issues. (Vorosmarty et al., 2010). For instance, Canada has regional water scarcity challenges even though the country is one of the water-rich areas in the world. Temporal water security is another challenge. For example in Chennai, the region became more water insecure in the medium to long term even though urban households became individually more secure in the short term after the investment in wells in urban areas (Srinivasan et al., 2013).

Since there are various perspectives and definitions to water security, the focus areas and themes differ in the water security literature. One of the rigorous literature review conducted by Cook and Bakker (2012) divides the water security literature into four themes; water security assessment tools focusing on water quantity and availability, water related hazards and vulnerability, human needs including food security and human development related concerns, and sustainability of water resources.

Each region has some special needs regarding its spatial properties and industrialization level. Thus, the regions may define their water security focus regarding their individual needs on water management. The research of Cook and Bakker (2012) shows the special framings of water security for Australia, China, and the Middle East and North Africa. For instance, Australia is accepted as the world's most arid continent and the water security definition in Australia has been focusing on the water availability predominantly. Australian government has four priorities while taking action for water security; climate change, using water wisely, securing water supplies and supporting healthy wetlands and rivers (Government of Australia, 2010).

The populous and industrial part of China is highly water insecure (Xia et al., 2007). To achieve water security in the region, the officials focused on water quality and quantity. Furthermore, the Middle East and North Africa (MENA) region focuses on sharing a scarce resource and increasing demand (Cook and Bakker, 2012).

For measurement of water security and comparison of countries in terms of water security levels, indices have been widely used. There are two early indices gaining importance in this measurement; Falkenmark Water Stress Index and Water Resources Vulnerability Index. These indices are focusing on the ‘physical’ water scarcity, so they have some inadequacies such as measuring access to water and issues of water infrastructure. Since infrastructural incapabilities may cause inefficient management of water, especially in less developed countries, and decrease their water security level, International Water Management Institute (IWMI) introduced the Water Poverty Index as another index to see the level of water insecurity of the countries (Srinivasan et al., 2017).

Climate change, as one of the water security challenges, leads serious environmental damages such as droughts, floods, wildfires and biodiversity loss while it is creating changes in water hydrology. Even though the global average precipitation increases, land surface has experienced decreased precipitation and runoff due to increasing evaporation, and oceans have mostly experienced increased precipitation. Thus, runoff decline occurs mostly in mid-latitudes and sub-tropicals and increases in high latitudes, southeast Asia, equatorial Africa and Asia (Arnell, 1999).

The climate change impacts differ regionally. For instance; Asia will face decreased freshwater availability and increased pressure on natural resources due to rapid urbanization and economic activities, while in Europe the impacts will mostly be experienced as high temperatures, droughts, increased heatwaves. Furthermore, in Latin America, disappearance of glaciers will probably affect the water availability and there is a risk of significant biodiversity loss in its tropical areas (Bulkeley, 2013). The regions around the Mediterranean, in central and southern Africa, Europe, central and southern America will face the increased impact of climate change on water resources stress (Arnell, 2004).

Rapid industrial development also challenges water security since it endangers the biodiversity and human health by causing pollution (Bogardi et al., 2012). Furthermore, cities reflect the level of social and economic activities which produce greenhouse gas emissions (Bulkeley, 2013). So, the populous cities with their rapidly growing population are regarded as a possible climate change problem, and the rapid urbanization and economic facilities are increasing the vulnerabilities of the cities to climate change.

While the pressure on water resources keep increasing under the negative effects of anthropogenic climate change (Vorosmarty et al., 2010), there is an increasing need of a broad range of perspectives and implications in water resources management to secure water needs. Regarding also the challenges on the water security, water governance is both key to the broad and integrative framing of water security and effective to manage multiple stressors on water resources successfully (Cook and Baker, 2012, and UNWWAP, 2006, 2009).

2.2. Integrated Water Resources Management (IWRM)

Integrated water resources development, use, and management strategies are regarded as the most effective way to achieve sustainable development of water resources in a changing environment with competing demands and hence it is considered a key to sustainable development. Integrated Water Resources Management is a systematic process for the sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objective (Biswas, 2004). In order for providing the sustainability of the water resources usage, an integrated management approach is needed capturing the change in socio-economic conditions and climatic variables at the catchment areas. Therefore, the Global Water Partnership (GWP) constructed the concept of Integrated Water Resources Management (IWRM).

The Global Water Partnership defines IWRM as “a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2013, p. 6). IWRM is developed for satisfying the need of equity, environmental sustainability and securing the water supply. Today, IWRM is used to ensure the water security which becomes a primary need for the sustainability of the water resources management.

IWRM captures the principles of water security: ‘‘a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’’ (Global Water Partnership, 2000). “Both definitions of IWRM and water security point out a broad and integrative framework to balance human and ecosystem needs” (Gleick, 2000; Pahl-Wostl et al., 2008; Savenije and Van der Zaag, 2008, p. 295). While the negative effects of climate change, population growth, urbanization on water resources create a challenge on planetary sustainability (Bogardi et al., 2012) and makes harder to implement successful IWRM strategies, the success of the implementation depends on the creating this balance in needs of human and ecosystem (Vorosmarty et al., 2010).

The decision problems regarding water resources such as water use and allocation, development, conservation, sustainability and sustenance of fragile ecosystems can be confusing and a decision support tool, such as a model built for understanding the water balance in a basin may bring about clarity. IWRM approach becomes valuable in this context. As economic development might create increasing demand for fresh water use, IWRM will be a fundamental tool to create a balance between the demand and conservation of the current resources. While doing so, decision makers will have to pay close attention to development and its effects.

Successful IWRM planning processes rely on an appropriate institutional framework composed of a mixture of central-local, river basin specific, and public-private organizations that provides the governance arrangements for administering. Another component of successful implementation of IWRM is enabling legislative and policy environment and a set of management instruments for gathering data and information, assessing resource levels and needs, and allocating resources for use (GWP, 2013). These components constitute a statement of the necessary governance conditions and reflect the main concern of IWRM, which is transforming governance arrangements (Medema et al., 2008).

There is a general consensus about integrated water management at catchment level as the approach to use for sustainable water resources management (GWP, 2013). It is therefore important to look at the overall basin and include all the elements in the basin that can affect and be affected by water. Addressing the issue of water security requires not only quantitative knowledge of water abstraction by each economic sector but also a strong understanding of the driving forces behind it. In any catchment, water availability problems occur when the demand for water exceeds the amount available during a certain period. Freshwater shortages occur frequently in areas with low rainfall and high population density and in areas with intensive agricultural or industrial activity.

The usage and implementation of IWRM depend mainly on the development level of the country (GWP, 2013). Countries have different targets depending on their social and economic conditions. While social conditions can affect the usage of the freshwater resources, economic conditions can have an impact on the implementation and design of the integrated water management practices. The country may or may not have enough social and economic structure to implement a particular practice. Thus, the countries utilize different IWRM tools proper to their purpose and socio- economic conditions.

When modeling for IWRM studies, the physical and spatial properties of the catchment area are crucial. The model results are more effective when they are studied for a specific catchment area because the properties of the catchment area, such as climatic variables, change by region. Therefore, it is important to choose the right IWRM tool to implement useful policy actions in water resource management which fits for the purpose and the properties of the catchment area.

2.3. WEAP as an IWRM Modelling Tool

WEAP is a useful modeling tool to understand the effects of changing environment conditions on water resources and simulate sustainable water management practice scenarios. The computer-based modeling tool was developed by the Stockholm Environment Institute (SEI). It is used as an Integrated Water Resources Management (IWRM) modeling tool, which provides a systematic approach for the sustainable development, allocation and monitoring of water resources use (Biswas, 2004).

WEAP includes a demand priority and supply preference approach (Yates et al., 2005). It describes water allocation system from water supplies to demand nodes with different priorities in allocation process of the freshwater. The WEAP modeling tool can be used to evaluate and analyze the results of different options in water allocation and monitoring processes.

The aim of WEAP is to close the gap between water management and catchment hydrology by addressing both bio-physical and socio-economic factors. While the model can be used for the policy actions, it can also be used to evaluate the impacts of likely water use on water resources like it is searched for Olifants catchment area (Arranz and McCartney, 2007). The scenarios analysis capacity and easy to use interface make WEAP a widely used IWRM model.

This tool was used for different purposes such as water supply options for the growing megacity of Yangon (Aung, 2014), rooftop rainwater harvesting for Mombasa (Ojwang et al., 2017), in the integrated assessment of no-regret climate change adaptation options for reservoir catchment and command areas in Kangsabati river basin in West Bengal, India (Bhave et. al., 2015).

The WEAP model is globally popular in the scenario analysis of water demand and supply balance (Hassan et al., 2017). In the Niger River basin, Mounir et al. (2011) used the model while searching the possible water resources management strategies. In California, the model helped to evaluate the possible impacts of climate change on water supply for irrigation in the Cache Creek watershed (McCartney, 2012). The future water demand and supply availability was also modeled using the tool in the Middle Dara Valley, Morocco while the area has been facing the land use changes caused by the climatic conditions (Mounir et al., 2011). These examples demonstrate the versatility of the model and application of different scenarios appropriate to the objective of the study. The results can guide policymakers to develop and take policy actions for sustainable water management practices.

2.4. Climate Change and WEAP

Climate change exacerbates the existing pressure on water security challenge and hence integrated water resource management practices become even more important. IWRM is accepted internationally as the way for efficient and sustainable management of water resources and for handling the conflicting water demands (UN-Water, 2017).

The priorities in adaptation to climate change should be reducing vulnerabilities of societies to shifts in climate trends, protecting the ecosystems providing water resources and closing the gap between water supply and demand (Bergkamp et al., 2003). In the absence of alternatives, vulnerability is often taken as the ability to overcome and adapt to climate stress (Adger, 2001). Thus, regarding the fact that climate change increases the vulnerability of the societies, urgent adaptation strategies are required to prevent or decrease the negative consequences of climate change. According to Adger (2001), integrated water management strategies should be studied regionally as a sustainable adaptation strategy under the changing climate regimes.

The impacts of climate change differ depending on the physical and spatial properties of the regions, and adaptation strategies differ by the social and economic capabilities of the nations. Therefore, adaptation strategies should be managed at the user level, not on a global scale (Adger, 2001). Studying on a regional scale helps to create the most efficient water resources management strategies. It also helps nations to decide their own strategies regarding the socio-economic dynamics of the population.

WEAP is an integrated water management tool commonly used in understanding the impacts of the climate change, population growth, technology on water supply and demand over a region (Rosenzweig et al., 2004). The model structure is proper to study on a regional scale and has the scenario-based approach making it easy to change desired variables and analyze the results. These opportunities are making WEAP modeling tool a highly preferred one in analyzing the climate change impact on water resources, which fits the purpose of this study as well.

The modeling tool is highly preferred in the purpose of evaluating the impacts of climate change. WEAP was used to model different regions such as The Tuolumne and Merced River Basins, Sacramento Basin in California, USA, Mahanadi River basin in India, also in Argentina, Brazil, China, Hungary and Romania to understand the water balance of the catchment areas under different scenarios such as climate change (Kiparsky et al., 2014). It provides guidance to policy makers to develop better strategies in sustainable management of the freshwater resources and gives more detailed information when the model schema is constructed on a regional scale.

2.5. Water Management in Istanbul

Istanbul is the most populous city in Turkey with 14.8 million (2016) inhabitants and 18.5 % of the country lives in Istanbul (TUİK, 2017). According to the assessment of the Istanbul Master Plan Study carried out by Istanbul Water and Sewerage Administration (İSKİ), the population of Istanbul will reach 18.1 million people in the year 2030. Also, Istanbul's population has been growing steadily with growth rate of 1.95 % in 2015, Istanbul is expected to stay as the most popular and crowded city in Turkey in addition to being the center of industrial activities in Turkey (Table 2.1).

Table 2.1. Population of Istanbul with respect to years (TÜİK, 2015).

Years	**1990**	**2000**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Population (people)	6.629.431	8.803.468	12.573.836	12.697.164	12.915.158	13.255.685	13.624.240	13.854.740	14.160.467
Population Growth Rate (%)	3.90	2.88	0.98	1.7	4.52	2.64	2.76	1.68	2.2
Population Intensity (person/km^2)	1280	1747	2420	2444	2486	2551	2622	2666	2725

While Istanbul's population growth rate was 3.9 % in 1990, it reduced to 1.68 % in 2012. Yet, the number of people per kilometer continues to increase. While population density was 1280 person/km^2 in 1990, it rose to 2666 person/km^2. So, the population density of the metropolis Istanbul also keeps increasing rapidly.

Furthermore, compared to other cities of the country, Istanbul is still the hub for industrial and socio-economic activities, therefore continues to attract migrants every year. Migration to the city, together with the socio-economic activities and urbanization, leads to insufficient infrastructure. The rapid urban development increases water demand and creates major infrastructural problems such as water supply, treatment and disposal (Eroglu et al., 2001).

Due to the rapid increase in the urban development projects and abundance of industry in the city, Istanbul is highly dependent on its water resources. The city had difficulties in meeting its water demand throughout its 2700-year history. It had experienced a drought between 2006 and 2008, recording the lowest rainfall in 50 years (Revolve Water, 2015). Besides the effect of climate change, poor urban planning in the infrastructure of the metropolis Istanbul is seen as a further cause of water shortages (Sokollu, 2014). Istanbul recently experienced major infrastructural issues in water management such as insufficient water supply, unsatisfactory wastewater treatment and disposal (Eroglu et al., 2001). A number of solutions such as construction of new reservoirs, exploitation of groundwater reservoirs, desalination of seawater, reuse of reclaimed wastewater, transfer of water from water-rich parts of Turkey by ocean tankers or balloons, reduction in water losses were suggested (Eroglu and Sarikaya, 1998). Since Istanbul is a developing city which has a poor infrastructural planning (Sokollu, 2014) and the water demand of the city is expected to increase, there is a need for good water management strategies in the transition process to sustainable water supply service (Yuksel et al., 2004).

Since 1994, Istanbul Water and Sewerage Administration (İSKİ) is prioritizing finding new water supply sources for the city to solve the water balance issues. Records of early 2000s reveal that, after the addition of new supply sources, the water supply has exceeded the water demand (Yuksel et al., 2004). However, Istanbul continued enlarging its physical boundaries and at the same time, the population of the urban area continued increasing. Currently, to fulfill the water demands of the metropolis Istanbul, İSKİ is investing on retrieving water from Melen River, which actually lies within the city limits of Düzce, nearly 250 km away from the city.

Melen Project started in 2007 and it supplied 263 million m^3/year freshwater to the city in 2017 (İSKİ, 2017). The project started with the construction of Melen regulator in 2007 and the water amount supplied by Melen River is increased with the second regulator constructed in 2014. İSKİ is currently building Melen Reservoir as a next step in the project to increase the water supply to the city (İSKİ, 2018a). When the reservoir construction is completed, the city will obtain even higher quantities (1077 million m^3/year) of freshwater from the Melen River.

Besides the highest current and future dependency to Melen River, there are three other external reservoirs the city has supplied water from; Istrancalar, Kazandere and Pabuçdere Reservoirs (İSKİ, 2018b). While Istrancalar Reservoir refers to the collection of five different reservoirs located on five streams (Düzdere, Kuzuludere, Büyükdere, Elmalıdere, Sultanbahçedere) which are supplying water in small amounts (6.2 million m^3/year in total), Kazandere and Pabuçdere Reservoirs have higher storage capacities (17.5 and 58.5 million m^3/year respectively). These reservoirs lie within the city limits of Tekirdağ located in the northwest of Istanbul and supply freshwater to the city since 1999.

Regarding the water security challenges, supplying water from non-local resources constitutes 'operational challenge' while it also has a possibility to affect the security level of the other areas around (Srinivasan et al., 2013). It reveals the necessity of a more holistic approach to provide a better water governance schema to secure water (Cook and Bakker, 2012). Hence, while socio-economic dynamics such as high population growth and urbanization in Istanbul also keep increasing, a more holistic approach in water management may be needed to secure the water resources today and in the future.

2. METHODOLOGY

In this study, WEAP modeling tool is used to analyze Istanbul's future water situation under different scenarios of socio-economic development, urbanization and climate change until 2100.

WEAP enables users to model water supply and demand balance over a catchment area. Thus, the model requires data for variables and parameters about the study area and catchment hydrology to calculate the water demand of the city and the existing supply of water. Figure 3.1 shows the activities in constructing the WEAP model.

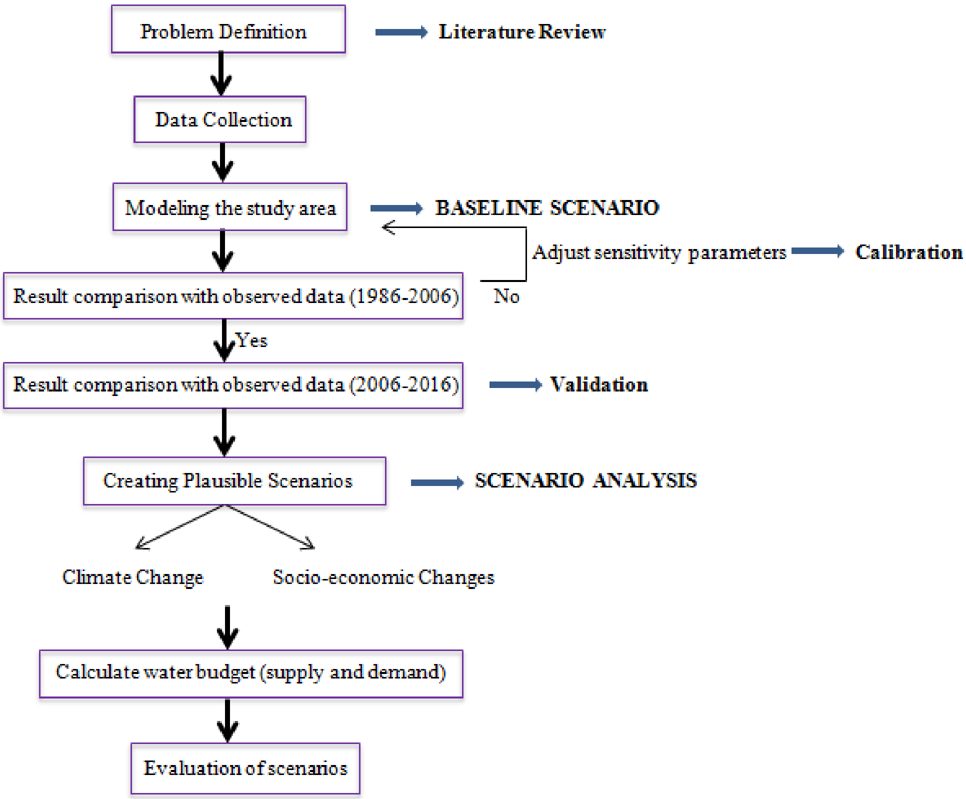


Figure 3.1. Flowchart of the activities in WEAP model.

2.1. Study Area

Istanbul is the largest city in Turkey, which has the highest population, 14.8 million in 2016, with a growth rate of 1.95 % in 2015 (TUİK, 2017). It also has the highest urbanization rate as being the center of socio-economic activities. So, the water demand of the city is increasing with the result of fast population growth and urbanization.

Moreover, the city has been facing water shortages throughout its history. The lowest rainfall in the last 50 years was recorded in 2006 (İSKİ, 2013). Regarding the demand increase and water shortage effects on water resources, integrated water management practices therefore gain more importance.

The freshwater demand of the city is supplied by 13 water resources including 10 reservoirs and 3 regulators (Yesilcay, Melen-1 and Melen-2 Regulators). The reservoir capacities and initial storage levels are listed in Table 3.1. The data regarding water resources are obtained from Istanbul Water and Sewerage Management (İSKİ), 2017.

Table 3.1. Water Reservoirs in Istanbul (11.09.2017).

Reservoirs	**Reservoir Capacity** **(**Million m³)	**Initial Storage Volume** (Million m³)	**Year of establishment**
Ömerli	235.4	162.97	1973
Terkos	162.3	102.75	1971
Büyükçekmece	148.9	82.16	1988
Kazandere	17.5	10.53	1999
Darlık	107.5	57.14	1988
Istrancalar	6.2	2.81	1999
Pabuçdere	58.5	35.13	1999
Sazlıdere	88.7	40.10	1996
Elmalı	9.6	0.73	1955
Alibey	34.1	24.72	1983
TOTAL	**868.7**	**518.35**	

Predominantly, Istanbul supplies its water need from surface water (Istanbul Governorship, 2015). Approximately 30 million m^3 per year groundwater is supplied in Istanbul (Baban et al., 2011) and General Directorate of Water Management Report (2016) does not list the groundwater as a major water supply source. Comparing to other existing sources, it is negligible since it accounts for a very small portion of the demand (van Leeuwen, 2015). Therefore, there is no groundwater node as a water supply in this model.

Istanbul has 13 water treatment plants (WTP), namely Ömerli, Kağıthane, Büyükçekmece, Elmalı, İkitelli, Taşoluk, Şile, Ağva, Bıçkıdere, Hacı Osman, Yalıköy, Danamandıra and Cumhuriyet

(İSKİ, 2017). The water is collected and stored in reservoirs, which are listed in Table 3.1. Then, freshwater is distributed to the municipalities after being treated in water treatment plants. There is an exception in the storage system, which is the latest water management project of Istanbul, Melen Project. After the construction of the first Melen regulator in 2007, Cumhuriyet Water Treatment Plant was built and the second Melen regulator was completed in 2014 to increase the water supply. The water coming from the Melen River is directly transferred to Cumhuriyet Water Treatment Plant and then distributed to assigned municipalities.

Cumhuriyet Water Treatment Plant was completed in 2012 and it currently supplies 720,000 m^3 /day freshwater to the city (İSKİ, 2017). İSKİ plans to construct a new reservoir as a next stage of the project to increase the water supply to the city. This reservoir is expected to be the largest water treatment plant of Istanbul after the completion of all stages. Once all stages are implemented, the city will obtain even larger quantities of freshwater from the Melen River, which is is an external water resource and lies approximately 250 km away from the city.

Istanbul has 39 municipalities in 2018. The municipalities are namely Adalar, Arnavutköy, Ataşehir, Avcılar, Bağcılar, Bahçelievler, Bakırköy, Başakşehir, Bayrampaşa, Beşiktaş, Beylikdüzü, Beyoğlu, Büyükçekmece, Beykoz, Çatalca, Çekmeköy, Esenler, Esenyurt, Eyüp, Fatih, Gaziosmanpaşa, Güngören, Kadıköy, Kağıthane, Kartal, Küçükçekmece, Maltepe, Pendik, Sancaktepe, Sarıyer, Silivri, Sultanbeyli, Sultangazi, Şile, Şişli, Tuzla, Ümraniye, Üsküdar, Zeytinburnu. The water supply sources (Table 3.1) including the Melen River supply the water demand of the listed municipalities.

2.2. WEAP Modelling Tool

WEAP is a useful modeling tool to calculate water supply and demand under varying hydrologic and policy scenarios. The model aids stakeholders to achieve sustainable water management practices. The modeling tool is used when the catchment area is studied with an Integrated Water Resources Management (IWRM) perspective, which provides a systematic approach for the sustainable development, allocation and monitoring of water resources use (Biswas, 2004). It is one of the widely used IWRM models and enables to create links between water demand and supplies.

WEAP includes a demand priority and supply preference approach (Yates et al., 2005). It formulates a water allocation system by linking water supply nodes to demand nodes with different priorities in allocation process of the freshwater. The demand priorities change with respect to their demand types such as agriculture, domestic, industry and municipality.

The aim of WEAP is to close the gap between water management and catchment hydrology by addressing both bio-physical and socio-economic factors. While the factors like climate, water hydrology and water quality are the ones related with the bio-physical properties of the catchment area, the issues related with population growth, water use efficiency and policy initiatives are accounted as socio-economic factors (Yates et al., 2005).

A crucial property of the model is that WEAP provides results under different scenarios such as climate change and socio-economic changes (Yates et al., 2005). The scenario-based approach provides a better understanding of the specific variables to the system such as water use and population change. Scenario analyses can be obtained by changing the values of the supply and demand node variables. The effects of climate variability, ecosystem changes, watershed condition, potential shortages and the results of different water management practices can be analyzed using different scenarios.

WEAP modeling tool has a user-friendly interface. It has five different views of the study area; the schematic view, data view, results view, scenario explorer view and notes view. The design of the WEAP enables the user to construct its own spatial and physical area. GIS layers can be added to provide clarity and act as a background in the schematic view of WEAP. Water supply and demand nodes can be determined with respect to spatial and topographical properties of the area. The flow chart of the water can be constructed by creating links between demand and supply nodes. The water balance at the catchment area is calculated as a final result, showing that how water demand and the water supply will change in time depending on the demands and hydrology of the catchment area. Another useful function of WEAP is its capability to integrate the outputs from other modeling environments. The data can easily be imported from or exported to a CSV, ASCII, Excel, Word, HTML or XML file (Sieber et al., 2015).

2.2.1. Data Requirements

WEAP creates links between water demand and supply nodes to model the water balance over a region, hence requires water demand and supply data for Istanbul. Also, data are required for modeling the catchment hydrology and the connection links between water demand and supply nodes. Catchment data need changes with respect to catchment simulation method. There are five catchment simulation methods in WEAP; Irrigation Demands Only Method (Simplified Coefficient Method), Rainfall Runoff Method (Simplified Coefficient Method), Rainfall Runoff Method (Soil Moisture Method), MABIA Method and Plant Growth Model (Sieber et al., 2015).

In this study, Rainfall Runoff Method (Simplified Coefficient Method) is preferred regarding the spatial and climate properties of the catchment area. The data requirements for this study are listed in the Table 3.2.

Table 3.2. Data Requirements on WEAP Model with Rainfall Runoff Method (Simplified Coefficient).

		DATA REQUIREMENTS	**UNIT**	**TIME FRAME**	**SOURCE**
Water Demand		Annual Activity Level (domestic)	capita	1986-2016	Turkish Statistics Institute (TUİK)
Water Demand		Water Use Rate (domestic)	m^3/activity	1986-2016	Istanbul Water and Sewerage Administration (İSKİ)
Water Demand		Water Use Rate (industrial)	m^3/annual activity	1986-2016	Organized Industrial Zones Information Site
Water Demand		Monthly Variation (of water use)	percent (%)	one year	Istanbul Water and Sewerage Administration (İSKİ)
Water Supply		Storage Capacity	m^3	1986-2016	Istanbul Water and Sewerage Administration (İSKİ)
Water Supply		Volume-Elevation Curve	m^3/m	1986-2016	Government Water Affairs (DSİ)
Water Supply		Net Evaporation	mm	1986-2016	General Directorate of Meteorology (MGM)
Water Supply		Observed Volume	m^3	1986-2016	Istanbul Water and Sewerage Administration (İSKİ)
Water Supply		Losses from System	percent (%)	1991-2014	Istanbul Water and Sewerage Administration (İSKİ)
Water Supply		Supply Preference Info*	unitless	1986-2016	Istanbul Water and Sewerage Administration (İSKİ)
Catchment Hydrology	**Land Use**	Land Class	percent (%)	1986-2016	Istanbul Branch of TMMOB Chamber of Environmental Engineers Report, 2014 and Oncu Atasayan, 2003
Catchment Hydrology	**Land Use**	Area	km^2	1986-2016	
Catchment Hydrology	**Land Use**	Crop Coefficient*	unitless	consistent	SacWAM Documentation. 5-16– Draft, September, 2016
Catchment Hydrology	**Land Use**	Effective Precipitation*	unitless	consistent	calculated by Smith (1992) Effective Rainfall Method
Catchment Hydrology	**Climate**	Precipitation	mm	1986-2016	General Directorate of Meteorology (MGM)
Catchment Hydrology	**Climate**	Evapotranspiration	mm	1986-2016	Boğaziçi University Climate Change and Politics Application and Research Center (İKLİMBU)

* used as a sensitivity parameter

Demand data are categorized as municipal, domestic, industry and irrigation demand in WEAP modeling tool. Water demand is basically calculated as multiplication of annual activity level with annual water use rate. In the model, demand nodes mainly represent municipalities. So, for the catchment area of Istanbul, domestic water demand of the city is calculated by the multiplying the population of a municipality with water use rate per person. Population growth is a driving force for the increase in water demand. The population data of each municipality in Istanbul with respect to years and the water use per person are obtained from TUİK. The values are imported to WEAP with their annual amounts.

As a consequence of dense industrialization in the metropolis Istanbul, industrial water demand gains high importance, while modeling the water demand and supply balance. Yet, irrigation demand of the city is not placed in the WEAP model since the reservoirs in the Marmara Catchment Region are not used for irrigation as explained in General Directorate of Water Management Report (2016).

For water supply calculation, the model requires data regarding the reservoirs and catchment hydrology. The necessary data for reservoirs are storage capacity, volume-elevation curve and net evaporation in the Rainfall Runoff Method (Simplified Coefficient Method). In the WEAP model, river head flow can either be specified as direct input values or be specified as originating from a catchment node (Sieber et al., 2015). Catchment node can also be directly linked with a reservoir as inflow information in WEAP.

For the climate data, precipitation and reference evapotranspiration (ETref) data are required for the Rainfall Runoff Method (Simplified Coefficient Method) in WEAP. Etref data differ with respect to land classes. Thus, it should be set for a reference land class, namely forest, grassland or urban for Istanbul.

3.2.2. Baseline Scenario

The baseline scenario represents the current situation in the Istanbul catchment basin both hydrological and socio-economically. The WEAP model, as stated previously, models the water supply and demand balance in the catchment. For a realistic representation of the Istanbul both for water demand and supply, a number of data sources are consulted (listed in Section 3.2.1).

Geographic Information Systems (GIS) layers are added to WEAP as a background in the schematic view to provide clarity of the study area. The boundaries of the study area are determined to include the locations of freshwater resources in the water supply system of Istanbul. The simulation period for the model is set from 1986 to 2100.

In WEAP modeling tool, water supply and demand nodes are geo-referenced with with respect to spatial and physical properties of the area. The schema in the catchment area can be constructed by creating links between demand and supply nodes. In this study, the water flow direction starts from catchment nodes to reservoirs as fresh water supply sources. They are connected by runoff and infiltration link. Then, the water in reservoirs is directed to demand nodes, which are municipalities of Istanbul, using transmission links.

One reservoir serves more than one municipality and one municipality is served by more than one reservoir. There are redundancies in the system to increase the resilience of the water delivery network. While creating transmission links from reservoirs to municipalities of Istanbul, which are water supply and demand nodes respectively, the information about which water treatment plant supplies fresh water to which municipalities are used to construct the model with more accurate results. The related information is obtained from İSKİ (Figure 3.2).

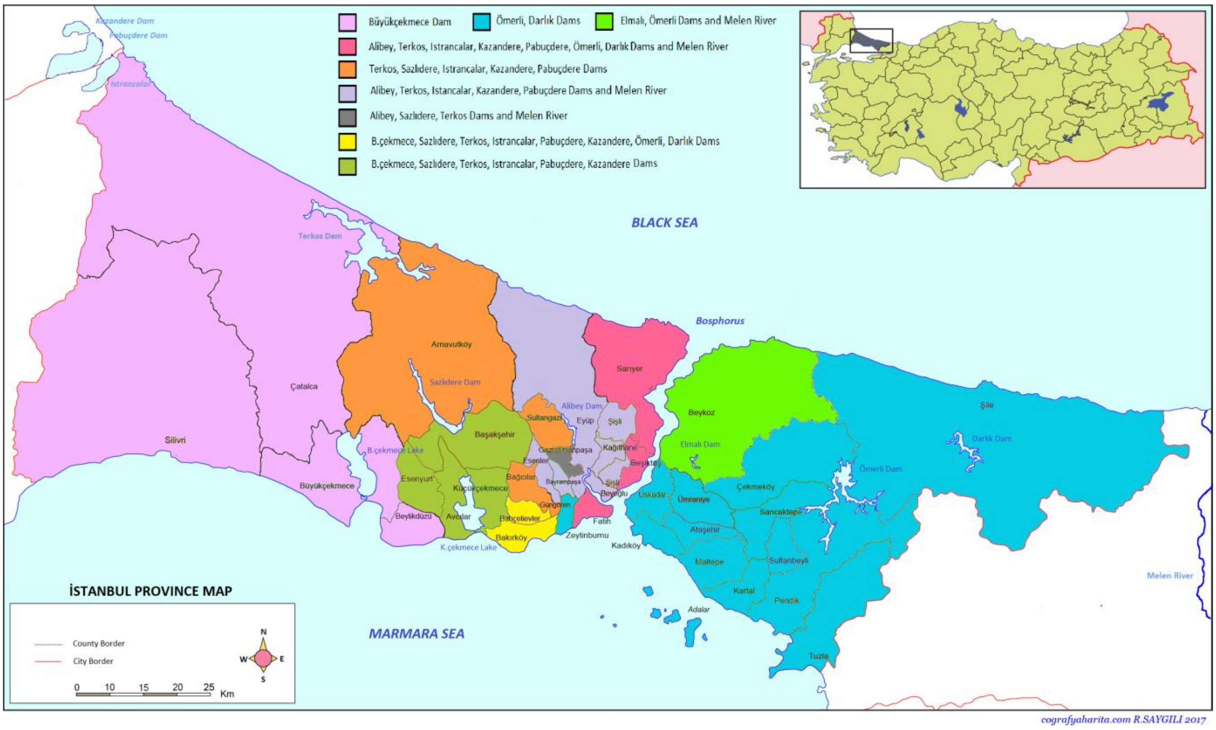


Figure 3.2. Distribution of water supplies to each municipality in Istanbul.

There are only reservoir nodes as a water supply in the model. In Rainfall Runoff (Simplified Coefficient) Method, the model requires the head flow data if there is a river as a water supply. Still, even if the head flow information is not inserted, the WEAP model is able to use the catchment hydrology to calculate the flow amount (Sieber et al., 2015). The same procedure applies for the calculation of inflow from reservoirs. Therefore, the rivers are not included as water supply sources in this model. The reservoirs have the necessary inflow amount supplied from catchment hydrology.

In Istanbul, water from the Melen River is directly treated in Cumhuriyet WTP, before being distributed to the municipalities. Thus, Cumhuriyet WTP is accepted as a reservoir node in the model similar to other reservoirs both for a better representation in the baseline and construction of the future scenarios. Hence, reservoirs as the water supply nodes in this study become Alibey, Büyükçekmece, Sazlıdere, Terkos, Istrancalar, Kazandere, Pabuçdere on European side and Ömerli, Darlık, Elmalı, and Cumhuriyet on Asian side in Istanbul.

The water demand nodes are the municipalities of the city which are supplied by reservoirs listed above. Therefore, while Istanbul has 39 municipalities, there are 11 demand nodes in the model, one of which is an industrial demand node. Figure 3.2 provides the information about which municipalities supply their water demand from which reservoirs. The WEAP model requires a schematic representation of the demand and supply nodes (Figure 3.3).

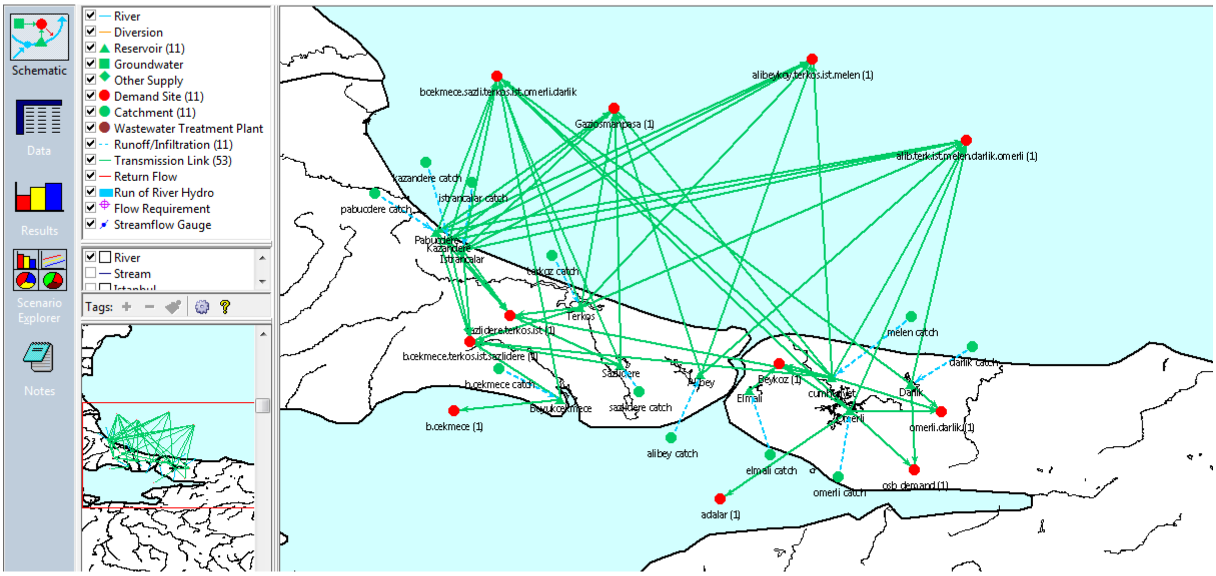


Figure 3.3. Model Schema.

Creating key assumptions is a user friendly property of WEAP model. It provides users to apply a change to all nodes at the same time. It is also very useful and time saving property, especially in the process of calibration and validation as well as scenario construction. Five key assumptions in this model are; annual water use rate per capita, monthly water use variation, effective precipitation, crop coefficient, and loss from system.

<u>*3.2.2.1. Water supply.*</u> The water supply nodes in the model are reservoirs located in and served by catchments. Data requirements for reservoirs include inflow, storage capacity, volume elevation curve and net evaporation data. These data are mainly the physical properties (Table 3.2). Yet, the WEAP model calculates the inflow to reservoirs using the catchment node data in the model.

Catchment hydrology requires mainly two data sets; land use and climate data. Land use data contain land class types and the information of (i) area, (ii) crop coefficient (transpiration and evaporation from crop surface) and (iii) effective precipitation (the percentage of rainfall available for evapotranspiration) for corresponding land classes. In this study, land classes are considered as forest, grassland and urban. It is crucial to insert land use change since the model WEAP is sensitive to area changes of corresponding land classes and utilizes land use data in calculating the water supply.

In the model, Effective Precipitation (Pe) value is represented in three different subgroups since Pe values in the catchment areas differ with respect to land use types such as the tree type in the forests or grass type. So, different Pe values are defined to the related catchment nodes which have closer land use type. Crop coefficiency (Kc) value differs only with respect to land use types (forest, grassland and urban) since it depends on the characteristics of the land use types.

Observed volume of the reservoirs can also be inserted the model. It is optional since the model uses observed volume data for the calibration of the model. After inserting the observed volume of the reservoirs into the model, WEAP enables the user to compare the simulated and observed volumes of each reservoir (Figure 3.4). Thus, this function is useful for the calibration process.

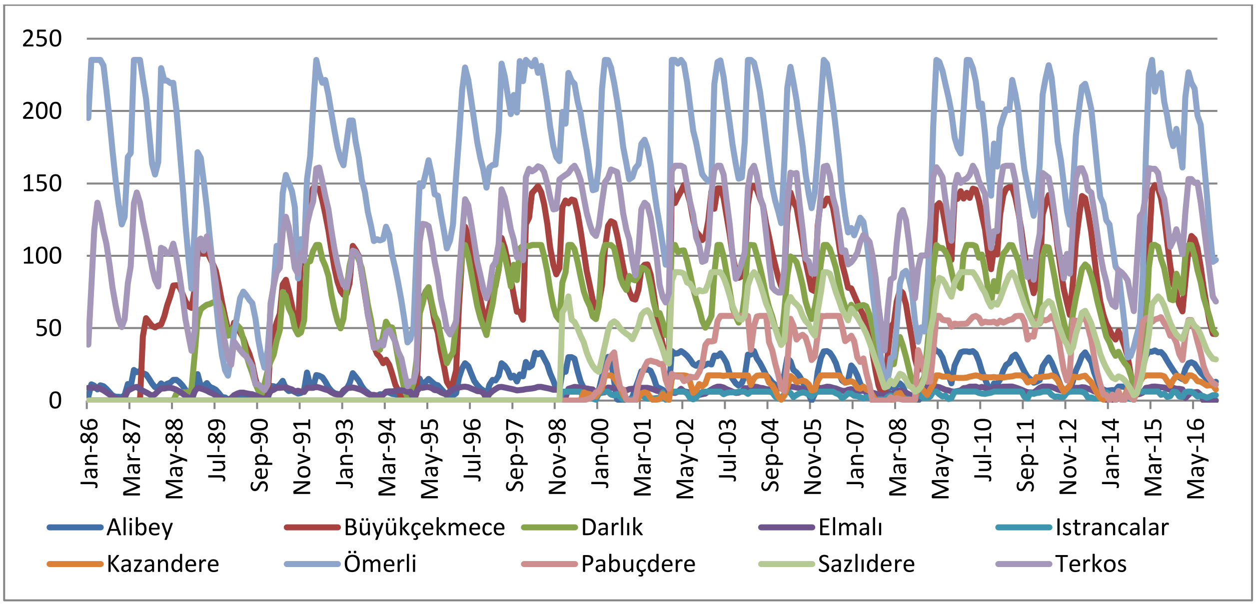


Figure 3.4. Storage Volumes of Reservoirs in Istanbul (million m^3)

Inflow of reservoir is calculated in the same way as rivers in WEAP. Catchment node can be directly linked to a reservoir as inflow data. The model calculates reservoir inflow using catchment climate data. Because of the complexity in the distribution of water supply, the model is sensitive to the calculations related to the reservoirs. The model may calculate inflows to reservoir in the time before the establishment of the reservoir. Thus, the storage capacity data of reservoirs are set starting from the establishment years of reservoirs to avoid any further miscalculations in the background of the model.

Catchments are connected to reservoirs using the runoff/infiltration link. Thus, inflow to reservoir can be calculated using catchment hydrology in WEAP. If there is more than one reservoir linked to the same catchment, runoff fraction should be specified to show the model runoff rate to each reservoir and it is required only if Rainfall Runoff Method (Simplified Coefficient Method) is used. In this study, each reservoir belongs to different catchment nodes, so there is no need for determining runoff fraction. Other data requirements for reservoirs are inserted to the model manually.

Net evaporation rate is also necessary for informing the model about water loss or gain amount in the surface of reservoir. It equals to the difference between evaporation and precipitation on the reservoir surface (Sieber et al., 2015). Evaporation rates in the surface of reservoirs, for the calibration and validation years (1986-2016), are obtained from the General Directorate of Meteorology (MGM).

3.2.2.2. Water demand. Water demand of the city is divided into two types; domestic and industrial. Domestic demand defines the water need at the household level. It is calculated using the population and water use data per capita (Appendix A, Table 1, Figure 1). Furthermore, industry demand accounts for the water use amount required for the industrial activities. As agricultural water need of the city is negligible (van Leeuwen, 2015), the domestic and industrial demands constitute the water demand of Istanbul.

For the major modeling assumptions, the user-friendly interface of the model WEAP enables to create key assumptions such as water use rate. This function of WEAP model provides users to apply a change to all nodes simultaneously. It is a useful and time saving property of the WEAP model (Sieber et al., 2015).

WEAP enables to insert the data of water demand parameters as annual activity levels such as population for domestic water need, industrial output or agricultural area. In this study, there are domestic and industrial water demands. For water demand calculations, the model multiplies population with water use rate for domestic water demand while industrial activity data include total water need for industrial activities. Activity levels are accepted as a measure of social and economic activity in the demand analysis of WEAP (Sieber et al., 2015). It is practical to apply annual water use rate as a key assumption, especially in the analysis of socio economic change scenario. However, in this analysis, the water use rate is not taken annually static but reflects monthly variation as well.

For the industrial demand of Istanbul, the data of annual water use are the only data obtained, which correspond to total annual water usage for industrial activities (Appendix A, Figure 2). Thus, the industrial demand node is constructed only by inserting the annual water use rate and monthly variation (i.e. there is no annual activity level specified for industrial water demand in this model).

Moreover, it is observed that the model is sensitive to the function types while entering data using yearly time-series wizard. The wizard is a tool to help constructing time series expressions in WEAP. These expressions include functions ranging from interpolation, step functions, smooth curves to linear, exponential and logistic projections (Sieber et al., 2015). In this study, linear and exponential projections are used regarding the past and future projections of data in consideration. Since some data do not cover the complete simulation period, the wizard function is useful to fulfill the missing values and to predict the behavior of such parameters. This tool is mainly used for interpolating area changes of land use types and possible population amount for the unknown years.

3.2.3. Calibration and Validation

WEAP has no built-in automatic calibration and validation routines, therefore calibration was done manually by comparing observed and simulated time series. Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty (Arnold et al., 2012). Model calibration is performed by carefully selecting values for model input parameters after comparing model predictions (output) for a given set of assumed conditions with the observed data for the same conditions. Validation involves running the model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration (Arnold et al., 2012). In this study, split set approach is used for the calibration and validation steps.

The current account year, which is the beginning year of the model, is set to 1986 and the reference years showing the running period of the model are between 1987- 2100. Last year of reference scenario is decided regarding the last year of the scenarios in the model. So, in this study, years from 1986 to 2006 are chosen as calibration period while the period of 2007 to 2016 is used as validation period of the model. The following years, from 2017 to 2100, are the ones selected to be analyzed under different scenarios for the water demand and supply balance in Istanbul.

For calibration and validation of the model, simulated reservoir storage volume is used as the main criteria of the evaluation. The results are compared to the observed storage volume of reservoirs in Istanbul, which are obtained in monthly time series from İSKİ.

In this model, most of the reservoirs supply more than one water demand node (in this case municipality). Thus, the supply priority in reservoirs gains importance in the distribution of water supply nodes to demand nodes, showing in which order demand nodes will be supplied for each reservoir. The model has supply preference tab under the section of the transmission link to meet the supply priority requirement. The arrangement on supply preference has importance for the model calibration process since it is a complex model in the sense of water demand and supply links. Since the distribution of water is a dynamic process and it cannot be determined exactly, the supply preferences have assumptions based on existing data for the reservoirs (supply nodes) supplying the same demand node. Thus, supply preference information is used as a calibration parameter.

WEAP enables users to export results to an Excel file for calculating the model evaluation results more easily. It also provides exporting visual comparison results. The reservoir storage volume results are evaluated using the equations (Equations 3.1 - 3.4) with respect to these quantitative statistics; the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and the standard deviation ratio (RSR).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Y_i^{sim}-Y_i^{mean})^2}{\sum_{i=1}^{n}(Y_i^{sim}-Y_i^{mean})^2+\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}\right] \tag{3.1}$$

$$NSE = 1-\left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{mean})^2}\right] \tag{3.2}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})*(100)}{\sum_{i=1}^{n}(Y_i^{obs})}\right] \tag{3.3}$$

$$RSR = \frac{RMSE}{STDEV_{obs}}\left[\frac{\sqrt{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{mean})^2}}\right] \tag{3.4}$$

where Y_i^{obs} is the ith observation for the parameter evaluated, Y_i^{sim} is the ith simulated value for the parameter, Y_i^{mean} is the mean of observed data for the parameter, and n is the total number of observations.

3.2.3.1. Sensitivity analysis. Sensitivity analysis can be used for different purposes such as searching the factors affecting each other or the impact level of the parameters to the model output variability (Park, 2016). It provides to observe which parameters have the highest impact to the model behavior, which enables the modeler to better calibrate the model. In this study, Crop coefficiency (Kc), Effective Precipitation (Pe), and supply preference information are used as sensitivity parameters in the calibration process. In the sensitivity analysis, the output (reservoir storage volume) variation as a result of 10 % percent changes (multiplier) in the certain input parameters is calculated by the flowing equation (Eq 3.5, Eq 3.6) and the sensitivity of the parameters is classified (Figure 4.11a, Figure 4.11a, Table 4.3).

$$Input\ variation = \frac{I - I_{BC}}{I_{BC}} \times 100 \quad (3.5)$$

$$Output\ variation = \frac{O - O_{BC}}{O_{BC}} \times 100 \quad (3.6)$$

where I and O are value of the input and output variables respectively, I_{BC} and O_{BC} are values of the output variables for the base-case scenario.

The impact level of climate (precipitation, evapotranspiration), water demand (population, water use) and reservoir leakage (loss from the system, net evaporation) parameters are analyzed to observe how much impact they have on the reservoir storage amount (output). Furthermore, since water demand is the main output to analyze model sensitivity to socio-economic changes directly, the impact of population and water use per capita on water demand is also analyzed for a better observation of the model behavior.

3.3. Scenario Analysis

This study aims to investigate the freshwater balance of Istanbul's catchment basin under different scenarios of socio-economic changes and climate change until 2100. These scenarios depend on the changes in the socio-economic conditions specifically in population dynamics and water use patterns, and changes in climatic conditions as plausible future scenarios. Using plausible scenarios helps to investigate mechanisms that affect water security (total water availability) of the metropolis and consequently suggest policy insights. For this purpose, plausible future scenarios intended to bridge between the science of water management and policy development (Table 3.3). At the same time, these scenarios are intended to be prospective and informative rather than being projective or prescriptive of future (Nassauer and Corry, 2004). These scenarios are used to evaluate simulated water demand and supply balance levels and determine possible infrastructural changes. With the use of these scenarios, the model is expected to contribute to the growing body of research on water management field.

Model results are constructed under three main future scenarios; Business as Usual (BAU), High Technology with low population (HT-LP) and Low Technology with high population (LT-HP) to observe the expected and extreme cases. The extreme case scenarios (HT-LP and LT-HP) are also examined with the moderate population growth projections (BAU population) and High Technology (HT) and Low Technology (LT) are created to see how effective water usage is and since policies that focus on population growth are harder to execute. Each scenario is created under the impacts of two future climate change projections, RCP 4.5 and RCP 8.5 (see section 3.3.2).

Table 3.3. Main Scenarios for 2100.

Plausible Scenarios	**Properties**
Business as Usual (BAU)	Current and expected hydrologic, climatic and socio-economic conditions (moderate water usage and population projections)
High Tech Low Pop (HT-LP)	Low water usage due to high technological progress for a society showing *lower than expected population* increase
High Tech (HT)	Low water usage due to high technological progress for a society showing *expected population* increase
Low Tech High Pop (LT-HP)	High water usage due to low technological progress For a society showing *higher than expected population* increase
Low Tech (LT)	High water usage due to low technological progress for a society showing *expected population* increase

3.3.1. Socio-Economic Change Projections

Socio-economic change projections reflect the changes in domestic water demand and include the projections of two main parameters; population and water use. The population projections are obtained from Turkish Statistic Institute (TUİK) with respect to years. For Istanbul, unfortunately there is only one population projection and it is accepted as “moderate population increase”. For Turkey, TUİK has three population projection levels: high, moderate and low population projections. For Istanbul’s population projection, TUİK’s population growth rates (for high, moderate, and low) are taken as proxy and the high and low population growth projections for Istanbul are calculated. As a further note, all scenarios include the same industrial water demand projection data due to limited study on this topic.

Each domestic water demand node has population projections for the municipalities of Istanbul which are served from the same water supply source (node). The overall population of these municipalities within each node is calculated and projected for both high and low growth rates (Appendix A, Table 1).

Water use projections for the metropolis Istanbul includes three levels as well; high, moderate and low water usage per capita. The projection data specific to Turkey is obtained from the global water use projection study of Neverre and Dumas, 2016, since the observed data used in their study fit the actual water usage data in Istanbul and currently the literature lacks long term water use projections for the study area (Appendix A, Figure 1).

The model also has scenarios reflecting the infrastructural changes planned for Istanbul such as planned reservoirs and Melen River capacity increase. These scenarios are based on Business As Usual (BAU) Scenario under the impacts of RCP 4.5 and RCP 8.5 climate change scenarios.

Furthermore, the supply preference from water supply nodes to demand nodes has a crucial role in the scenario construction process similar to the calibration process. İSKİ published the future supply preference for planned water supply capacity, and the scenarios reflect those supply preference changes. For example, İSKİ plans two reservoirs for the Anatolian side (İsaköy and Sungurlu Reservoirs) and one for the European side (Karamandere Reservoir). In addition to these reservoirs, İSKİ plans to increase the amount of water withdrawn from Melen River with the construction of Melen Reservoir (694 million m^3 water/year). With this infrastructural change, Melen River will become the dominant water supply source with 1077 million m^3 water/year (DSİ, 2018), which is located outside the city limits.

Today, Istanbul has four external water supply sources (i.e., located outside the city limits); Melen River, Istancalar, Pabuçdere and Kazandere Reservoirs. To demonstrate the role of these supply sources on water security of the city, there are three scenarios which exclude external water supply sources from the water supply and demand schema; (i) Melen River and (ii) Istrancalar, Kazandere and Pabuçdere Reservoirs and (iii) all external water supply sources (Melen River, Istancalar, Pabuçdere and Kazandere Reservoirs) at the same time. In these scenarios, the expected supply preferences for the rest of the reservoirs depend on the assumptions. The assumptions do not include significant changes in water supply but are designed in the way that is most likely to create lowest unmet water demand. Moreover, to examine the dependency level to Melen River, as an external source to the city, the Melen River is also excluded from the planned future infrastructural changes scenario including planned reservoir constructions but excluding Melen River supply. Besides, Melen River is the main supply source in future plans. To examine the impact of the changes in supply amount from the river, there is another scenario which Melen River is the considered as the backup supply source. This scenario is again created by changing the supply preference priorities from reservoirs to demand nodes. These further socio-economic change scenarios are created over BAU scenario.

3.2.2. Climate Change Projections

Climate change scenarios simulate the impacts of change in climatic conditions according to IPCC's future climate projections of Representative Concentration Pathways (RCP). There are four RCP scenarios regarding their radiative forcing targets in 2100; RCP 8.5, RCP 6, RCP 4.5 and RCP 2.6. The radiative forcing values imply the net impact of all anthropogenic greenhouse gases (positive forcing from greenhouse gases and negative forcing from aerosols). The positive forcing from CO_2 constitutes the dominant factor (van Vuuren et al., 2011). RCP scenarios include a wide range of assumptions about global population, total greenhouse gas emission and concentrations, land-use changes, technological development and climate change policy initiatives. In this study, climate change scenarios include the scenarios of RCP 4.5 and RCP 8.5 as medium and high emission scenarios respectively. These scenarios stabilize radiative forcing at 4.5 and 8.5 W m^{-2} in 2100.

Under RCP 4.5 and RCP 8.5 scenarios, climatic parameters differ. Catchment hydrology requires precipitation and evapotranspiration values as climate data input in the Rainfall Runoff Method

(Simplified Coefficient Method). Boğaziçi University Climate Change and Politics Application and Research Center had provided the necessary data for the future precipitation and evapotranspiration values for both RCP 4.5 and RCP 8.5 scenarios (Figure 3.5, Figure 3.6).

Consequently, the model has 25 different scenarios; 9 scenarios for socio-economic change impact analysis, 6 for climate change impact analysis and 10 for further scenarios.

*3 (Population projections) * 3 (water usage projections) = 9*

3 (main scenarios) 2 (climate change projections) = 6*

*5 (Scenarios created over BAU scenario) * 2 (climate change projections) = 10*

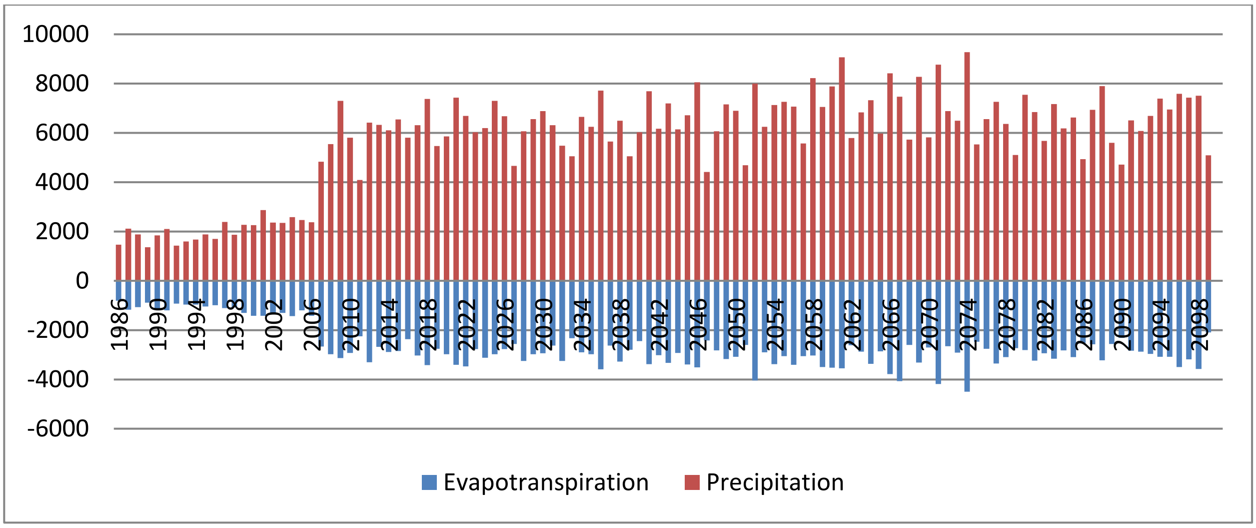


Figure 3.5. Climate data under the RCP 4.5 (million m^3 / year).

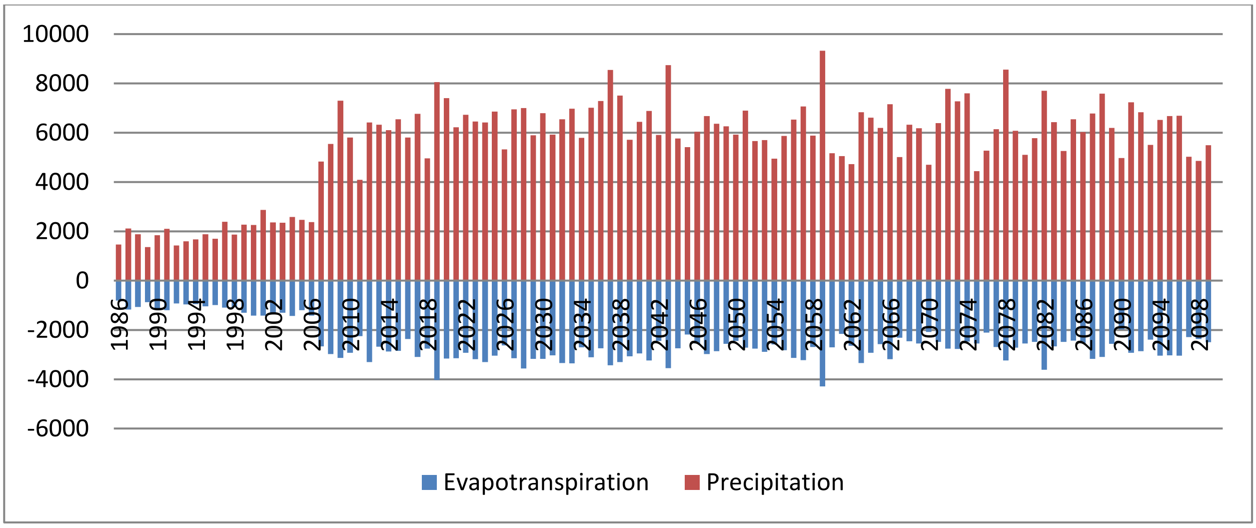


Figure 3.6. Climate data under the RCP 8.5 (million m^3 / year).

4. RESULTS

4.1. Calibration and Validation Results

Model results for the calibration and validation period have satisfactory values of NSE, R^2, RSR, and PBIAS (Table 4.1, Table 4.2). The results are accepted as satisfactorily if NSE ≥ 0.5, $R^2 \geq 0.5$, RSR ≤ 0.7 and PBIAS ± 0.25 % for streamflow (Moriasi et al., 2007). While the optimum value is 0.0 for PBIAS, positive values imply underestimation bias and negative values imply overestimation bias (Moriasi et al., 2007). The graphs of comparison between simulated reservoir volume and observed reservoir volume for the simulation period is also helpful to analyze the results and calibrate the model for the better (Figure 4.1, Figure 4.2). As these graphs and the model evaluation parameters indicate, the model behaves satisfactorily and is ready to be used in future scenario simulations.

Table 4.1. Evaluation parameters of model results (NSE, PBIAS, R^2, RSR) for the calibration period (1986-2006).

	Alibey	Bçekmece	Darlik	Elmalı	Istrancalar	Kazandere	Ömerli	Pabuçdere	Sazlıdere	Terkos
NSE	0,696	0,860	0,898	0,891	0,794	0,773	0,917	0,726	0,890	0,836
PBIAS	-44,860	-3,782	-12,503	-17,606	-2,108	-17,270	-6,113	-32,801	5,583	2,563
R^2	0,767	0,877	0,907	0,902	0,829	0,815	0,923	0,785	0,901	0,860
RSR	0,544	0,363	0,329	0,330	0,516	0,542	0,297	0,587	0,318	0,385

Table 4.2. Evaluation parameters of model results (NSE, PBIAS, R^2, RSR) for the validation period (2006-2016).

	Alibey	Bçekmece	Darlik	Elmalı	Istrancalar	Kazandere	Ömerli	Pabuçdere	Sazlıdere	Terkos
NSE	0,832	0,826	0,853	0,831	0,858	0,817	0,880	0,835	0,910	0,926
PBIAS	-26,407	-0,839	-21,667	0,641	1,628	3,354	-20,307	-1,878	3,127	-2,071
R^2	0,856	0,852	0,872	0,856	0,876	0,845	0,893	0,858	0,918	0,931
RSR	0,423	0,367	0,399	0,441	0,364	0,432	0,357	0,438	0,307	0,267

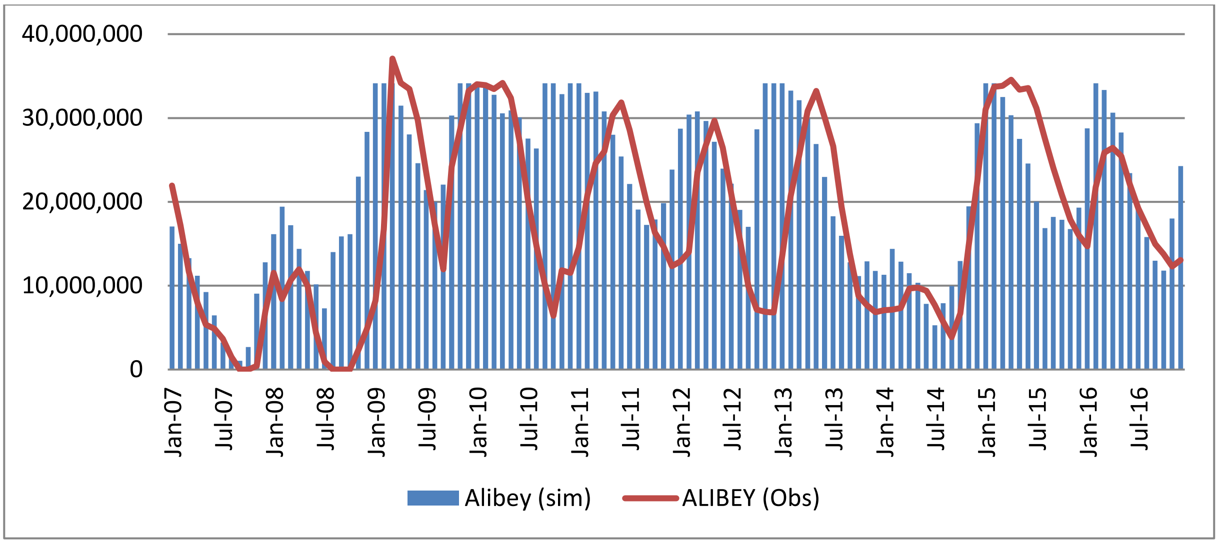


Figure 4.1. Comparison of observed and simulated reservoir volume for Alibey (m^3) (Validation period: 2007-2016).

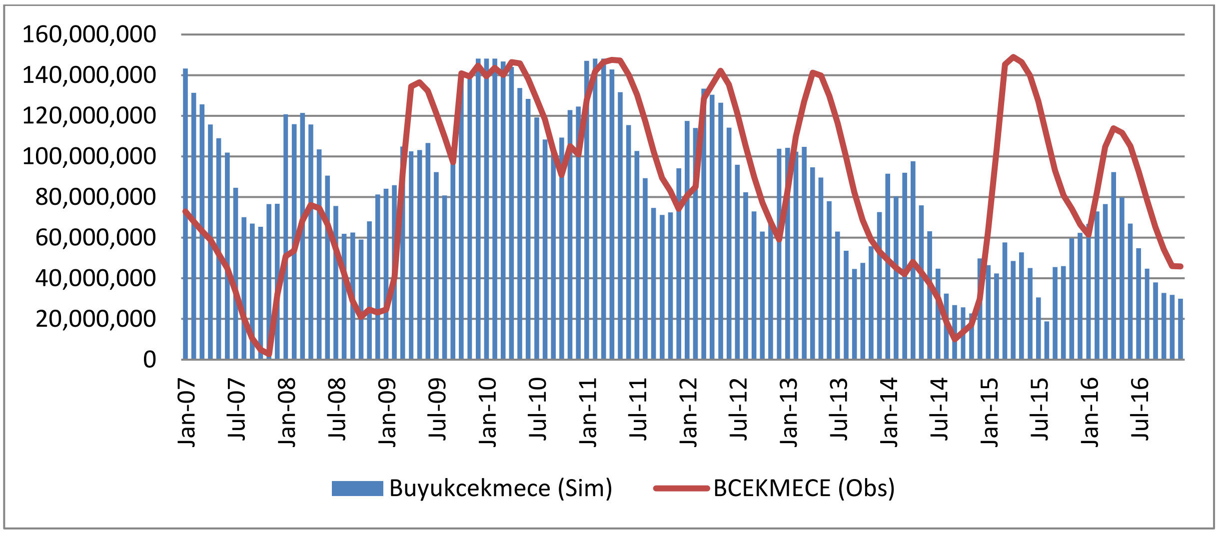


Figure 4.2. Comparison of observed and simulated reservoir volume for Büyükçekmece (m^3) (Validation period: 2007-2016).

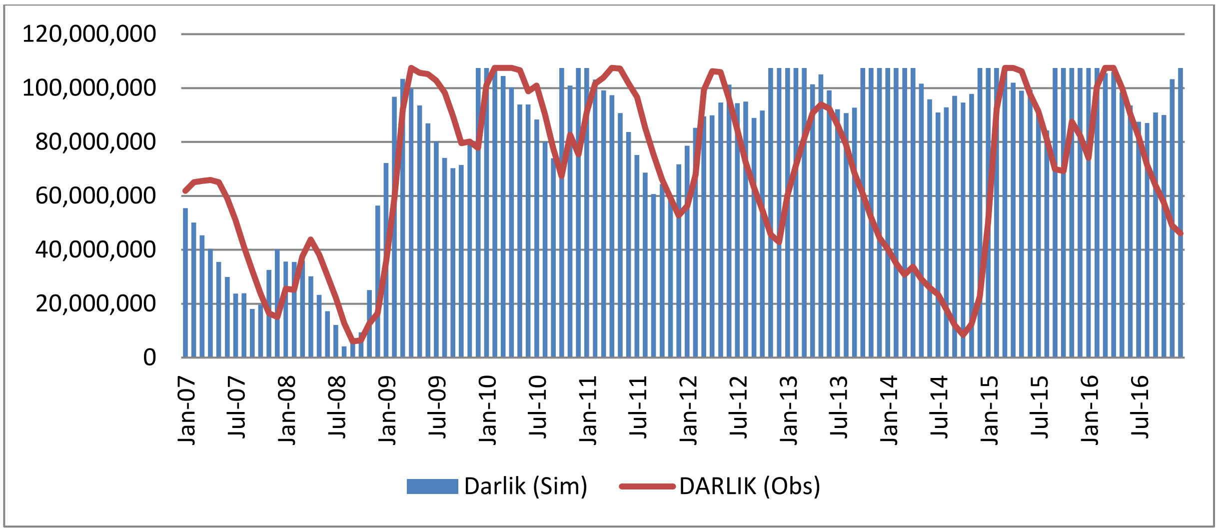


Figure 4.3. Comparison of observed and simulated reservoir volume for Darlık (m^3) (Validation period: 2007-2016).

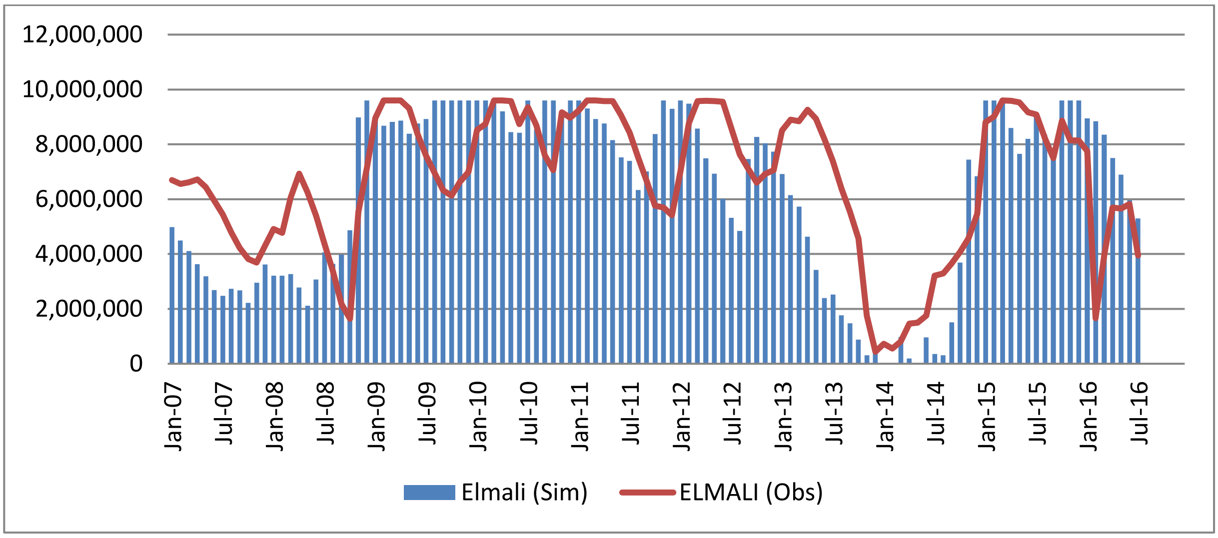


Figure 4.4. Comparison of observed and simulated reservoir volume for Elmalı (m^3) (Validation period: 2007-2016).

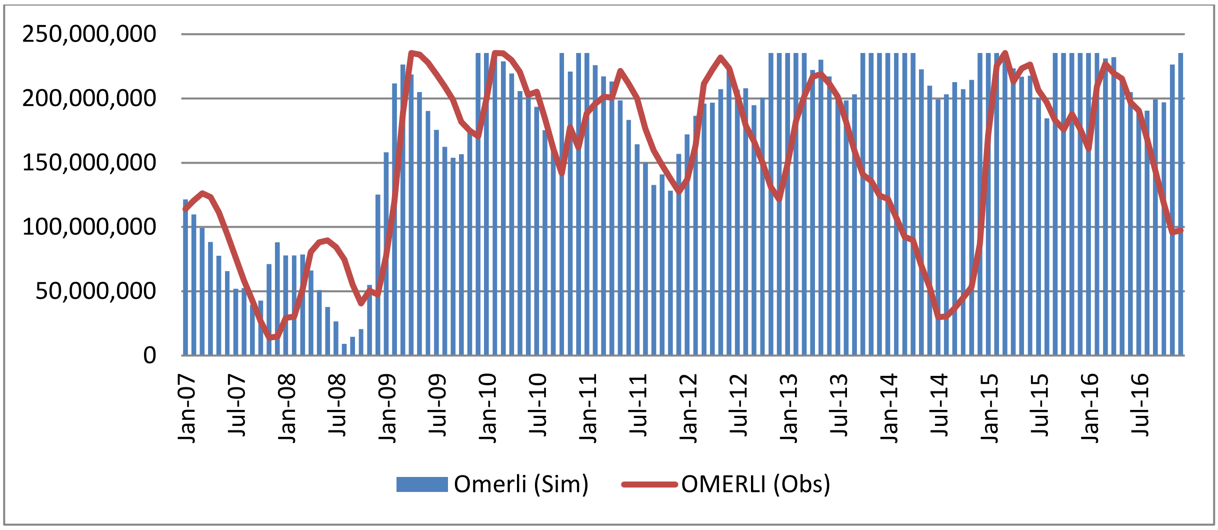


Figure 4.5. Comparison of observed and simulated reservoir volume for Ömerli (m^3) (Validation period: 2007-2016).

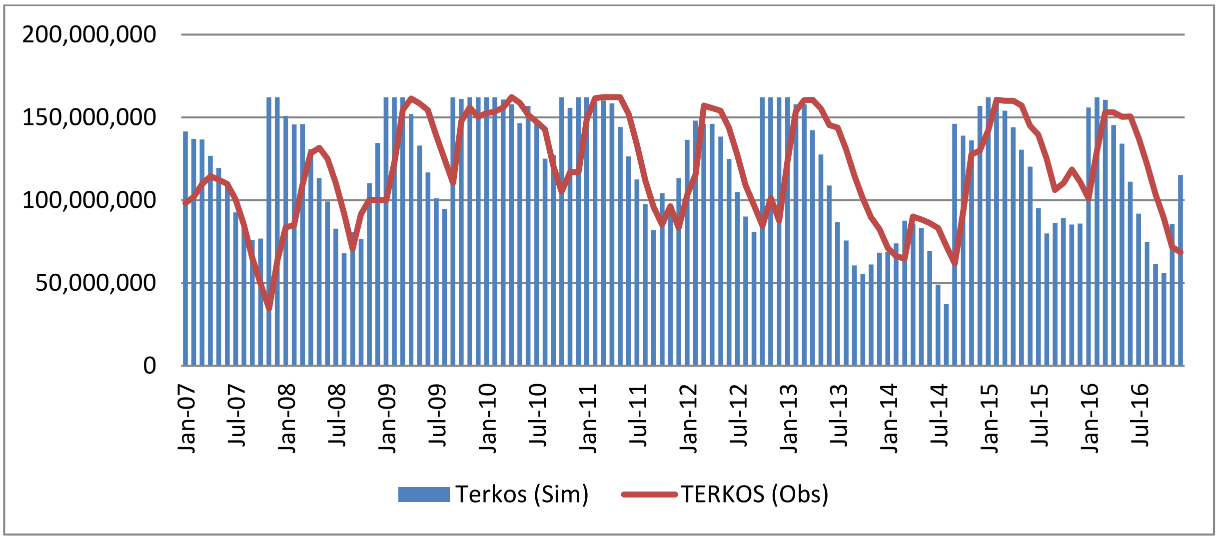


Figure 4.6. Comparison of observed and simulated reservoir volume for Terkos (m^3) (Validation period: 2007-2016**).**

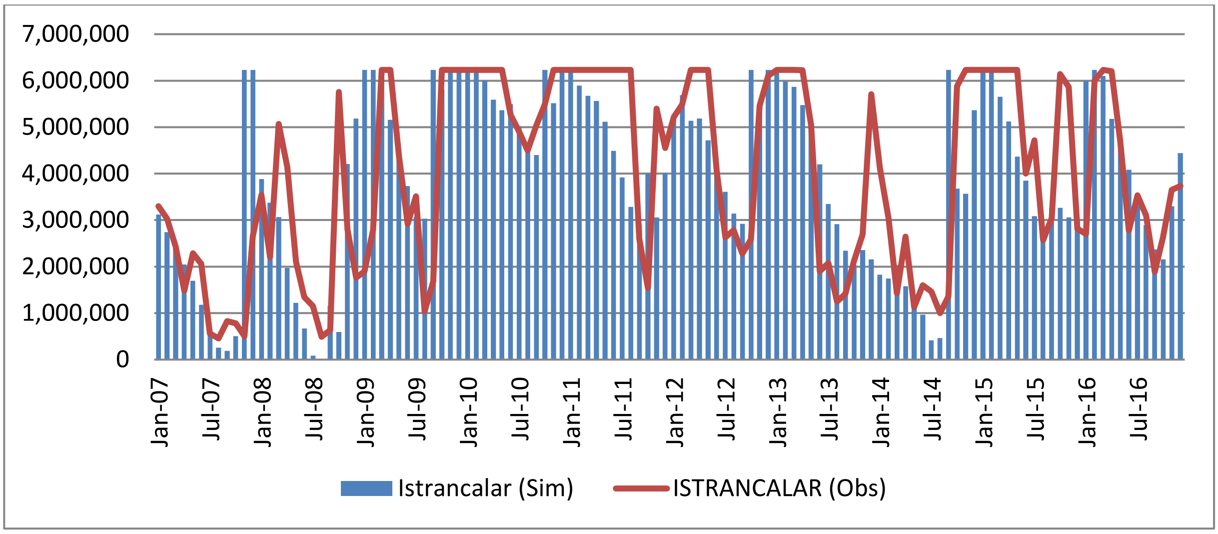


Figure 4.7. Comparison of observed and simulated reservoir volume for Istrancalar (m^3) (Validation period: 2007-2016).

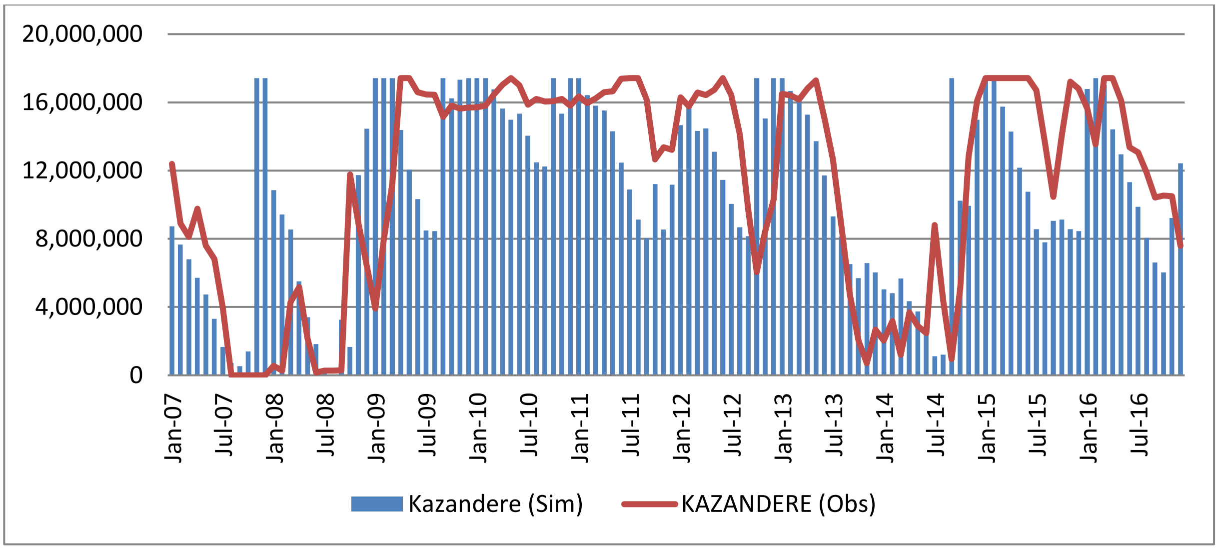


Figure 4.8. Comparison of observed and simulated reservoir volume for Kazandere (m^3) (Validation period: 2007-2016).

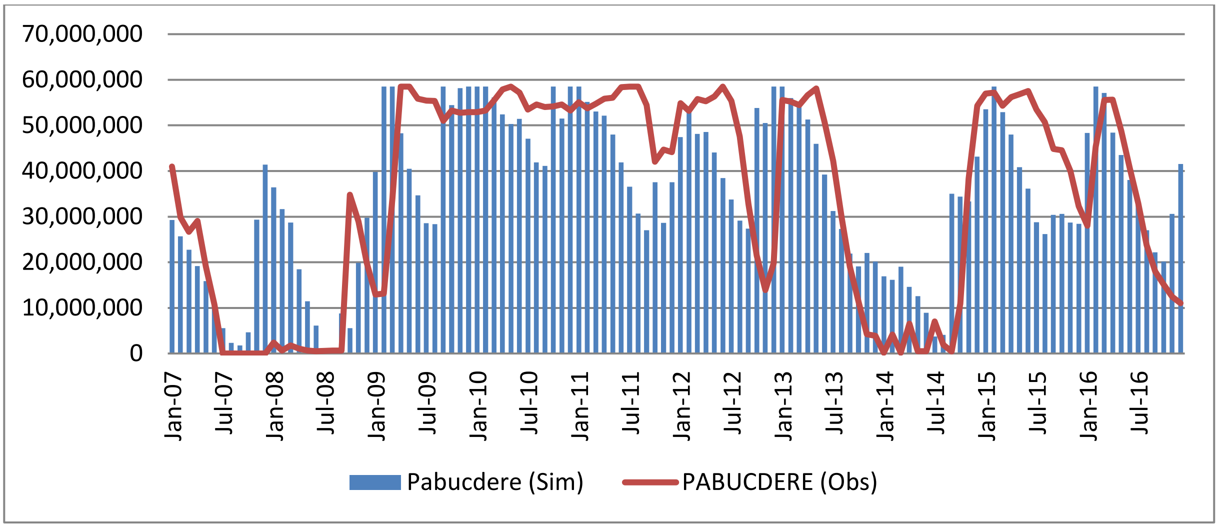


Figure 4.9. Comparison of observed and simulated reservoir volume for Pabuçdere (m^3) (Validation period: 2007-2016).

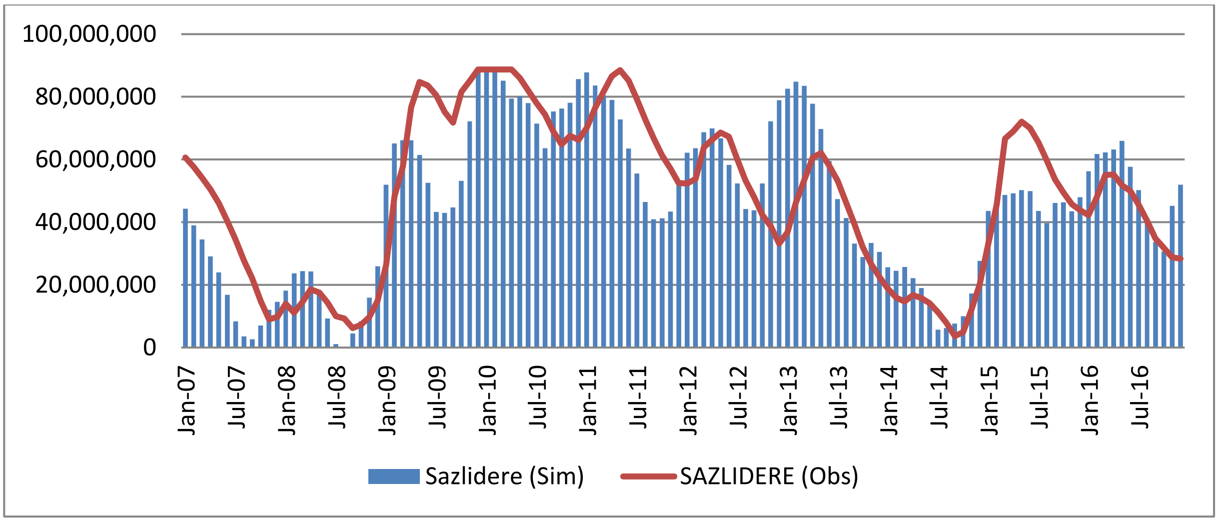


Figure 4.10. Comparison of observed and simulated reservoir volume for Sazlıdere (m^3) (Validation period: 2007-2016).

4.1.1. Sensitivity Analysis Results

The results of sensitivity analysis indicate high model sensitivity to the climate parameters of precipitation and evapotranspiration, medium sensitivity to loss from system and crop coefficient, and less sensitivity to the parameters of water demand (population and water use), net evaporation from the reservoirs, effective precipitation (Table 4.3).

Regarding results, precipitation parameter has the highest impact on the reservoir storage volume among all input parameters, as precipitation decreases reservoir storage volume also decreases significantly (Figure 4.11a). With a close look at other input parameters different than climate parameters (Figure 4.11b), the model is sensitive to crop coefficient and loss from the system (i.e., loss due to infrastructural issues). Reservoir storage volume increases as crop coefficient value decreases and decreases as water loss amount from the system increases.

Population and water usage per capita are the main socio-economic change parameters. The model multiplies population with water usage value to find water demand amount. Thus, as sensitivity analysis results imply, these two parameters have the same impact on water demand. Still, their impact on reservoir storage volume is low.

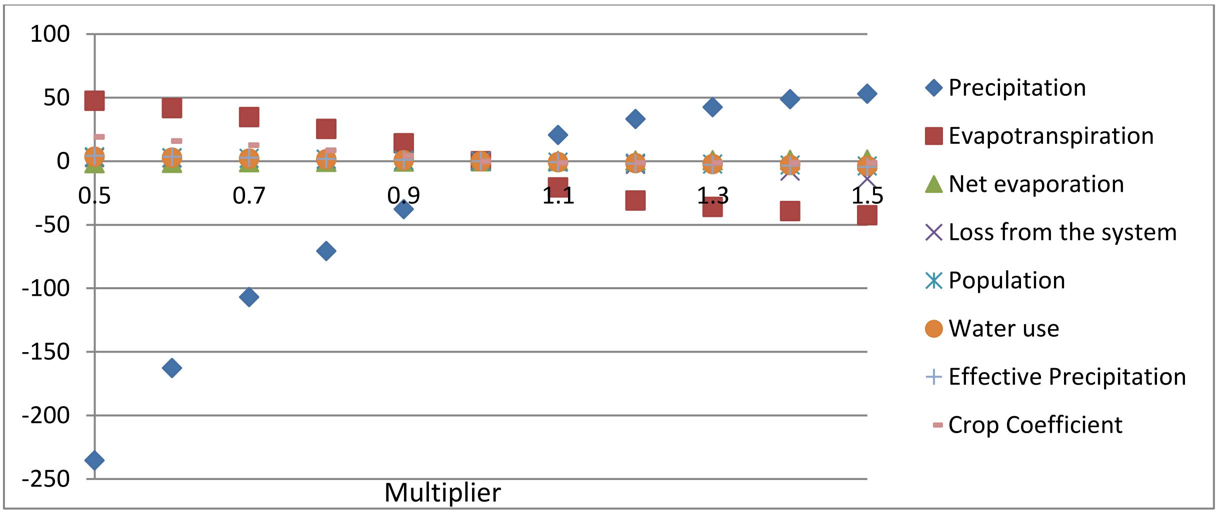


Figure 4.11a. Output Variation (%) of model input parameters.

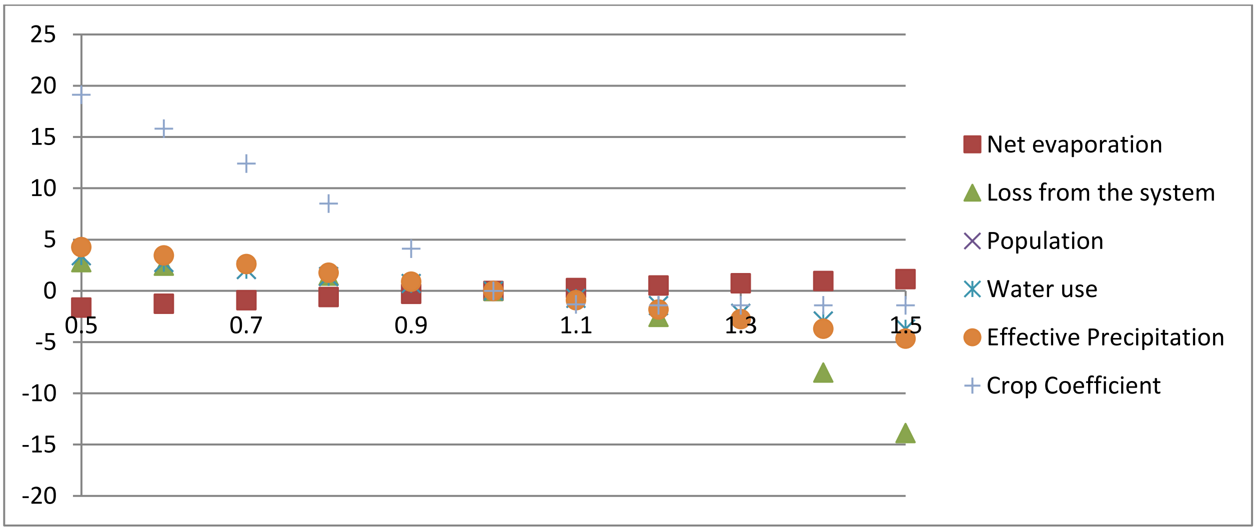


Figure 4.11b. Output Variation (%) of selected model input parameters.

Table 4.3. Parameter Sensitivity Classification.

Parameter	Sensitivity Class
Precipitation	Very High
Evapotranspiration	Very High
Crop coefficient	Medium
Loss from the system	Medium
Effective Precipitation	Low
Population	Low
Water use	Low
Net Evaporation	Low

4.2. Water Demand Under Different Scenarios

Water demand is examined for five main scenarios. Model results indicate that water demand is sensitive to changes in both technology and population (Figure 4.12). The results also show monthly water demand distribution and the impacts of three scenarios over this distribution, Business as Usual (BAU) as the expected scenario and High Tech Low Pop (HT-LP) and Low Tech High Pop (LT-HP) as extreme scenarios creating highest (LT-HP) and the least (HT-LP) water demand (Figure 4.13).

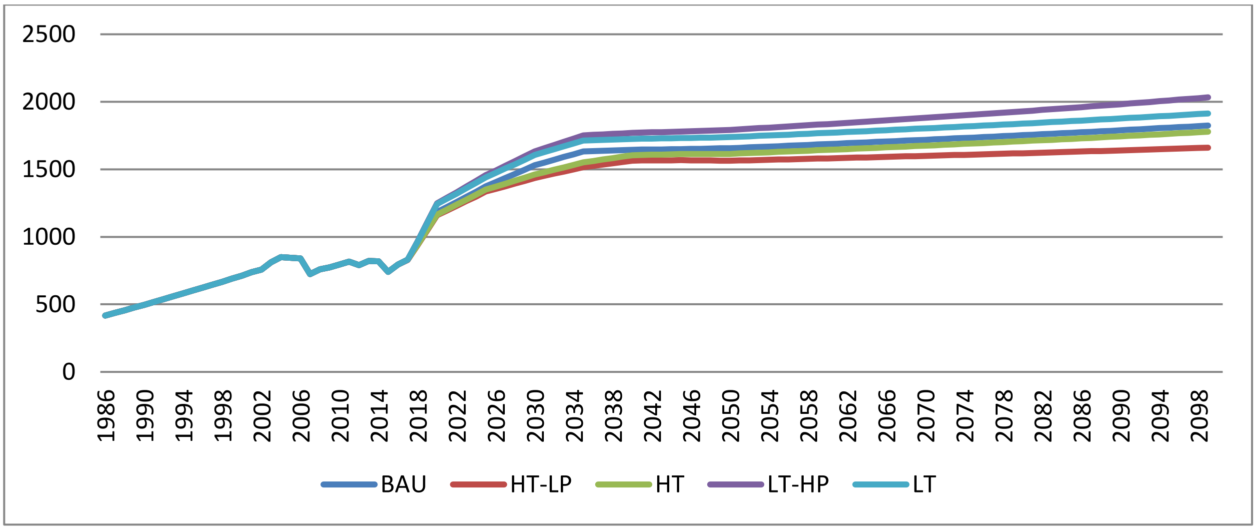


Fig 4.12. Water Demand under different scenarios (million m^3 / year).

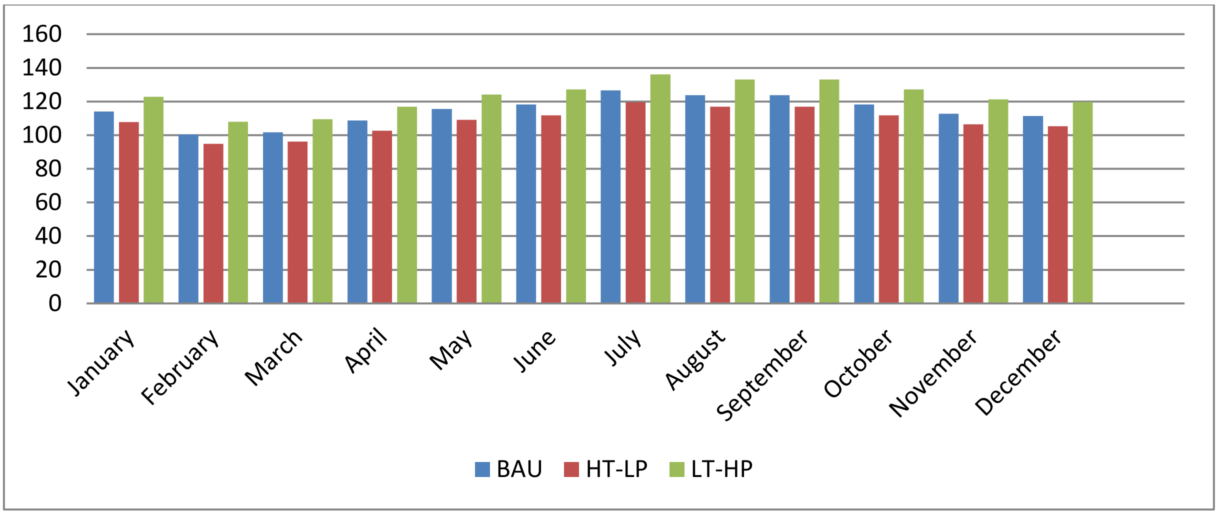


Fig 4.13. Water demand monthly distribution for different scenarios (million m^3/month).

Regarding the high level projections for both population and water use per person, high level population increase *(LT-HP)* can create around 200 million m^3 higher water demand than the expected (moderate) population increase *(BAU)* and higher water usage *(LT)* creates around 85 million m^3 higher water demand than expected water usage *(BAU)* around year 2100. Therefore, high population increase creates relatively higher rise in water demand than high water usage increase. Furthermore, when compared to the expected water demand *(BAU scenario)*, the model indicates that the highest reduction in water demand (160 million m^3/year) would be obtained when higher technological progress is combined with a low population increase *(HT-LP scenario)* (Figure 4.14).

Moreover, with the impact of low population increase, water demand increase rate could decline sharply even though water use amount per capita increases and it concludes less water demand *(LT-LP)* than expected *(BAU)* after 2074. As similar, water demand *(HT-HP)* can get higher than expected *(BAU)* due to high population increase although technological improvements provide less water demand than expected until 2040. The huge impact of population on water demand increase rate can also be easily observed in the scenario including moderate water usage (moderate technology (MT)) as a result of technological improvements *(MT-HP and MT-LP)* (Figure 4.14).

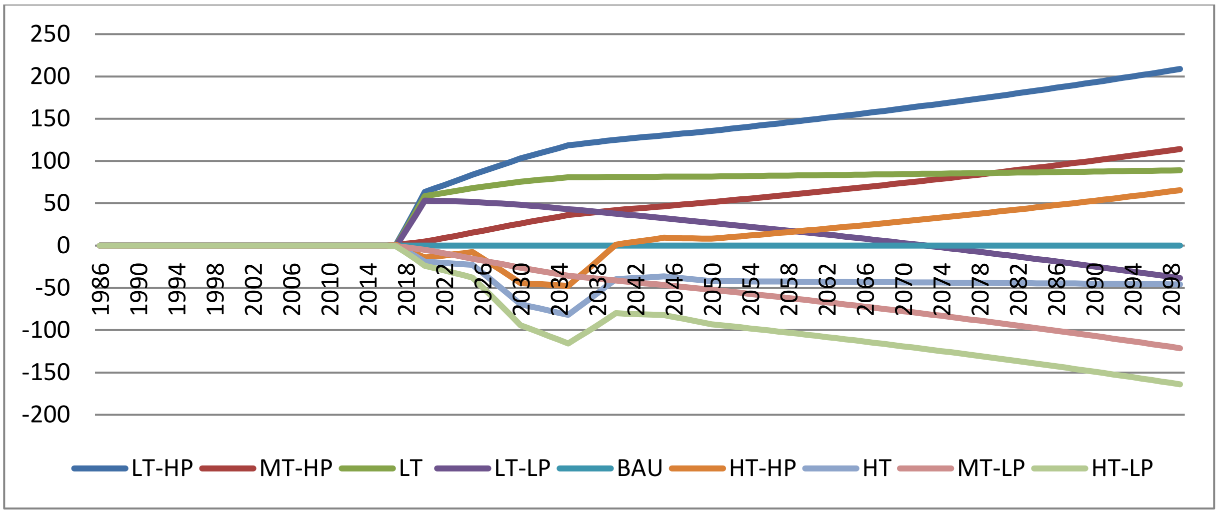


Fig 4.14. Comparison of water demand of all scenarios with BAU scenario (million m^3 / year).

4.3. Results with The Current Water Supply Sources

To understand how the water security level of Istanbul will be affected from changes in climate, technology and population, the listed plausible scenarios in Section 3.3 are ran (Figure 4.15, Figure 4.16). According to model simulations, 5 %, on average, of the future water demand will not be supplied with existing water supply sources under RCP 4.5 scenario while it can rise up to 17 %. The respective unmet water demand rates are 7 % (average) and 27 % (the highest) for RCP 8.5 scenario. Climate change projections (both RCP 4.5 and RCP 8.5) indicate the severe impact of climate parameters (precipitation and evapotranspiration) on water supply.

The impacts of climate change on water supply and therefore on unmet water demand become more preeminent after 2030s (Figure 4.15, Figure 4.16). The model shows that there is no unmet water demand with the planned water supply increase as a result of the construction of new reservoirs (Figure 4.18). Still, the unmet water demand with the current water supply sources shows how influential climate change is on water supply sources and which years will be affected by climate change more (Figure 4.15, Figure 4.16). Moreover, the model results demonstrate variation of unmet water amount before and after 2040 under different climate change scenarios (RCP 4.5 and RCP 8.5). The simulations reflect more dispersed and higher quantity of unmet water demand after 2040 for RCP 8.5 scenario but an opposite trend is observed for RCP 4.5 scenario. Before 2040, RCP 4.5 scenario results have higher unmet water demand than RCP 8.5 scenario results.

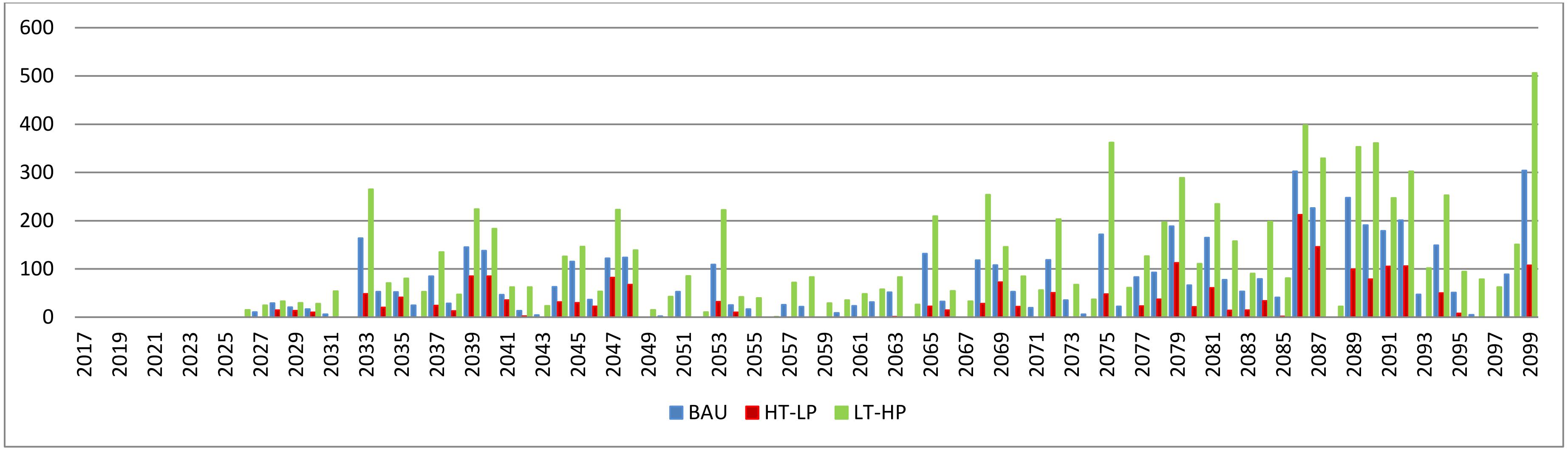


Fig 4.15. Unmet water demand under RCP 4.5 (million m^3/year).

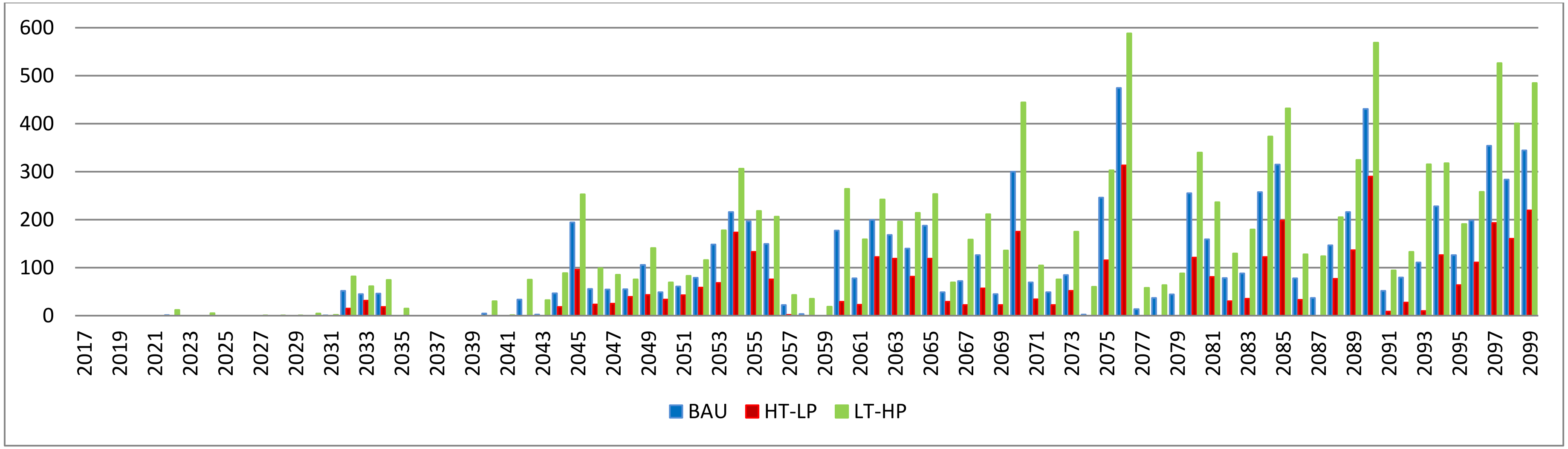


Fig 4.16. Unmet water demand under RCP 8.5 (million m^3/year).

The distribution of unmet water demand with the current water supply sources differs with respect to months. The highest unmet water demand occurs in July, August, September and October. With the severity of changes in climate, in August, the gap between unmet water demands can rise to 6 million m^3 between climate change scenarios of RCP 4.5 and RCP 8.5 (Figure 4.17).

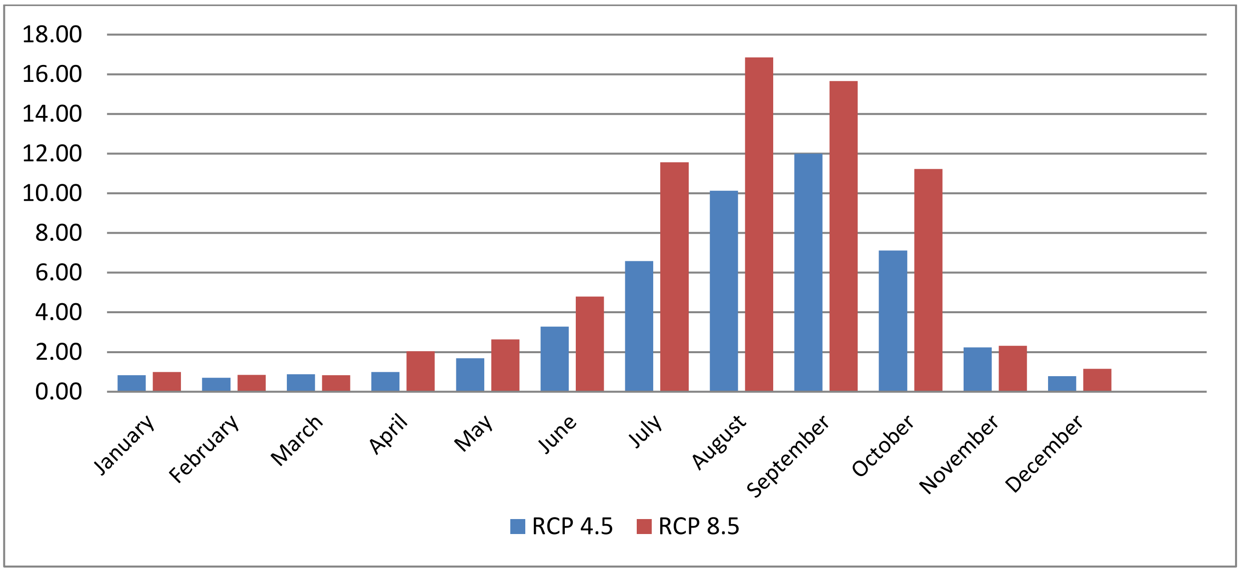


Fig 4.17. Unmet water demand monthly average distribution under both RCP 4.5 and RCP 8.5 (million m^3/month).

Furthermore, the model calculates surface runoff as the remaining precipitation amount after subtraction of evapotranspiration amount. The precipitation values increase significantly after 2007, therefore creating an increase in the water supply amount (Figure 4.18, Figure 4.19). This vast difference occurs due to the high water supply from Melen River with the beginning of Melen Project in 2007. The river has provided significant contributions to the water supply system in Istanbul.

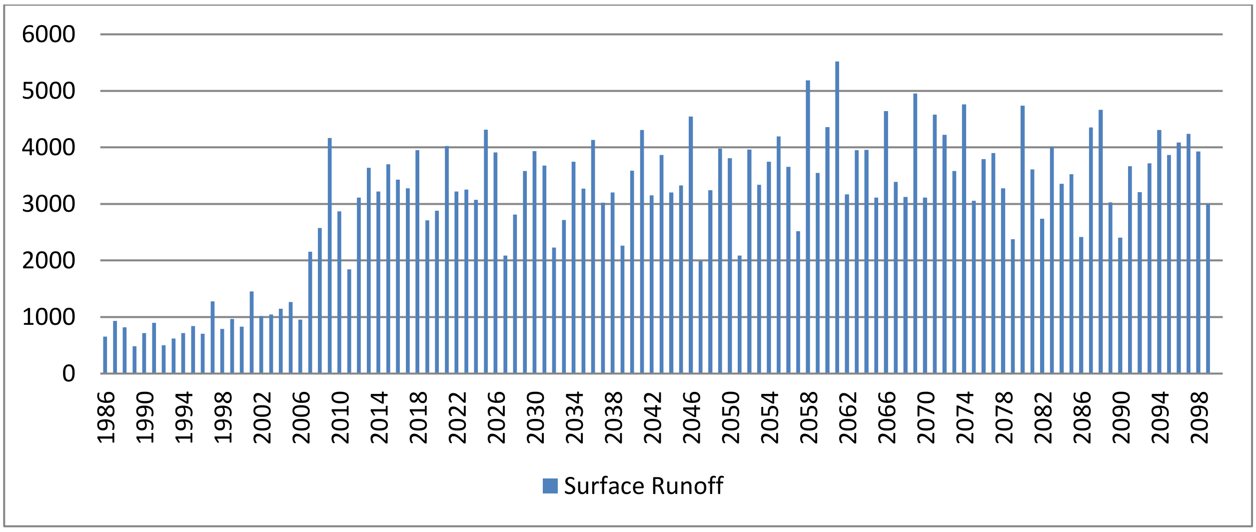


Fig 4.18. Surface Runoff for BAU Scenario under the RCP 4.5 (million m^3 / year).

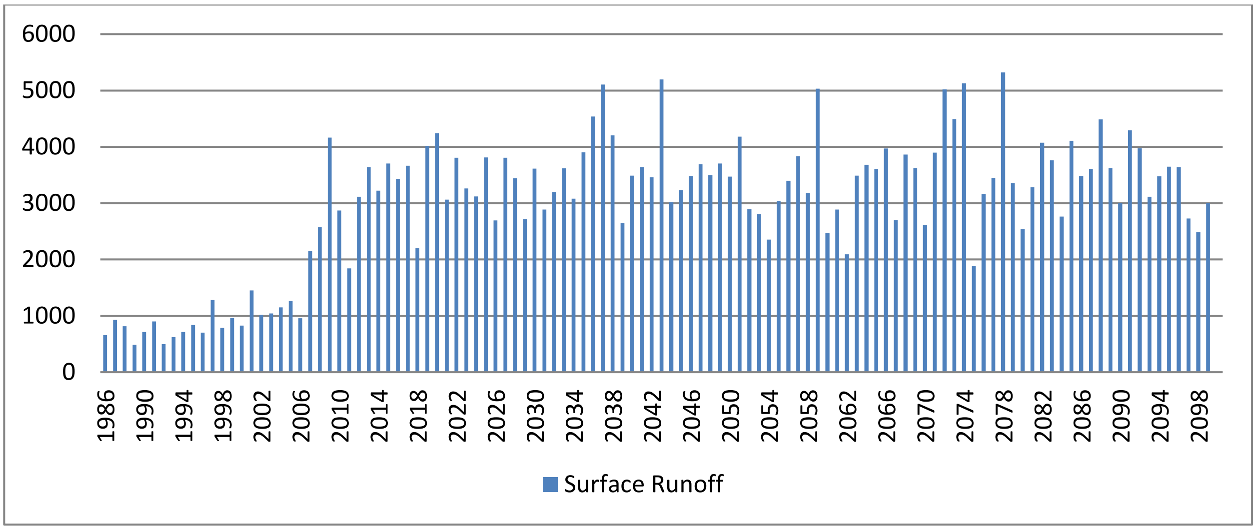


Fig 4.19. Surface Runoff for BAU Scenario under the RCP 8.5 (million m^3 /year).

4.4. Results of The Planned Future Infrastructural Changes Scenario

With the addition of three reservoirs (within Istanbul city border) and Melen Reservoir (outside of the city border), the possible water scarcity issue of the metropolis can be solved. As model results indicate, even when climate change projections are reflected, if the water distribution systems are updated and majority of the water demand is supplied by the Melen River, the model shows no unmet water demand until 2100 (Figure 4.20). In the scenario reflecting *the future infrastructural changes* under RCP 4.5 and RCP 8.5 scenarios, all reservoirs are expected to stay almost full since Melen River is accepted as the main supply source (Appendix B, Figures 1.1- 1.14). All results related with the future infrastructural changes are investigated on BAU scenario.

However, if the supply priorities stay in the same way as today, i.e. Melen River is utilized as the backup source plan for most of the demand nodes, the greater impact is observed in the reservoir storage volumes for the local reservoirs of Istanbul. Current reservoirs of Ömerli, Darlık, Elmalı and planned reservoirs of İsaköy and Sungurlu will be the ones highly affected if *the Melen supply stays as the backup supply source*, while the impacts get more serious and unpredictable with the higher impact of climate change (RCP 8.5 scenario) (Figures 4.21 – 4.34). The impact of Melen supply priority change on the rest of the current local and external reservoirs (Alibey, Büyükçekmece, Sazlıdere, Terkos, Istrancalar, Kazandere, Pabuçdere) and the other planned future reservoir (Karamandere) will be less under RCP 8.5 scenario but all reservoirs will still be affected by the changes in climate (Appendix B, Figures 2.1 – 2.14).

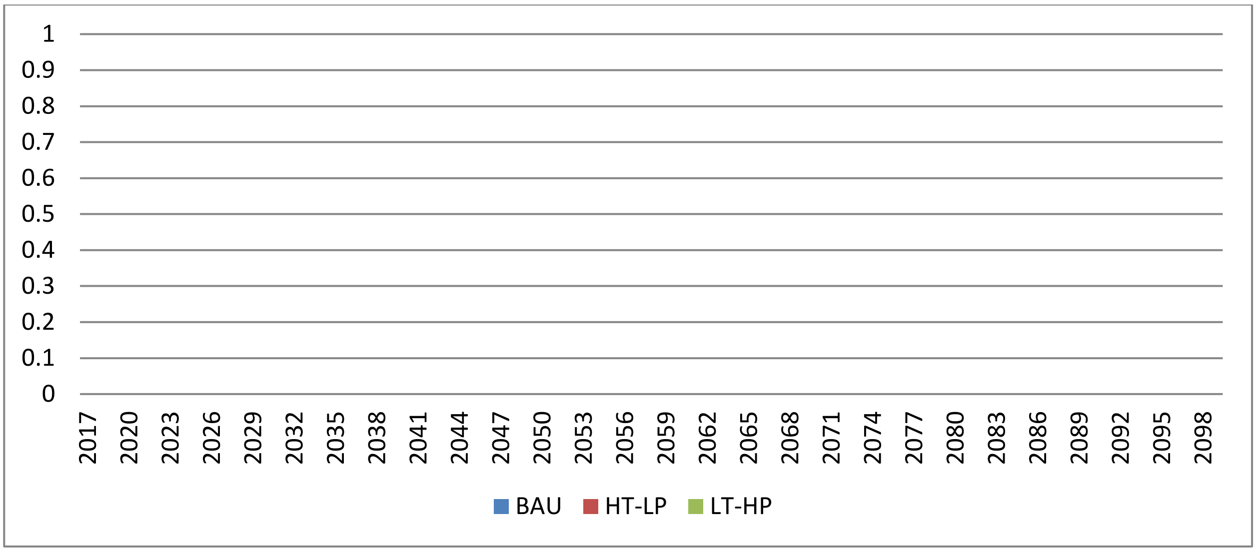


Fig 4.20. Unmet water demand with the planned future infrastructural changes under both RCP 4.5 and RCP 8.5 (million m^3/year).

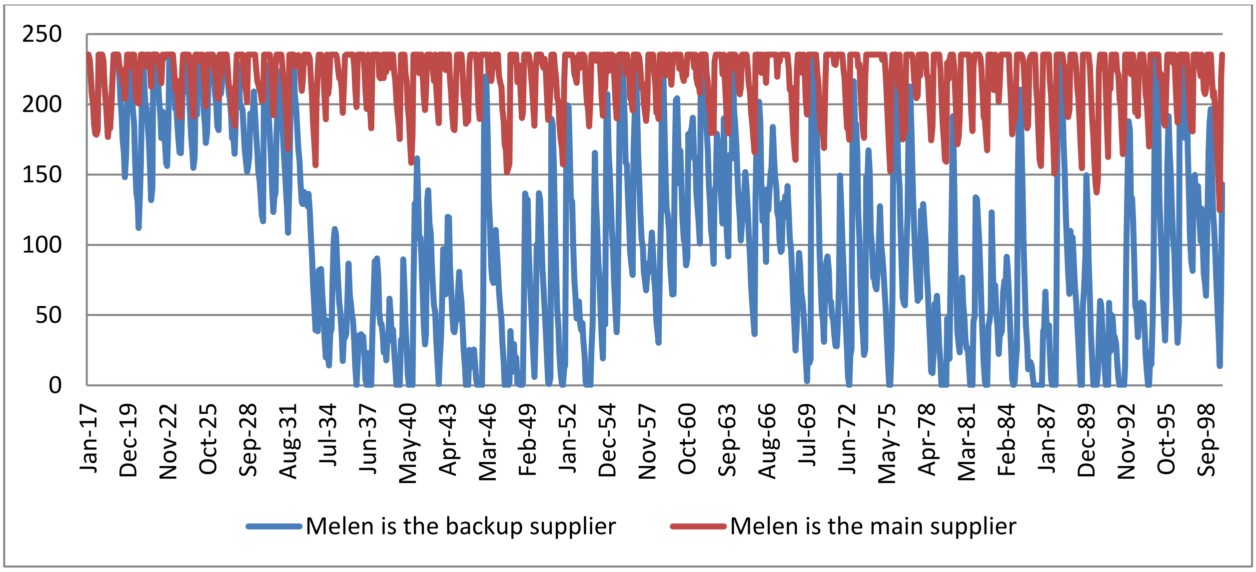


Fig 4.21. Storage Volume of Ömerli Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

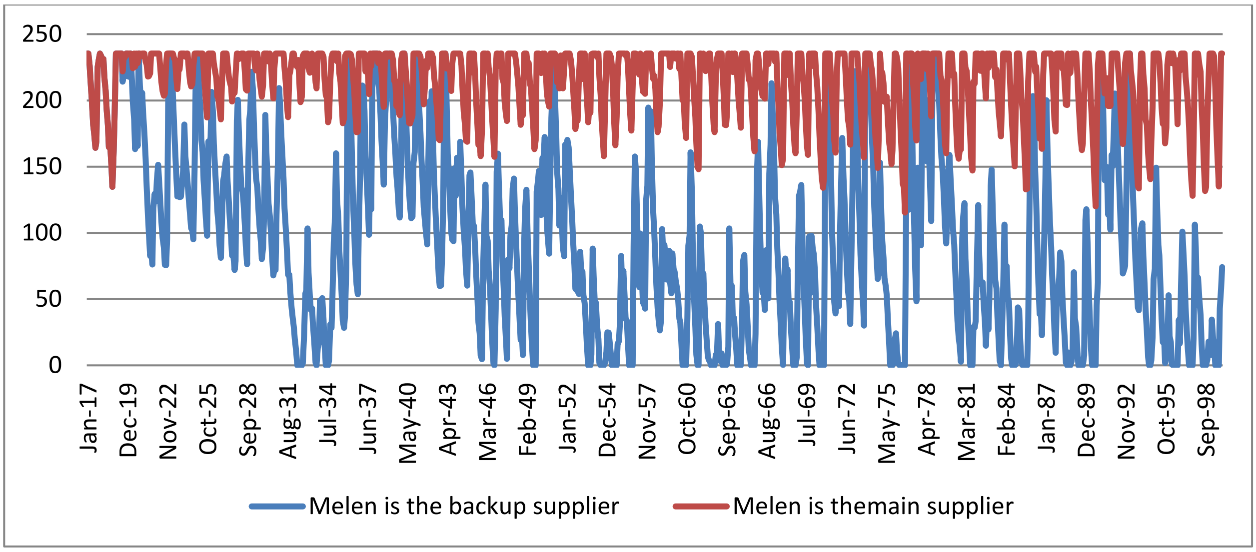


Figure 4.22. Storage Volume of Ömerli Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

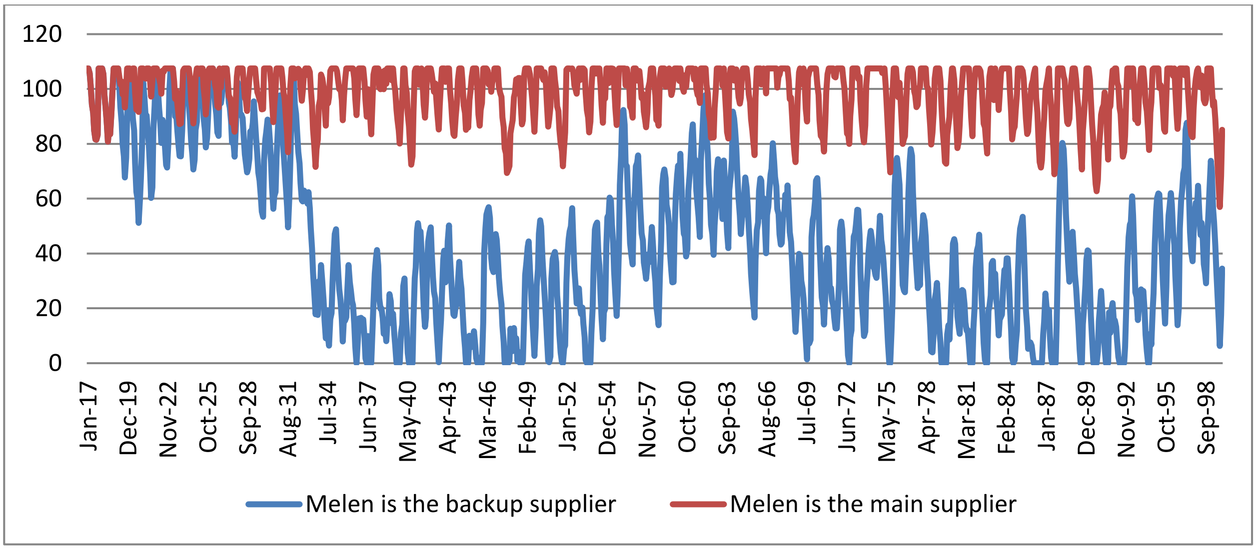


Figure 4.23. Storage Volume of Darlık Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

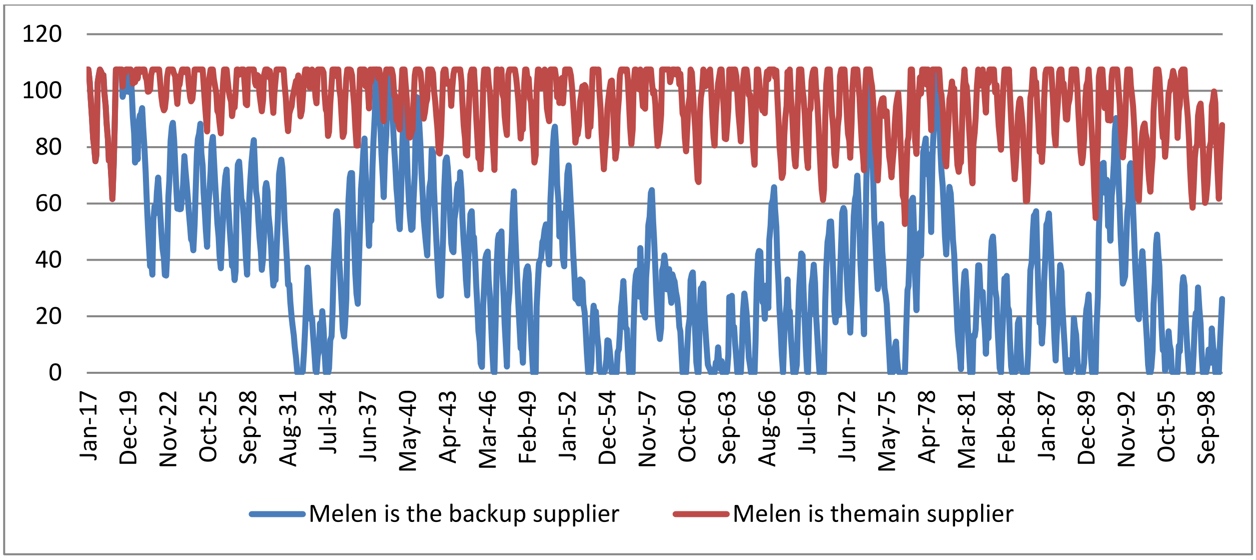


Figure 4.24. Storage Volume of Darlık Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

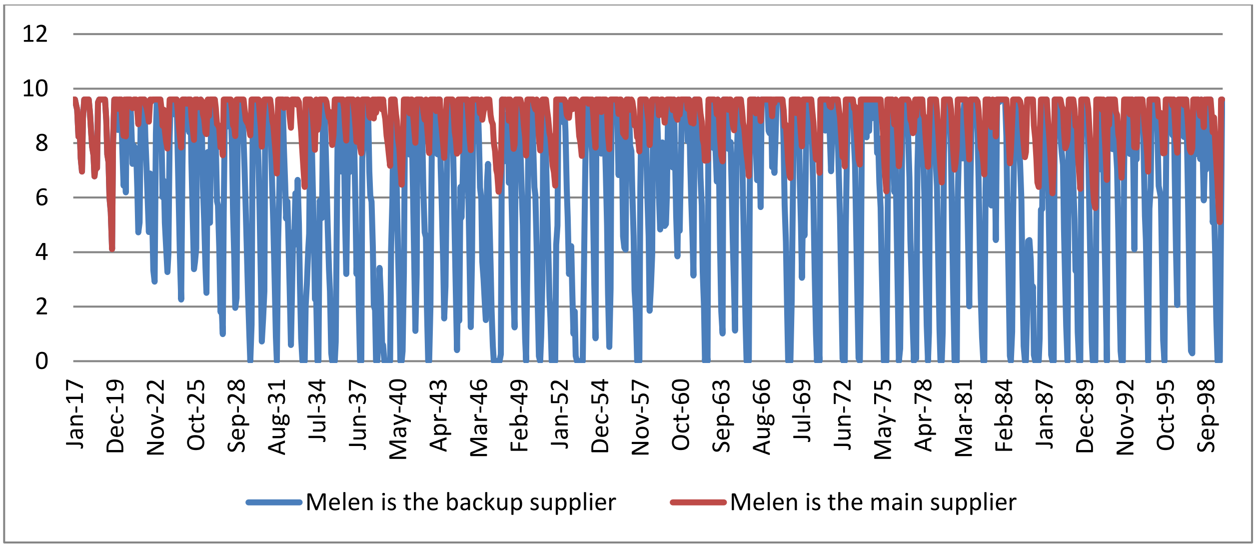


Figure 4.25. Storage Volume of Elmalı Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

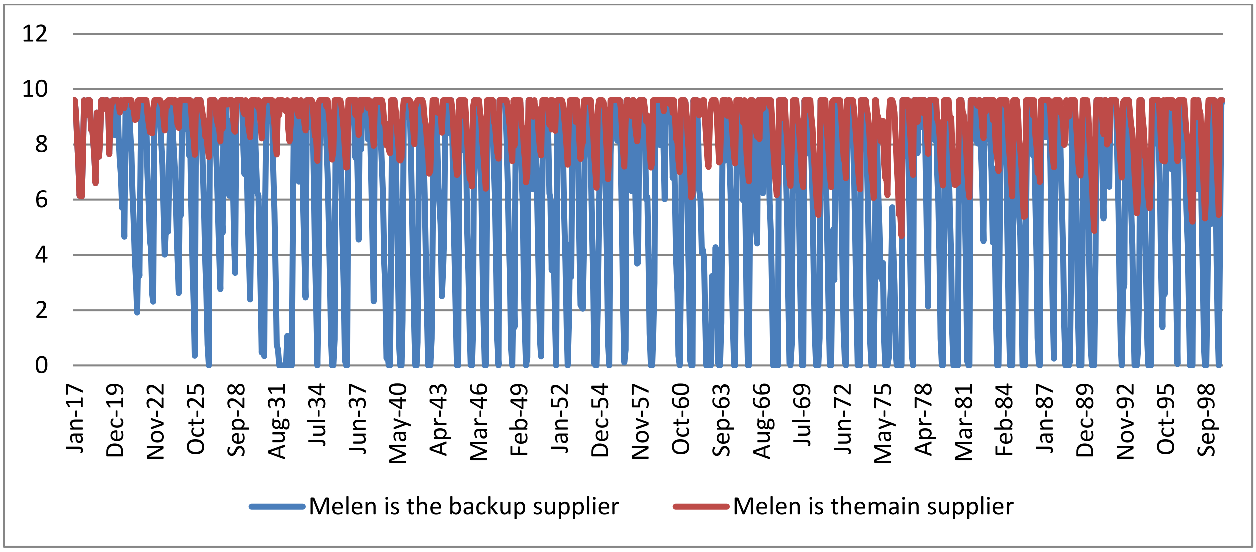


Figure 4.26. Storage Volume of Elmalı Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

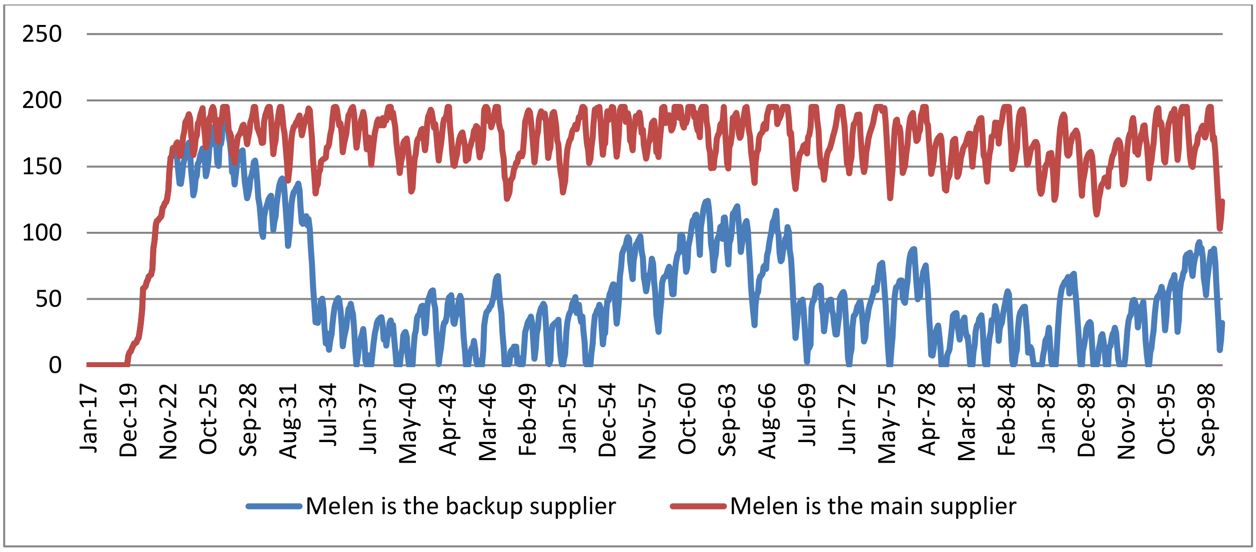


Figure 4.27. Storage Volume of İsakoy Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

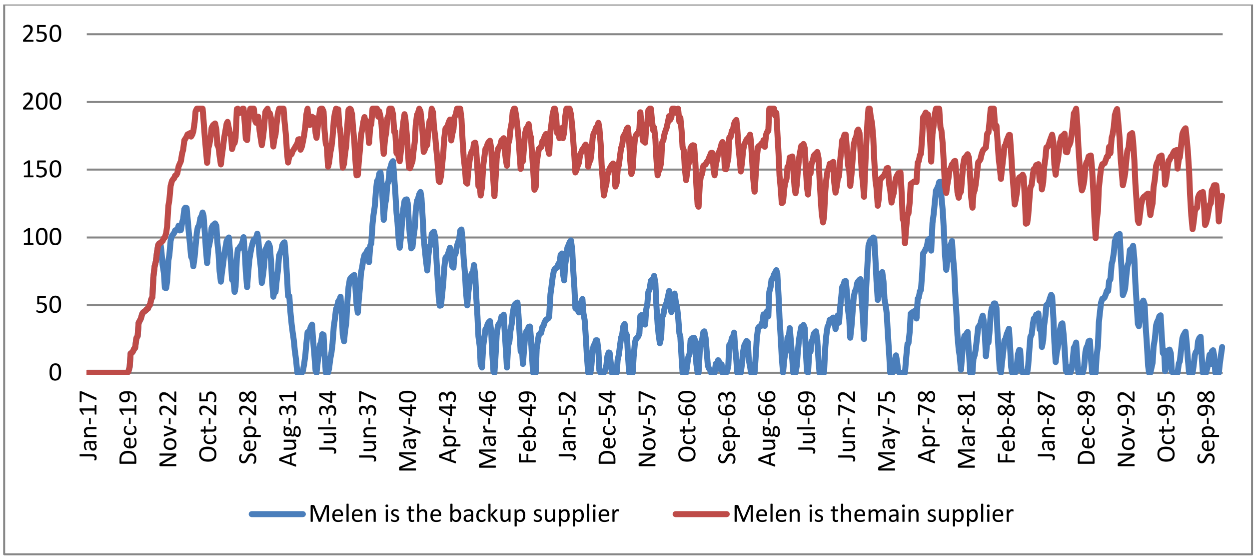


Figure 4.28. Storage Volume of İsakoy Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

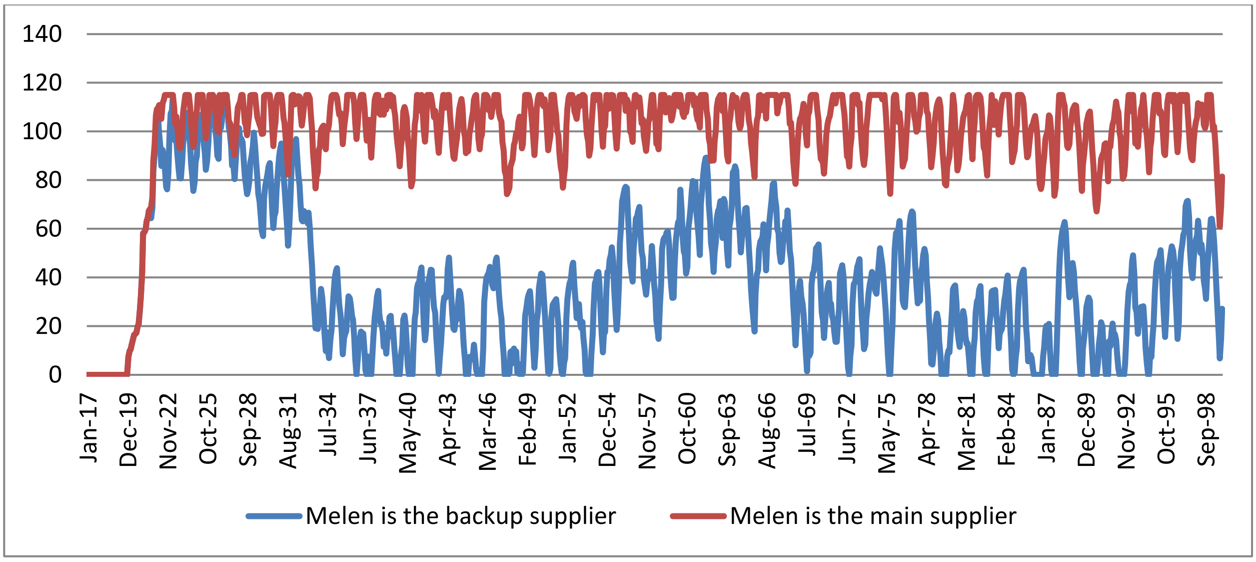


Figure 4.29. Storage Volume of Sungurlu Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

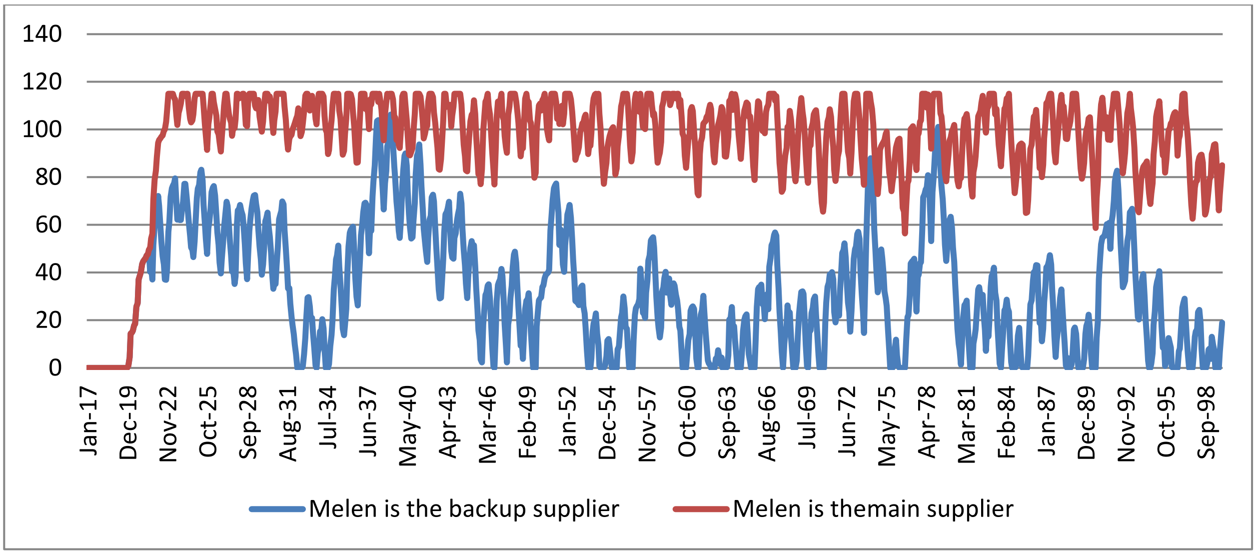


Figure 4.30. Storage Volume of Sungurlu Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

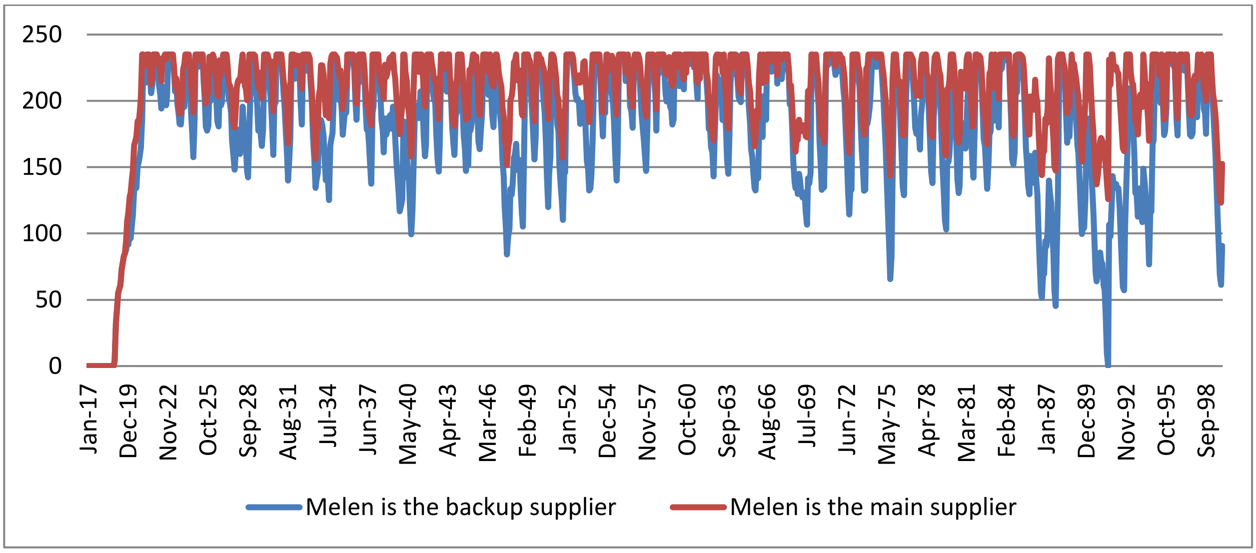


Figure 4.31. Storage Volume of Karamandere Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

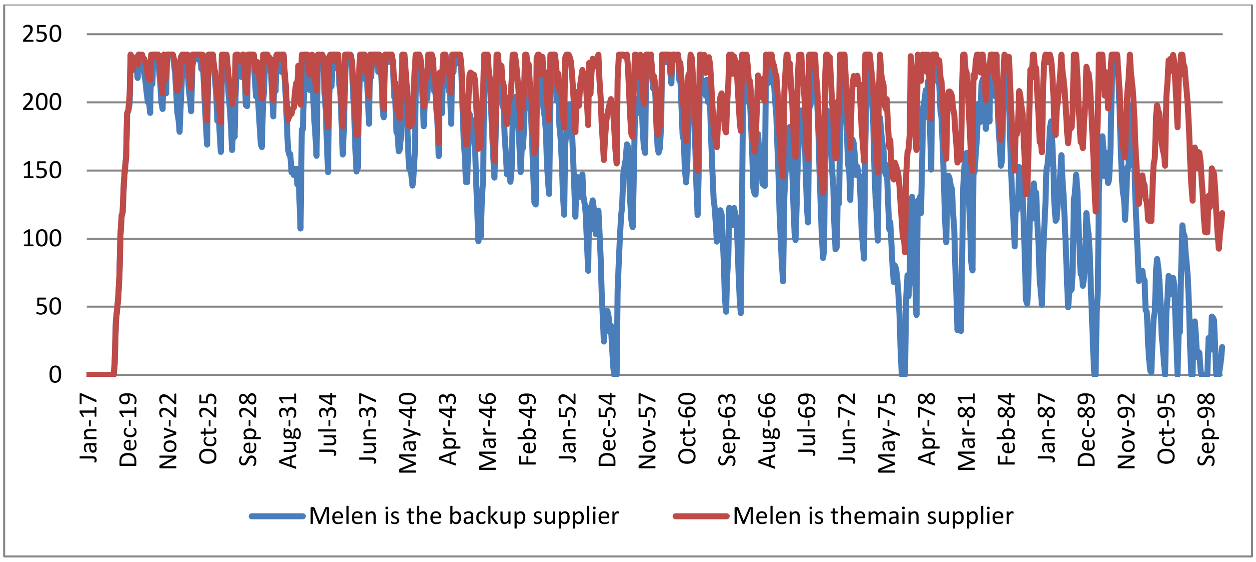


Figure 4.32. Storage Volume of Karamandere Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

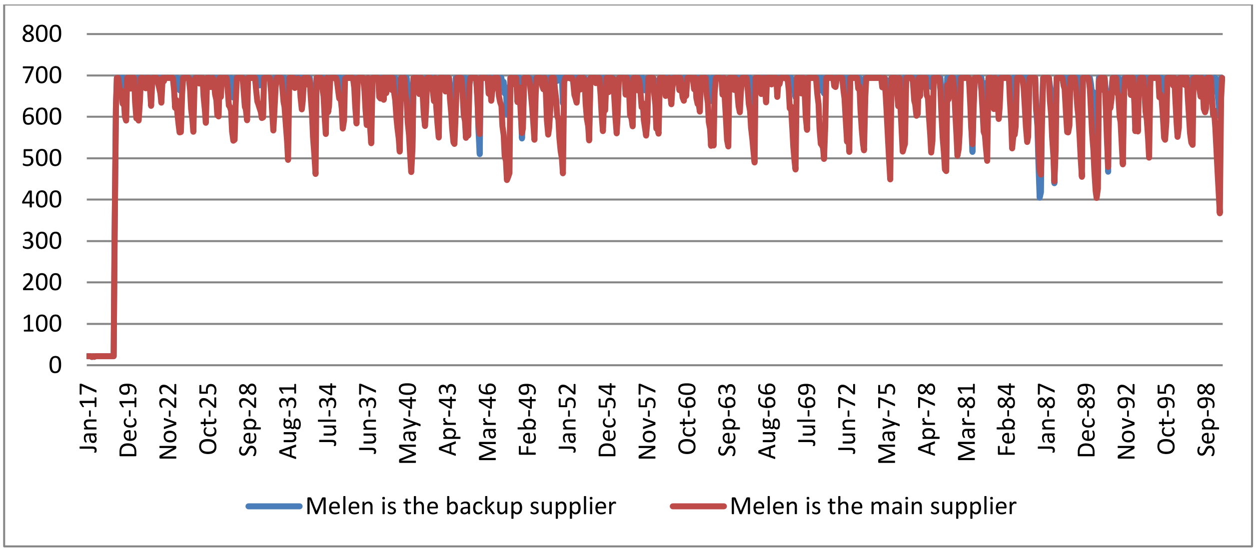


Figure 4.33. Storage Volume of Melen Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

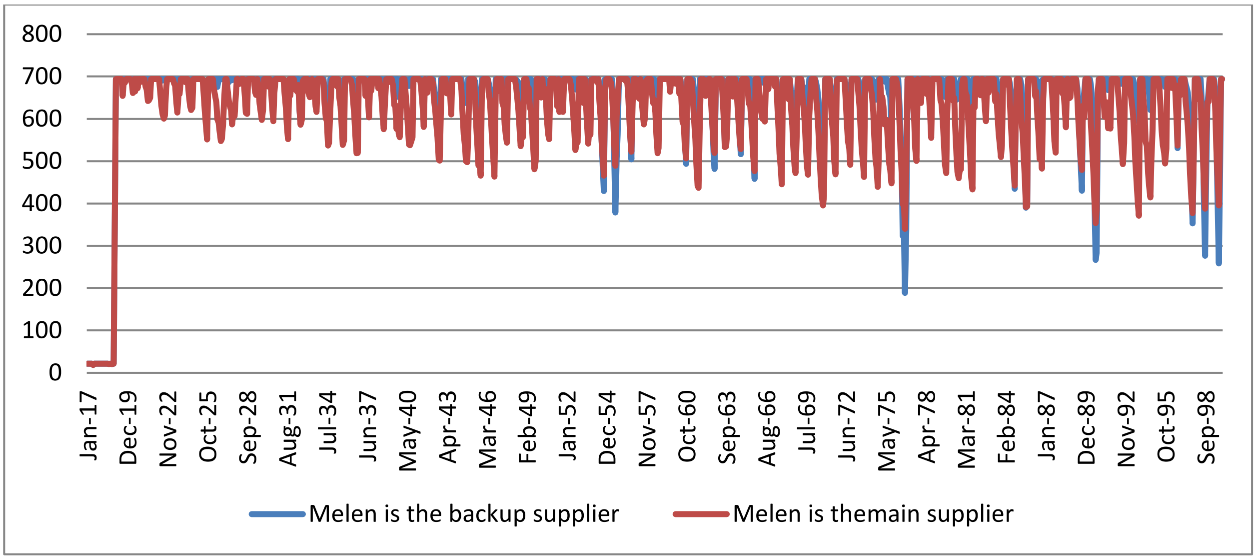


Figure 4.34. Storage Volume of Melen Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

4.5. Results without External Water Supply Sources

According to model results, with all reservoirs (both internal and external ones), the city will have improved water security with very low unmet water demand levels. However, it is important to better understand the level of dependency on external water supply sources, since currently and in the future, majority of the water supply will be supplied from external water supply sources such as Melen River, Istrancalar, Kazandere and Pabuçdere Reservoirs.

To examine the dependence of Istanbul's water supply structure on external resources, hypothetical scenarios are created where the water supply sources outside of Istanbul's municipal boundaries are removed from the model (Melen River and Istrancalar, Kazandere, Pabuçdere Reservoirs). This scenario demonstrates that local water supply sources are not adequate to satisfy the water demand under RCP 4.5 (Figure 4.35) and RCP 8.5 (Figure 4.36) scenarios. The city is highly dependent on external water supply sources to fulfill the needs of increasing population, changing water use behavior and climatic conditions. The amount of unmet water demand without external water supply sources varies but all municipalities (demand nodes) will have unmet water demand under both climate change scenarios (Figure 4.37, Figure 4.38).

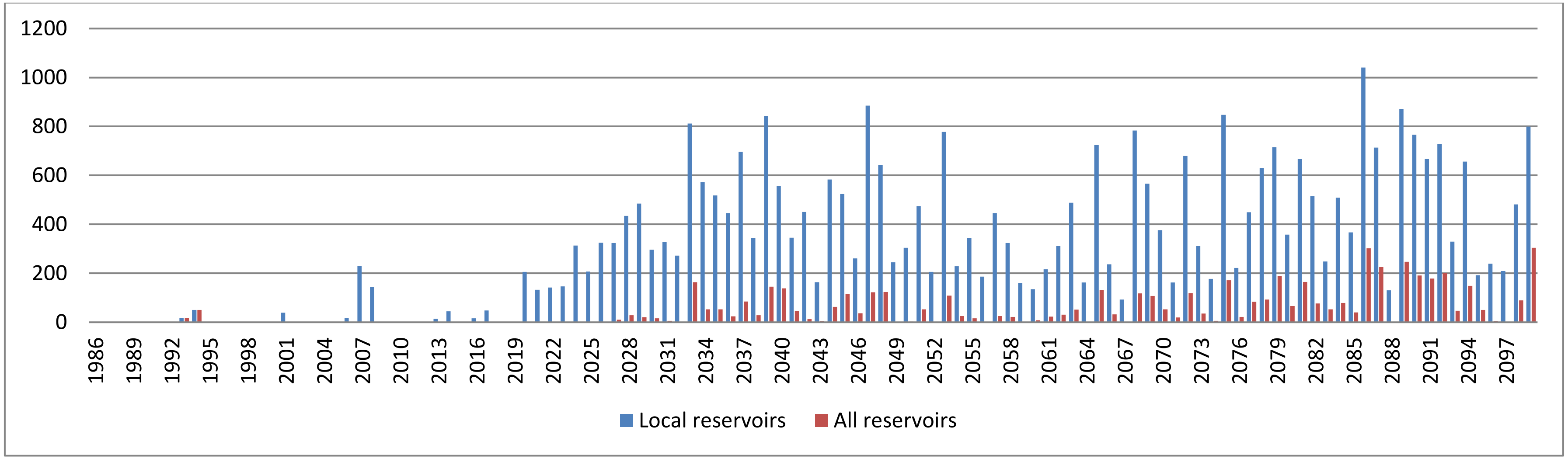


Figure 4.35. Unmet water demand with local reservoirs vs all reservoirs (RCP 4.5) (million m^3/year).

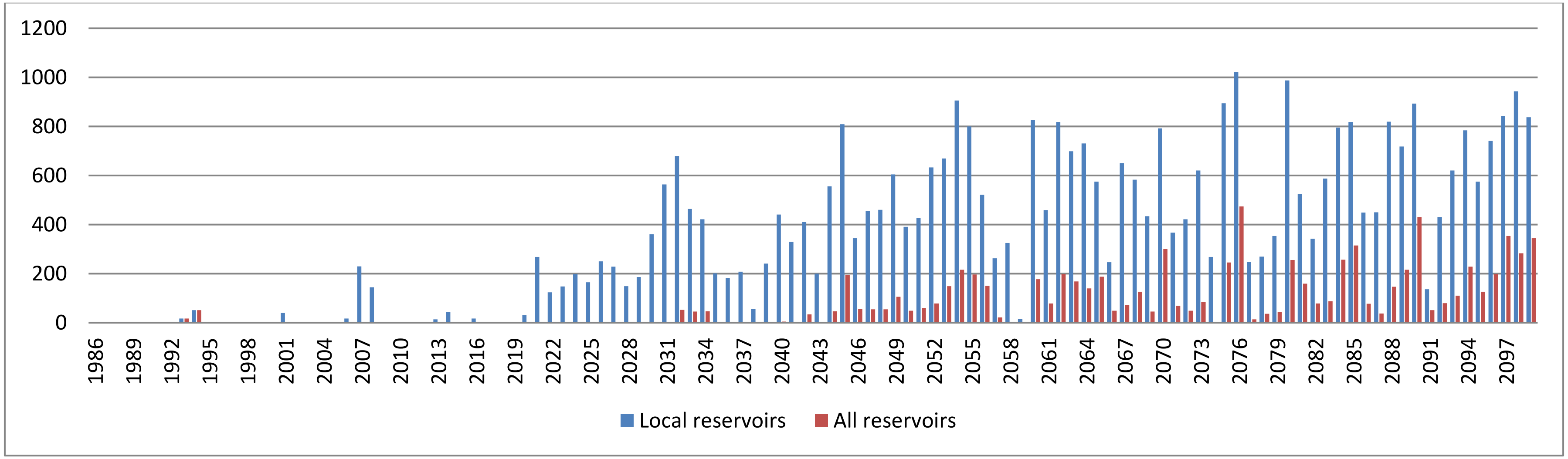


Figure 4.36. Unmet water demand with local reservoirs vs all reservoirs (RCP 8.5) (million m^3/year).

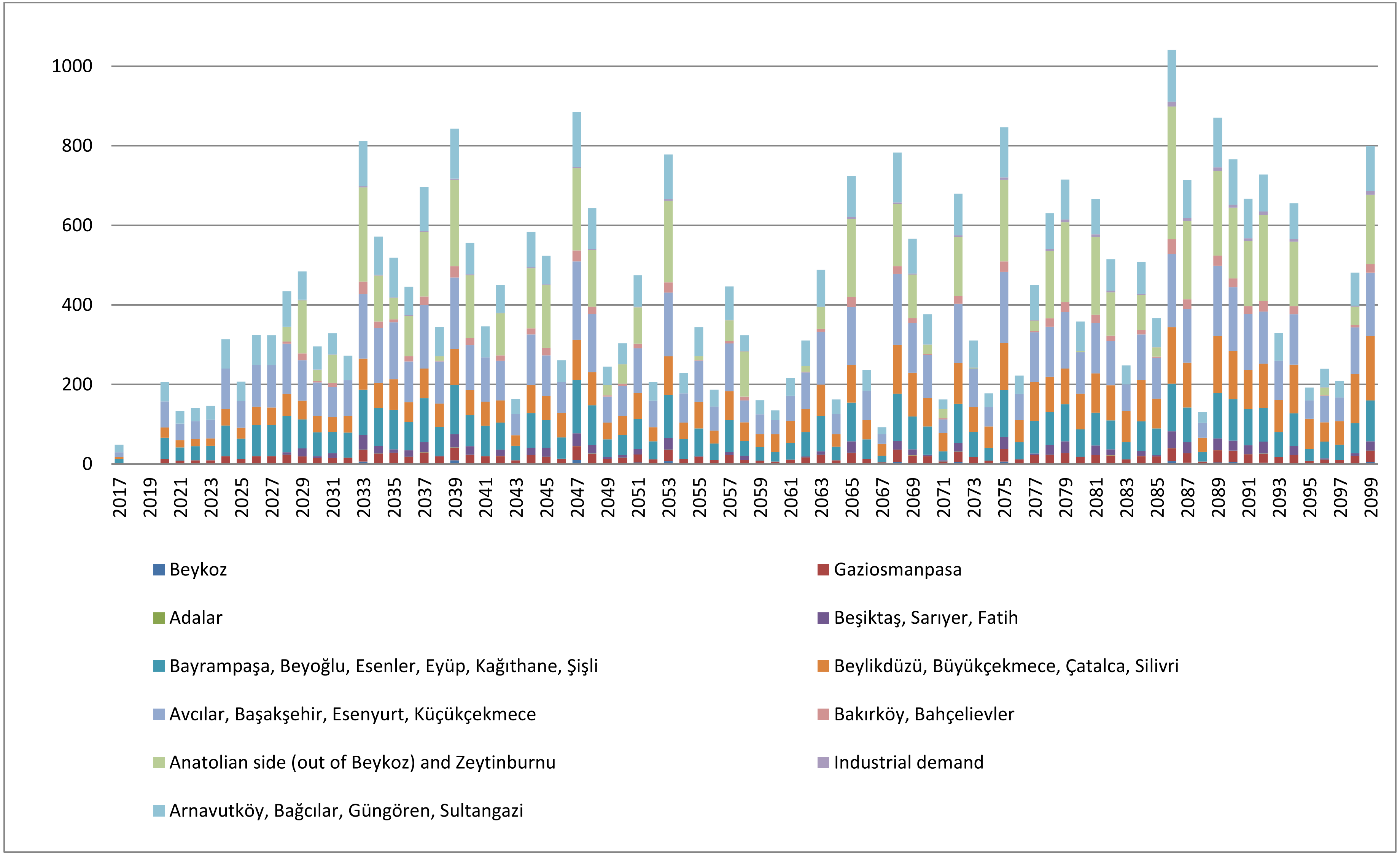


Figure 4.37. Unmet water demand without external supply sources (RCP 4.5) (million m^3/year).

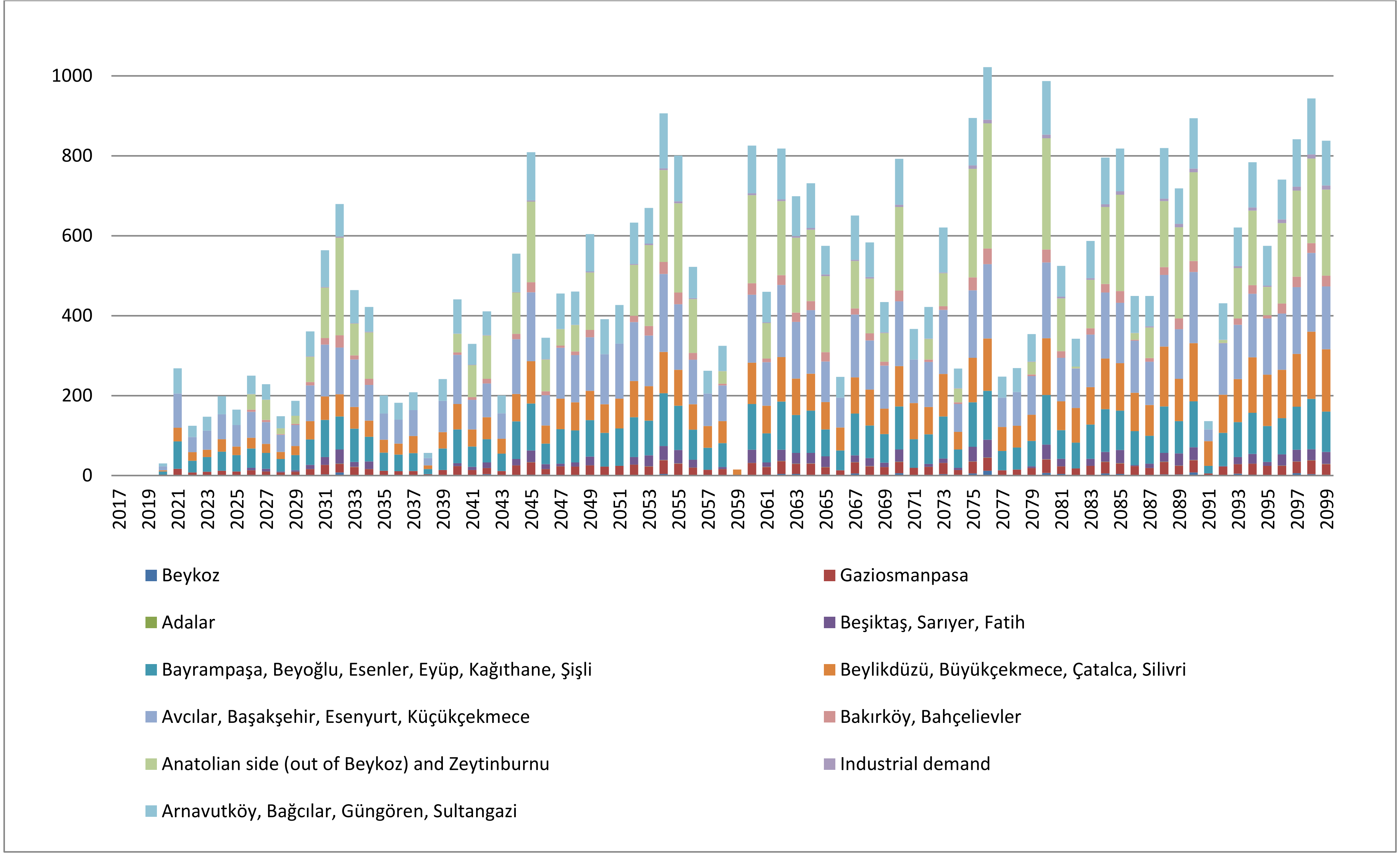


Figure 4.38. Unmet water demand without external supply sources (RCP 8.5) (million m^3/year).

After observing the overall impact of excluding external water supply sources from the model, other scenarios are created to examine the separate impacts of each external reservoir for a closer look. There are two scenarios created by removing external reservoirs from the model separately, one excludes Melen River only and second one excludes Istrancalar, Kazandere, Pabuçdere Reservoirs from water supply sources. These scenarios under the RCP 4.5 (Figure 4.39) and RCP 8.5 scenarios (Figure 4.40) show higher dependency to water supply from Melen River than Istrancalar, Kazandere and Pabuçdere Reservoirs. The figures include the expected unmet water demand amount (under BAU scenario) in case the city keeps supplying its water need only from the current supply sources and does not invest in infrastructural changes such as new reservoir construction (Figure 4.39, Figure 4.40).

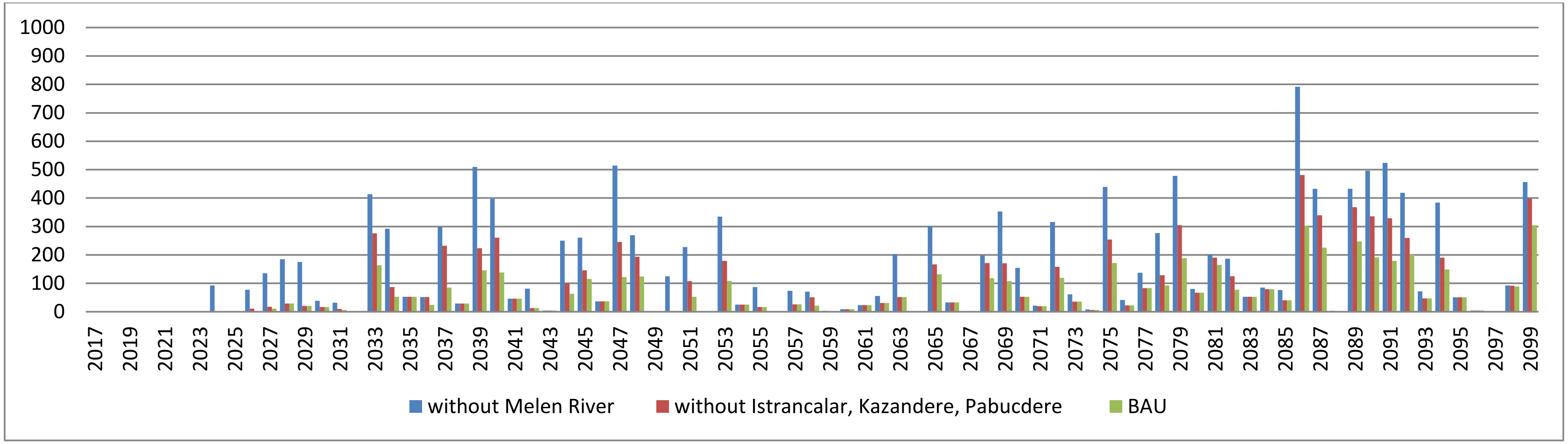


Figure 4.39. Unmet water demand without external supply sources (separately) vs BAU under RCP 4.5 scenario (million m^3 / month).

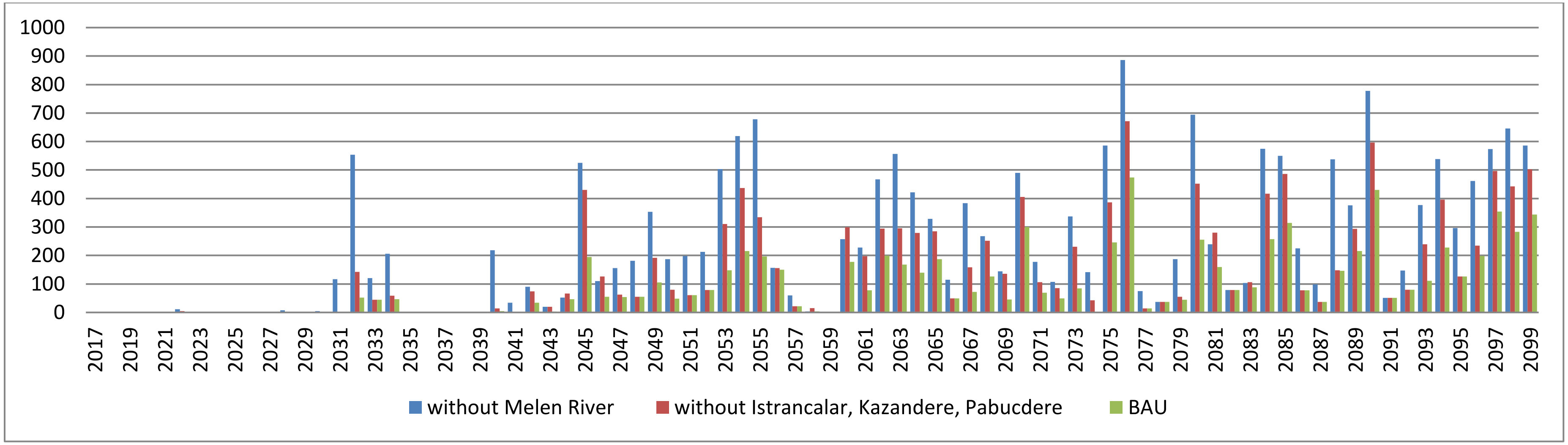


Figure 4.40. Unmet water demand without external supply sources (separately) vs BAU under RCP 8.5 scenario (million m^3 / month).

4.6. Water Insecurity Levels of Demand and Supply Nodes

The WEAP model gives the modelers the opportunity to represent supply and demand nodes in a detailed fashion. In this model, supply nodes represent the reservoirs and demand nodes represent the municipalities. Each reservoir (supply node) serves more than one municipality. The water delivery infrastructure is built to have redundancies to minimize water dependence on a single supply source. With this model capability, the water security issues are analyzed at the demand and supply node level.

For *the scenario with the current water supply sources,* a number of municipalities in Anatolian side such as Ataşehir, Çekmeköy, Kadıköy, Kartal, Maltepe, Pendik, Sancaktepe, Şile, Sultanbeyli, Tuzla, Ümraniye, Üsküdar, Zeytinburnu will have higher water security risk as they are dominantly served by Ömerli and Darlık Reservoirs. In European side, the municipalities served by Büyükçekmece Reservoir (Beylikdüzü, Büyükçekmece, Çatalca, Silivri) will also be under more water security risk (Figure 4.41, Figure 4.42). The fluctuations in the figures show the water amount which cannot be delivered to demand nodes (the unmet water demand) (Appendix C, Figure 1.1, Figure 1.2). Moreover, the municipalities in Anatolian side supplied by Ömerli and Darlık Reservoirs and the ones supplied by Büyükçekmece, Terkos, Istrancalar, Kazandere, Pabuçdere and Sazlıdere Reservoirs (Avcılar, Başakşehir, Esenyurt, Küçükçekmece) have the highest increase in water demand amount (Figure 4.41, Figure 4.42) due to their increase in population.

Furthermore, the security level is also analyzed for *the planned future infrastructural changes scenario*. Ömerli, Darlık, Elmalı, İsaköy, Sungurlu Reservoirs are more vulnerable to the changes in Melen River supply priority change and at the same time, they are the ones primarily supplying the water need of Anatolian side of the city (currently supplied by Ömerli, Darlık and Elmalı). Those reservoirs are not capable of supplying water need satisfactorily (Figures 4.21– 4.26). It concludes that the water need of the Anatolian side will not be met without the help of the water supply from Melen River, even with the supply increase as a result of the planned reservoir constructions (İsaköy and Sungurlu). Fortunately, Büyükçekmece Reservoir will be enough to meet the demand of the municipalities (Beylikdüzü, Büyükçekmece, Çatalca, Silivri) that it serves with the construction of Karamandere Reservoir. Yet, Büyükçekmece Reservoir is not enough to secure the future water need on its own as being the only supply source of these municipalities today.

In the *planned future infrastructural changes scenario*, the evaluation of the changes in reservoir storage volumes investigates the impacts of climate change closer. Since the future water supply of the city is highly dependent on Melen and there will be no unmet water demand with its significant water supply amount, the displacement of Melen Reservoir enables to observe the water shortage/drought years easily. Reservoir storage volumes for *the planned future infrastructural changes scenario* but excluding Melen Reservoir (Figure 4.41a, Figure 4.42a) and unmet water demand with the current supply sources (Figure 4.15, Figure 4.16) are examined. The model results indicate that the expected water shortage years differs with respect to climate change scenarios, highlighting the unpredictability of the impacts of climate change. The years of 2033-34, 2038-40, 2047-48, 2053-54, 2069-70, 2078-79 (severe), 2086-87, 2089-90 (severe), 2093-94, 2098-99 are the possible drought years under RCP 4.5 scenario while 2032-34, 2044-45, 2053-55 (severe), 2062-64, 2075-76 (severe), 2084-85, 2088-90 (severe) and 2094-99 for RCP 8.5 scenario. According to model results for both RCP 4.5 and RCP 8.5 climate change scenarios, there is higher probability to observe droughts in the following periods: 2032-34, 2044-48, 2053-55, 2075-79 (severe), 2084-87, 2088-90 (severe), 2093-99. The severity levels are higher for the RCP 8.5 scenario, leading reservoirs to become almost empty (for the case without Melen River).

Furthermore, the comparison of the future reservoir storage volumes with and without Melen Reservoir (Figure 4.43, Figure 4.44) shows the overall insecurity of the city without the Melen River.

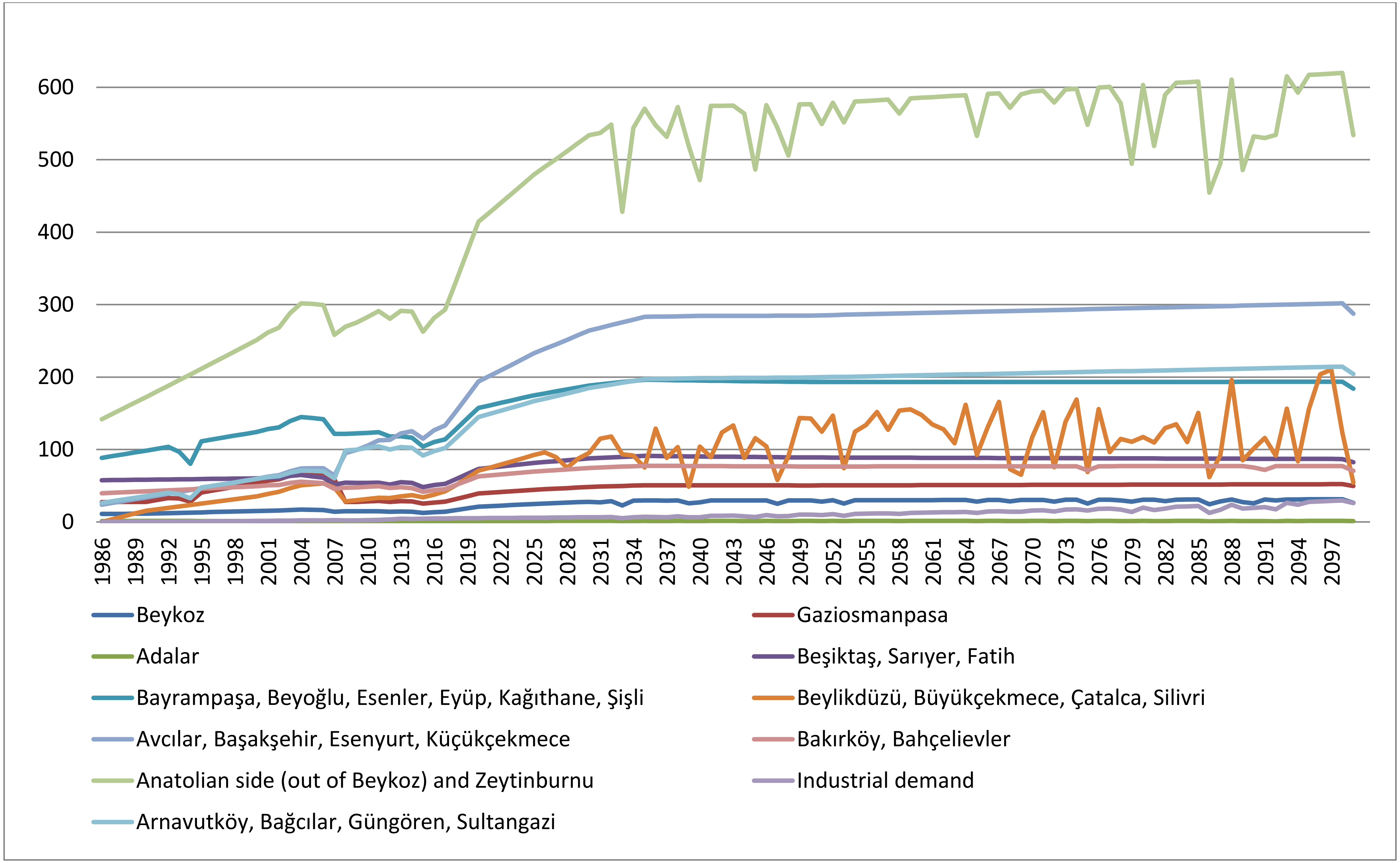


Figure 4.41. Water Supply Amount Delivered to Demand Nodes (RCP 4.5) (million m^3/year).

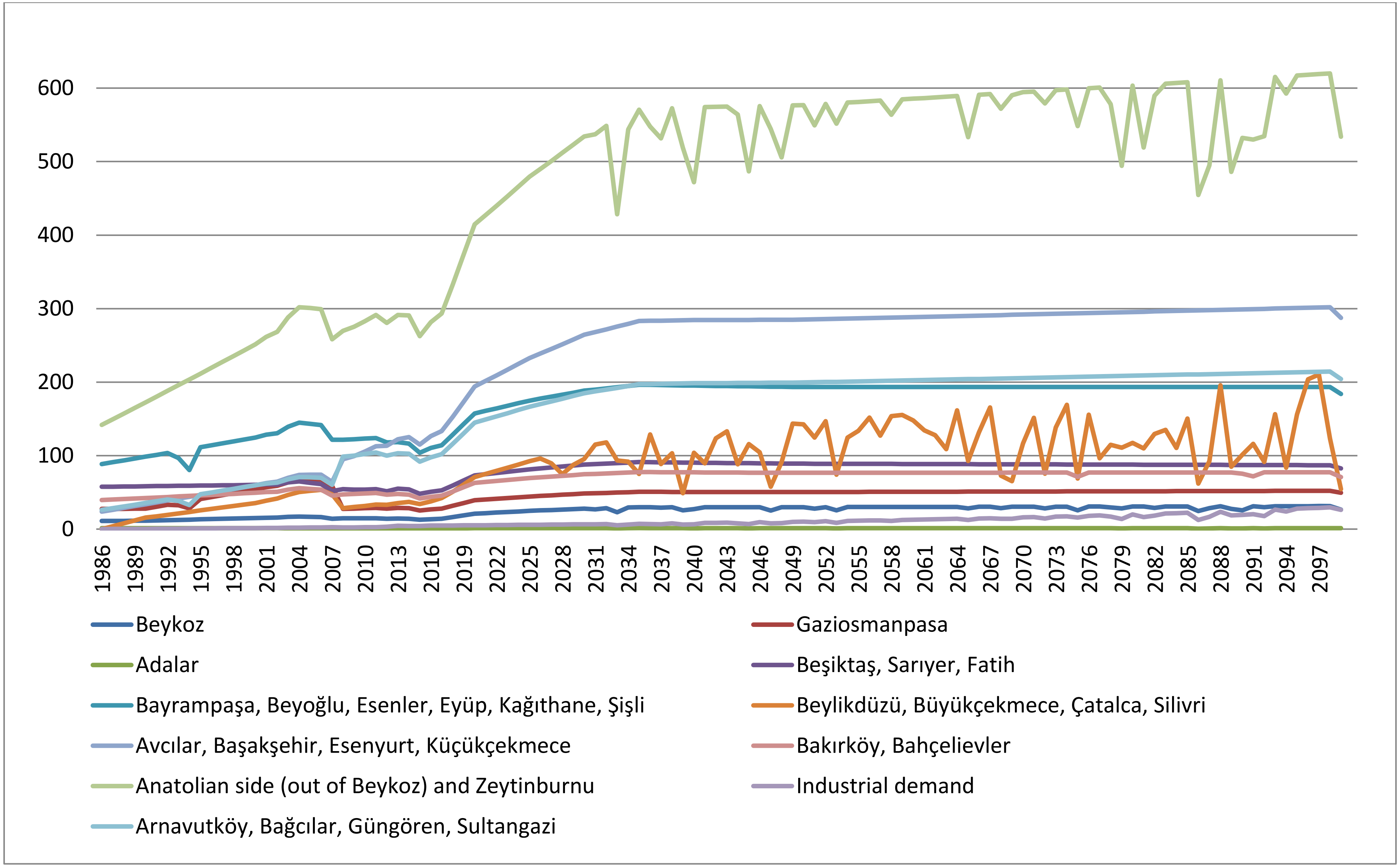


Figure 4.42. Water Supply Amount Delivered to Demand Nodes (RCP 8.5) (million m^3/year).

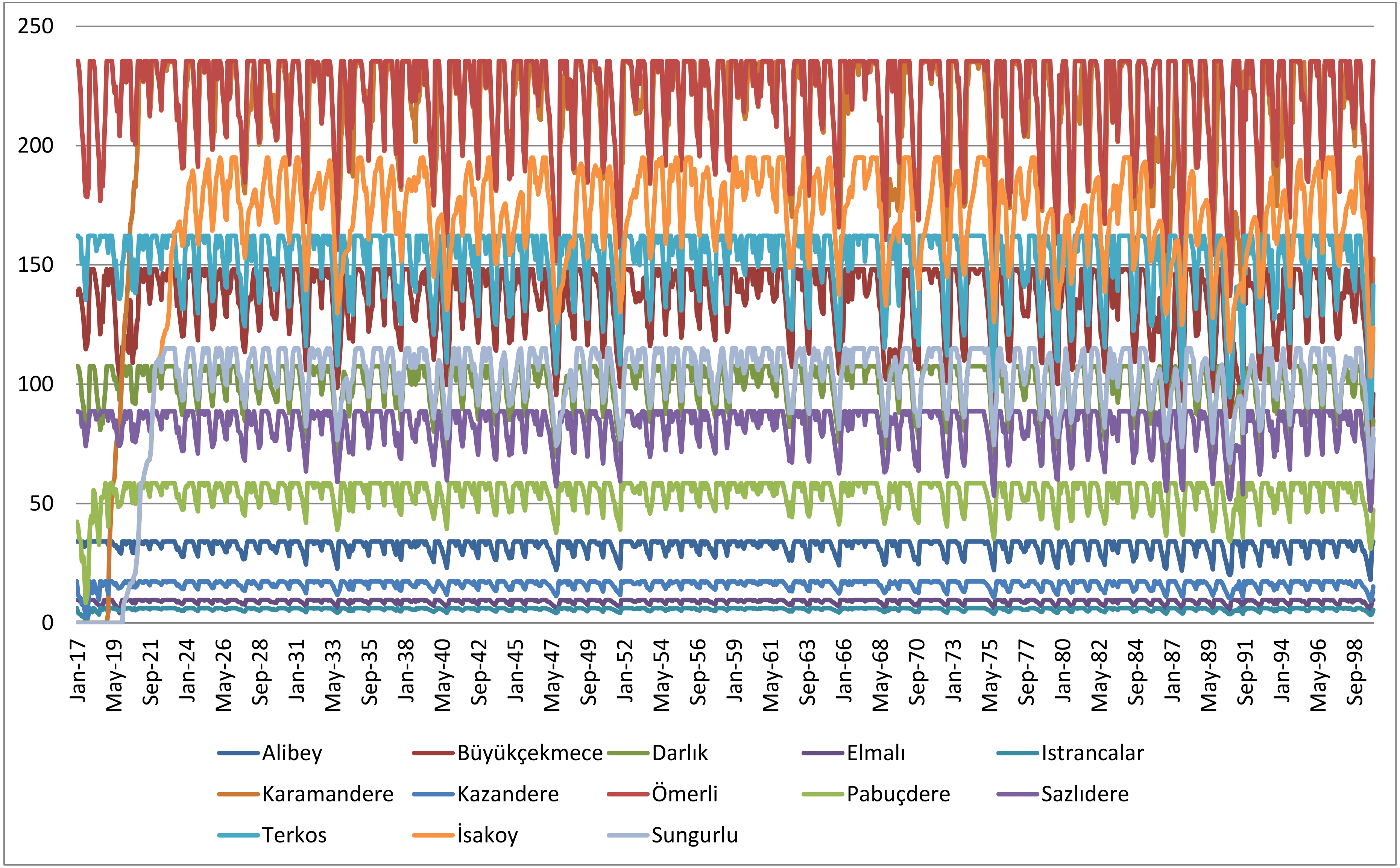


Figure 4.43a. Reservoir Storage Volumes for the future infrastructural changes scenario including Melen Reservoir (RCP 4.5) (million m^3/year).

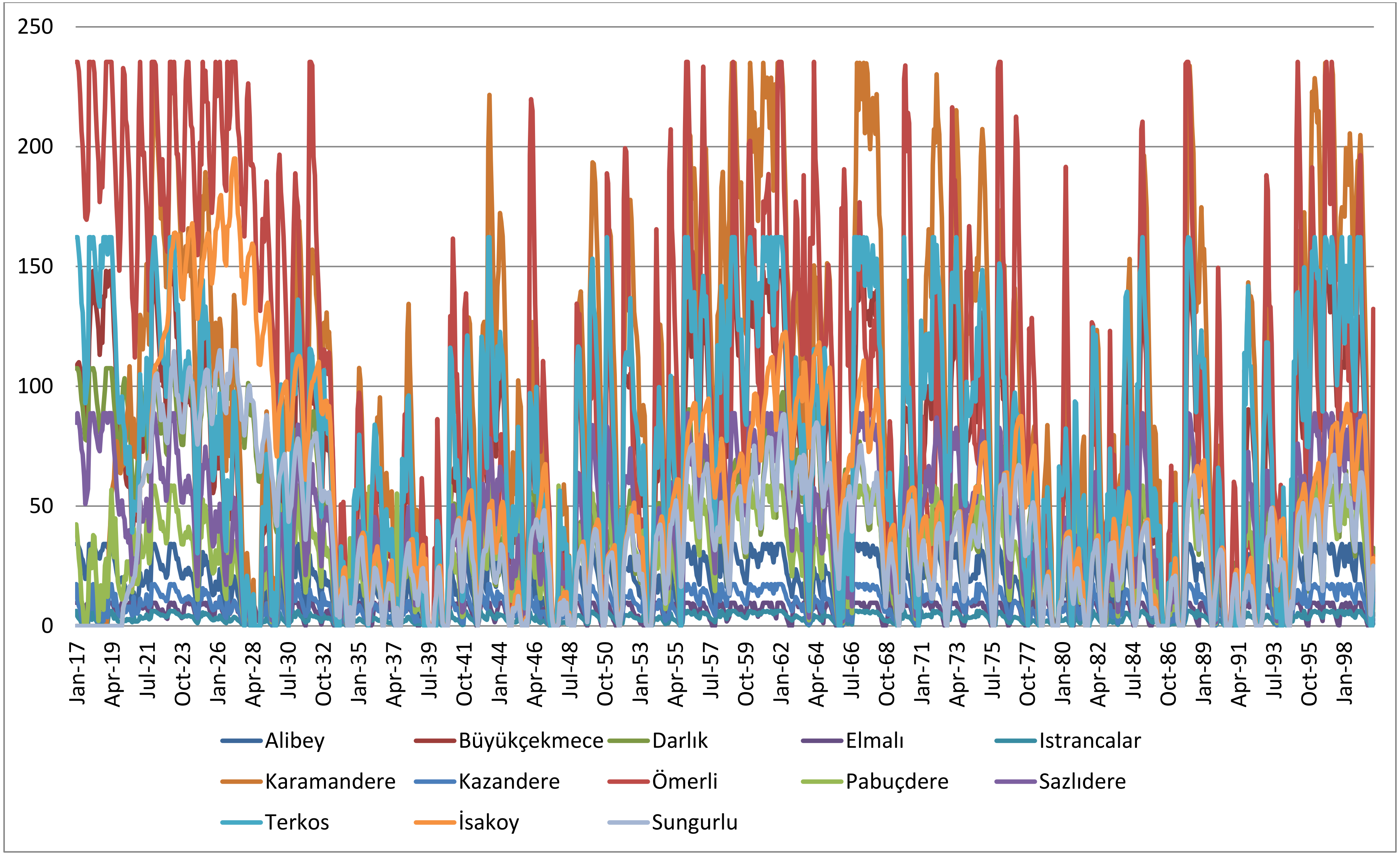


Figure 4.43b. Reservoir Storage Volumes for the future infrastructural changes scenario but excluding Melen Reservoir (RCP 4.5) (million m^3/year).

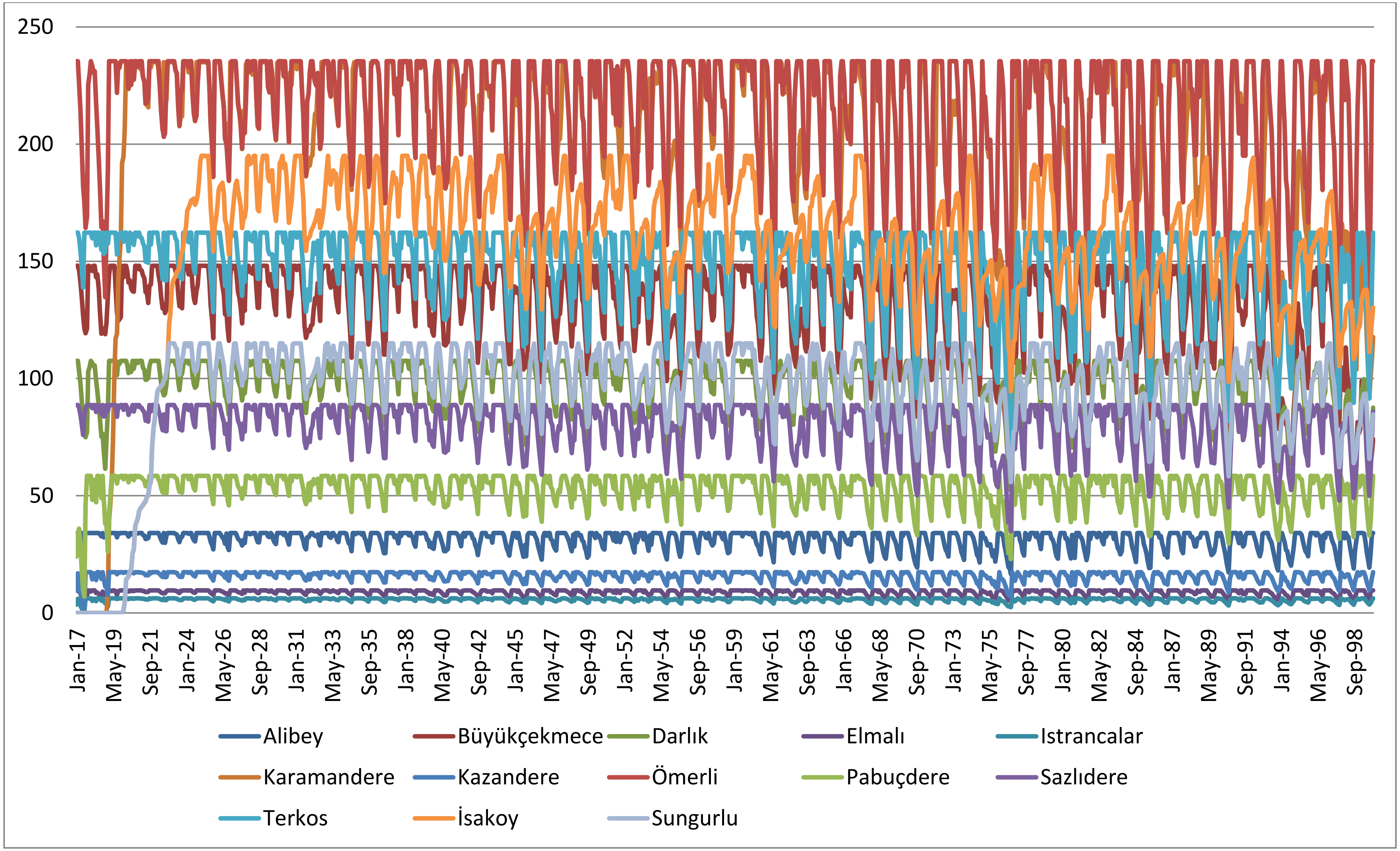


Figure 4.44a. Reservoir Storage Volumes for the future infrastructural changes scenario including Melen Reservoir (RCP 8.5) (million m^3/year).

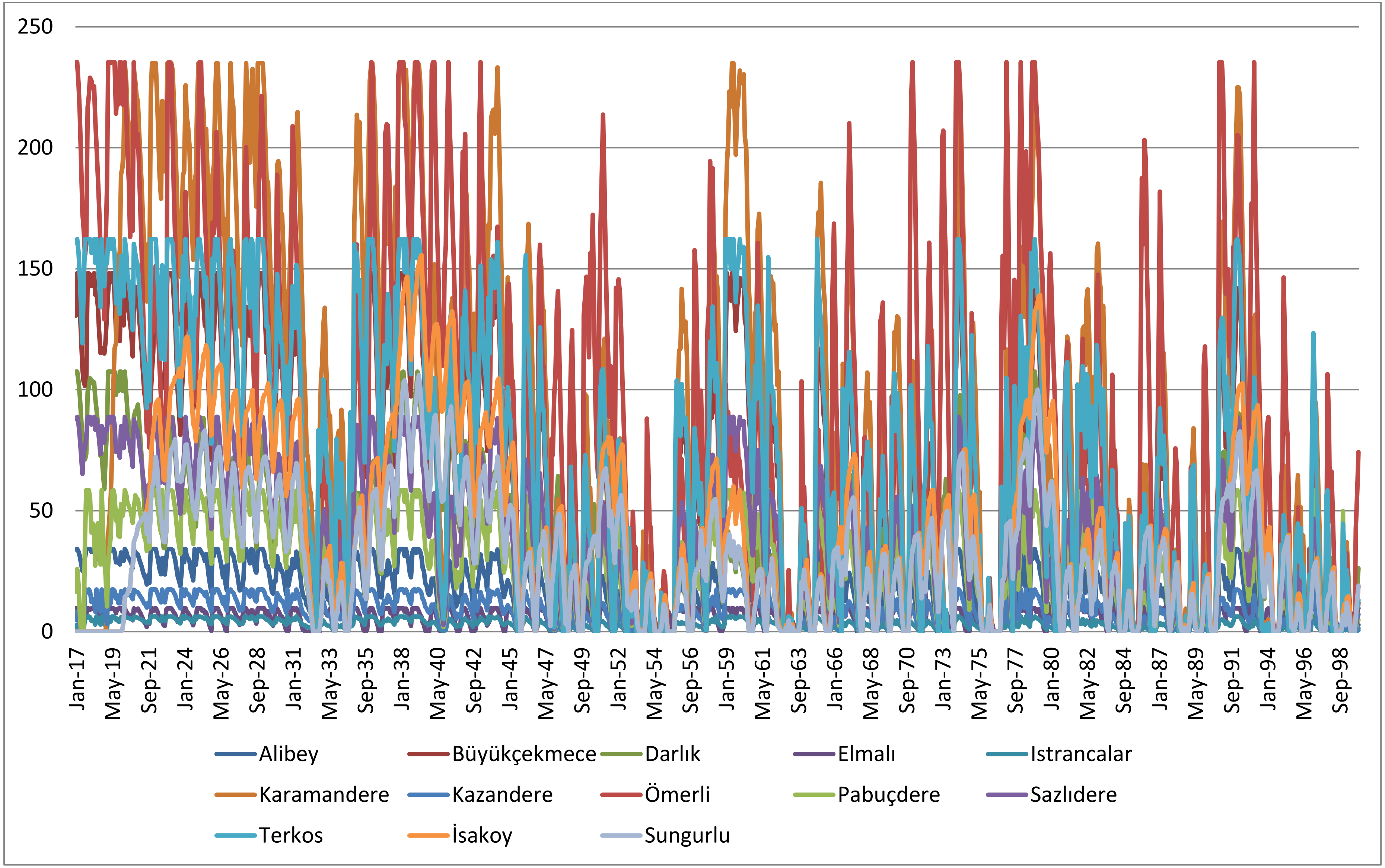


Figure 4.44b. Reservoir Storage Volumes for the future infrastructural changes scenario but excluding Melen Reservoir (RCP 8.5) (million m^3/year).

5. DISCUSSION

5.1. Discussion of Results

Istanbul is expected to have a fast increasing water demand under the effects of socio-economic changes (both population increase and water usage behavior) in the future as the model results show. Currently the city provides its water supply from local reservoirs (within the city limits) and external resources (outside city limits). The model results indicate that the water security of Istanbul is enhanced with external water supply sources such as Melen River and Istrancalar, Kazandere, Pabuçdere Reservoirs, but still full security is not obtained. Especially Melen River has high importance in providing water security of the city, as it provided 340 million m^3/year water supply, 34% of total water demand in 2017, and is projected to supply 1077 million m^3/year water for the future, meaning that Melen River would have the capacity to supply all water demand of the city on its own for the year 2017 (1020 million m^3/year). Regarding the model results, Melen River, with the projected water supply capacity, will supply 65 % of the water demand in 2040 and 59 % in 2100 in the BAU scenario. Thus, with the significant amount of water supply from Melen River, the model indicates that there is no unmet water demand under *the planned future infrastructural changes scenario* (Figure 4.17). However, climate change will further exacerbate the pressure on water supply resources, especially for Ömerli, Darlık, Elmalı Reservoirs and planned reservoirs of İsaköy and Sungurlu, (Figures 4.21– 4.34 and Appendix B, Figures 2.1 – 2.14) and the water supply and demand balance will be further stressed in Istanbul in future.

The water amount supplied from Melen River is projected to be 1077 million m^3/year (DSİ, 2018). To better understand the existing and future dependency on Melen River in water supply system of the city, further scenarios are created over the planned future infrastructural changes scenario. These scenarios reflect potential changes in water supply priority from reservoirs to the demand nodes (municipalities), ie. *Melen River is the main supply source* vs *Melen River is the backup supply source*. If *Melen River is the backup supply source,* the city would be able to supply less water from Melen River, approximately 450 million m^3/year (RCP 4.5) and 410 million m^3/year (RCP 8.5) on average (2020-2100). Yet, the reservoirs on Asian side, Ömerli, Darlık, Elmalı, İsaköy and Sungurlu, are not capable of meeting water demand of the city without the high water supply from Melen River. Therefore and unfortunately, the utilization from the Melen River as the backup supply source would probably not be possible in the future.

Migrations to the metropolis challenge the water supply issue of Istanbul (Akbas, 2005). The geopolitical context of the city has high influence on migration rates. Furthermore, as model indicates, the higher rate of population increase (HT-HP) could lead to faster increase than expected (BAU) in water demand even though it combined with a low water usage due to the technological improvements after 2040 (Figure 4.14). The population projection unpredictability and population increase have a significant impact on water demand, which is more influential than water usage, will further challenge the water security of the city.

Melen River is accepted as the security point of the water need of the city until 2040 (DSI, 2018). However, the planning agency has an anthropocentric focus and targets to fulfill the water demand of the metropolis in expense of the ecosystem needs. Building reservoirs negatively affect the river flow regime (McCartney, 2009) and threaten the biodiversity of the watershed (Bogardi et al., 2012). With the combined effects of pressures on both water demand and supply, such as migration unpredictability, damaged quality of water sources and biodiversity loss, water supply amount will probably be less than model results indicate. Therefore, the city will probably not have the expected water security level to meet the water demand of the city. It creates the urgent need of new approaches protecting biodiversity while securing water for human.

Moreover, the current water management of the city points out to both spatial and temporal challenges of water security. Since securing water in one place may lead to insecurity in another place (Srinivasan et al., 2017) and Istanbul heavily depends on external water resources (Melen River and Istrancalar, Kazandere, Pabuçdere Reservoirs), this will possibly create insecurity for the nearby cities where external sources are located such as Düzce, Sakarya, Kocaeli. In a study conducted to determine the suitability of Melen River for the freshwater abstraction, Melen River is found to be heavily polluted by domestic sewage, industrial and animal waste (Akıner and Akkoyunlu, 2012). Today, ISKI is a major water authority in Melen Watershed protection since the river is a significant source for drinking water in Istanbul after the Melen Project (Ozturk et al., 2013). In the area, wastewater management plan suggested by ISKI was implemented different than proposed (Ozturk et al., 2013). Instead of upgrading the treatment quality, the treatment plant capacity is increased more than twice the existing capacity in Düzce Wastewater Treatment Plant. With the planned construction of a new wastewater treatment plant in Cumayeri Distinct, the effluents from current and planned treatment plants will be discharged to the planned Melen Reservoir and the effluents can be reused as water supply for partly for industrial and irrigational activities as authorities suggested (Ozturk et al., 2013). Despite such studies like minimizing pollution in the main stream, the negative changes in water quality parameters in the river are observed (Erturk et al., 2010). Moreover, as the results of a study analyzing the river flow rate change in Melen Watershed indicate, excessive water withdrawal from Melen River may lead to drought in the river and threatens the wildlife (Akıner and Akkoyunlu, 2012).

Furthermore, the model results indicate an increase in the frequency of extreme events. Unmet water demand amount is expected to occur in unpredictable quantity and time as climate change impact increases. The temporal insecurity also challenges the water security of the city. Until 2040, existing water supply would be adequate to fulfill the water demand and the planned infrastructural changes enhance the water security level of the city. However, with the pressures of climate change on water resources and increasing water demand, resources will probably not provide the expected water supply amount and the city may experience water shortages. Especially in RCP 8.5 scenario, the unmet water demand increases sharply after 2040, signaling a concerning situation in terms of water security (Figure 4.15, Figure 4.16). Additionally, in *the scenario without external supply sources*, the model results indicate that the city will not be able to supply its water need from only local reservoirs (Figure 4.35, Figure 4.36). Still, when compared to *Business as Usual Scenario (BAU)*, it is possible to decrease the unmet water demand amount around 100 million m^3/year on average (2017-2100) if *High tech low pop (HT-LP)* society is achieved (Figure 4.15, Figure 4.16). It reveals the necessity of further studies to manage the water usage in Istanbul.

When evaluating model results, the model limitations should be regarded. WEAP modeling tool may have some miscalculations while transferring surface runoff from catchments to reservoirs and unpredictable water transfer limitations from reservoirs to demand nodes. After inserting climate data to catchments, the model calculates and transfers surface runoff from catchments to reservoirs but the runoff transfer year starts from the beginning time for climate data, not from the establishment year of the reservoir. It creates over calculation for reservoirs which have later establishment time compared to the initial climate data year. Thus, the beginning time of climate data needs to be arranged regarding the establishment time of reservoirs. Also, there is no certain algorithm followed while transferring water from reservoirs to demand nodes. The best way to manage water transfer is to change supply priority preferences as also used in calibration period. Yet, it still has uncertainty regarding the limit range during water transfer from reservoirs to demand nodes. So, the model has weaknesses during model construction process. Yet, it is highly powerful in scenario analysis and result presentations.

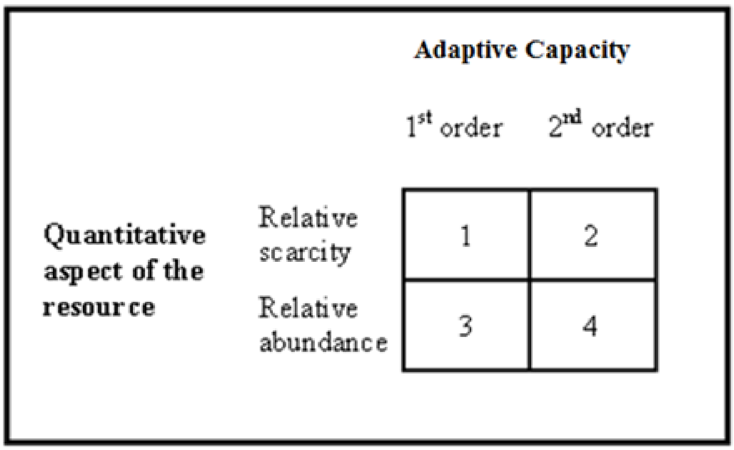
Another level of uncertainty is initiated with the future climate projection data. Future climate data are represented in two scenarios RCP 4.5 and RCP 8.5. These climate data were driver from downscaled global circulation models and have high uncertainty embedded in them. When these uncertain climate projections are provided as input to the model, there is inevitable high uncertainty in the output of the model in terms reservoir storage volumes.

With all aspects, regarding the increasing pressures on water demand and supply balance in Istanbul, there is an undeniable need to develop a more sustainable water management capturing a broader spatial and temporal water security in the city.

5.2. Water Governance in Istanbul

Regarding the necessity of enhancing the management efficiency of water resources under the pressures, the analysis of the current condition would be beneficial to create better governance in Istanbul. The Turton and Ohlsson Matrix (Figure 5.1) is helpful in evaluating the scarcity/abundance level of water resources and the adaptive capacity of the society.

In the matrix showing possible variations for resource types (natural and social resources) and quantitative aspects of these resources (Figure 5.1), Turton and Ohlsson (1999) analyze the first and second order resource scarcity levels. Second order (social) resource refers to the set of possible adaptive behaviors in a broader social context. So, it shows how societies react when they face natural resource scarcity. In this matrix, regarding the available freshwater amount per capita 1.519 m^3/ pers.yr (DSİ, 2017), Istanbul is a first-order (natural) resource scarce city. The city is not able to supply enough water to the citizens with its local natural resources. Yet, the model results show no unmet water demand with *the planned future infrastructural changes* (Figure 4.17), meaning that the city has second-order (social) resource abundance. Therefore, even though supplying water from external resources challenges the water security level, Istanbul may be accepted as having an enhanced adaptive capacity to the water scarcity the city faced. Therefore, the city is 'structurally-induced water abundance' according to the definitions interpreted from the matrix. It has the ability to manage adaptations to water scarcity by generating a suitable set of coping strategies (Turton and Ohlsson, 1999).



Matrix showing possible variations of type of resource and quantitative aspects of the resource (Turton & Ohlsson, 1999).

Figure 5.1. Turton and Ohlsson matrix.

However, the fact that such adaptive behaviors include high dependency to external resources needs to be evaluated broadly. Since it creates spatial challenge to the water security of nearby cities, the city needs to be a more sustainable water management which results in less damages to both environment and the citizens of nearby cities.

From a broader perspective, creating a more sustainable water management requires the joint contributions of all stakeholders. Water security could not be achieved without the engagement of all stakeholders (Bogardi et al., 2012). Markets, governments or civil-society movements cannot reach a sustainable integrated water management approach on their own. Thus, IWRM practices governed broadly and guided by policies is necessary. Governance should integrate all processes shaping society, economy and environment (Water Initiative, 2011). In this context, the study reveals the necessity of studies to change human water consumption habits in the context of policy and education and also the technological improvements. Such studies are required to create a more water secure future for Istanbul while protecting the nature and human water needs and to decrease the dependency to the external supply sources.

Policy constitutes a broad range of focus including interdisciplinary linkages (food, climate, energy, economy and human security), sustainable development, protection against water-related hazards (Cook and Baker, 2012). Policy regulations designed by joint contributions of all stakeholders would create better water management strategies. In the pilot study conducted in Singapore, available water resource per capita had increased in spite of the population growth with the help of policy interventions (Jensen and Wu, 2018). In Turkey, İSKİ currently has differentiated unit prices for different water uses in household consumptions, changing with respect to consumption amount, and designates fix but higher unit price for companies to decrease their water usage. Since such policy regulations also direct societies to consume water wisely, around 50 million m^3 /year water could be saved with better policy initiatives especially when supported with educational facilities. It creates less water use per capita as model results indicate (Figure 4.14). For instance, a proper regulation in bill prices would reduce unnecessary use of water at home or lead industrial areas to find ways to decrease their water consumption.

To decrease water usage, the awareness of the society is crucial as well as policy regulations. İSKİ has been designing activities to show how important water is and how crucial it is to manage individual uses, especially in schools, to increase awareness (İSKİ, 2018c). In a study focusing on water usage awareness in Istanbul, activities in every communication channels such as advertisements on television, the street boards and workshops at schools were found necessary to increase awareness (Yıldırım, 2009).

Furthermore, studies can be conducted with the regional/cultural context for a better understanding of cultural shifts in a society. Regarding the definitions of community sensitivity by Elshafei et al. (2015) and environmental awareness by van Emmerik et al. (2014), awareness studies are helpful to learn which shifts are effective to shape society behaviors against environment protection and create community actions as a result (Srinivasan et al., 2017). For instance, the flood density was decreased after channelization in Kissimmee River Basin in Florida even though the priorities turned back to protecting wetlands due wetland storage decline. It concludes the necessity for the long term evaluation of the cultural behaviors (Srinivasan et al., 2017). So, the studies focusing on the ways to increase water consciousness regarding the cultural perspective of the society in Istanbul would also be beneficial to decrease water consumption.

Model results indicate that water usage per capita is influential on total water demand of the city. If water-conserving technology is incentivized and used widely by the community, then the city can save around 50 million m^3 /year water (Figure 4.14). Yet, it can also lead to 85 million m^3 /year water loss unless the studies to fasten technology implications and society awareness is a focus area in the city (Figure 4.14). Both policy initiatives and educational campaigns focusing on increasing awareness would be necessary to achieve reduction in water demand. Such activities to decrease water demand would be necessary to achieve water security under the pressures of climate change.

In recent literature, megacities like Istanbul consider desalinization as a possible tool for achieving water security (Kibaroglu et al., 2011). Istanbul is already using all existing water resources including local and external ones. In future with the changing and exacerbating climatic conditions, the city might also need to invest in technologies that will help to increase water supply such as desalinization, water reuse and rainwater harvesting while also fastening the studies created to decrease water demand.

6. CONCLUSION

Providing water security of populous cities has been an increasing challenge. Istanbul is the major industrial and commercial center of the country while maintaining its attractiveness to migrants from other cities. Therefore, water security is highly critical for the development of the city. The water stress on existing resources has been exacerbating due to climate change and population increase. This study aims to investigate the future impact of changes in socio-economic conditions (both population increase and water use preferences) and climate on water resources that Istanbul utilizes until 2100. Water Evaluation and Planning Programme (WEAP), as an Integrated Water Resources Management (IWRM) tool, is used to model the catchment area and create the possible and plausible future scenarios to better evaluate the current and future water demand and supply balance in the city.

In the model, socio-economic changes mainly depend on the changes in population and water use and has an impact on water demand. Water use differs with technological improvement levels; low water use for a high technological society (HT), moderate water use for expected technology level (MT) and high water use for a low technological society (LT). The classification of population growth differs in three levels as well; high, moderate (expected) and low. There are three plausible future scenarios for representing the socio-economic changes (both changes in population and water use); *Business as Usual (BAU)* with expected population increase and no significant change in water efficiency technology, *High Technology with low population (HT-LP)* and *Low Technology with high population (LT-HP)* to observe the expected and extreme cases. The extreme case scenarios (HT-LP and LT-HP) are also examined with the moderate population growth projections (BAU population) to see the impact of effective water usage. The comparison of the projections created under RCP 4.5 and RCP 8.5 scenarios reflects the climate change impact on water supply and demand balance. Furthermore, the model is highly sensitive to the changes in climate parameters of precipitation and evapotranspiration as sensitivity analysis results indicate.

Model results indicate that water demand is sensitive to changes in both technology and population (Figure 4.12). Due to fast and unpredictable increase rate, population is more influential than the impact of technology (i.e., water use) on water demand (Figure 4.14) while water supply is highly affected by the changes in the climate. The impacts of climate change on water supply and thus the expected increase in unmet water demand become more preeminent after 2030s (Figure 4.15, Figure 4.16). Under the RCP 8.5 scenario, the simulations point out more dispersed and higher quantity of unmet water demand after 2040 although the model results show higher unmet water demand before 2040 for the RCP 4.5 scenario. With the current water supply sources, the city will not be capable of supplying 5 % (RCP 4.5) and 7 % (RCP 8.5) of the future water need on average (2017-2100).

The city is highly dependent on external water supply sources, especially Melen River, which is threatened by biodiversity distraction, population increase and climate change. The river is accepted as the security point for the water need of the city until 2040 (DSİ, 2018), which is located in the border of Düzce. This dependency might have a higher toll on the Melen watershed, its biodiversity, and the ecosystems services that it provides to citizens of its watershed, especially with the increasing pressures of climate change and population increase. Furthermore, depending on external sources at a high level leads spatial water insecurity. It threatens the water security of the surrounding cities where external sources are located such as Düzce, Sakarya, Kocaeli while it is increasing water security of Istanbul. Transferring water from Melen River to Istanbul will jeopardize the water security of the people in these areas. Furthermore, İSKİ plans to increase this dependency on external resources by building a new reservoir supplied by Melen River. The river supply will increase to 1077 million m^3/year with the Melen Reservoir and regulators.

The planned future infrastructural changes scenario provides a full scale observation of the future water supply system. In this scenario, especially Melen River has high importance in providing water security of the city, as it provides 340 million m^3/year water supply, 34 % of total water demand in 2017. Regarding model results, Melen River, with the projected water supply capacity, will supply 65% of the water demand in 2040 and 59 % in 2100 in the BAU scenario. Therefore, there is no unmet water demand for both climate change scenarios if the planned water management strategies are implemented (Figure 4.20). However, the water insecurity of the reservoirs come to light when Melen River is the backup supply source and all the reservoirs are heavily affected by the changes in climate (Figures 4.21– 4.34 and Appendix B, Figures 2.1 – 2.14). The city could have reduced the water amount supplied by Melen River approximately 450 million m^3/year (RCP 4.5) and 410 million m^3/year (RCP 8.5) on average if Melen River is the backup supply source. Yet, the results indicate that the reservoirs, especially Ömerli, Darlık, Elmalı, İsaköy and Sungurlu, are not capable of meeting water demand of the city without the high supply from Melen River.

The main scenarios (BAU, HT-LP, LT-HP) reflect the vulnerability of different municipalities to the changes that the city will face. The municipalities having the most unmet water demand are mainly the ones located in Anatolian side and supplied by current reservoirs of Ömerli, Darlık, Elmalı and planned reservoirs of İsaköy and Sungurlu. Moreover, the same municipalities supplied by Ömerli and Darlık Reservoirs and the ones supplied by Büyükçekmece, Terkos, Istrancalar, Kazandere, Pabuçdere and Sazlıdere Reservoirs (Avcılar, Başakşehir, Esenyurt, Küçükçekmece) have the highest increase in water demand amount (Figure 4.41, Figure 4.42). For the scenario without external water supply sources, the amount of unmet water demand varies but all demand nodes (municipalities) have unmet water demand under both climate change scenarios (Figure 4.37, Figure 4.38).

Even though Istanbul currently has high adaptive capacity due to infrastructural implementations to cope with the water scarcity, the high dependency to external supply sources threatens the water security of both Istanbul and nearby cities. Therefore, regarding all challenges created by anthropogenic and climatic conditions on water resources, water needs to be governed more strategically to create alternative sustainable management strategies. To enhance the management capacity in the city, this study suggests to accelarate the initiatives to decrease water demand by changing human water consumption habits together with the technological improvements. With the strategic applications in policy, educational facilities and technology, the city could decrease water demand around 50 million m^3/year as model results indicate. In the case where Melen River and Reservoir are not the major supplier of the city, other technological solutions such as rainwater harvesting and desalinization would also be necessary to enhance water security.

Participation of all stakeholders (markets, governments and civil-society movements at both local and national level) would provide a better policy regulation, which captures a broader definition of water security, to protect water resources and motivate societies to use water strategically and to decrease water use rate. As well as policy regulations, educational facilities are crucial to increase awareness of the society, which has a direct impact on water use rate. When such studies are combined with technological improvements, a more water secure future can be created for the metropolis Istanbul.

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APPENDICES

APPENDIX A: OBSERVED AND PROJECTED DATA IN THE MODEL

Table 1. Annual population change percentage for each demand node in the WEAP model and corresponding municipalities (observed and projected data).

Demand node (Bayrampaşa,Beyoğlu,Esenler,Eyüp,Kağıthane,Şişli) Served by supply nodes (Alibey, Terkos, Istrancalar, Kazandere, Pabuçdere Dams and Melen River)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	0.42%	0.33%	0.19%	0.12%	0.02%	0.02%
2.39%	2.13%	3.01%	0.23%	average	0.40%	0.29%	0.16%	0.10%	0.02%	0.02%
				low	0.38%	0.26%	0.14%	0.09%	0.01%	0.01%
Demand node (Ataşehir,Çekmeköy,Kadıköy,Kartal,Maltepe,Pendik,Sancaktepe,Şile,Sultanbeyli,Tuzla,Ümraniye,Üsküdar,Zeytinburnu) served by supply nodes (Ömerli and Darlık Dams)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	1.43%	1.25%	0.98%	0.69%	0.31%	0.20%
4.30%	3.54%	3.91%	2.26%	average	1.35%	1.11%	0.86%	0.59%	0.26%	0.15%
				low	1.27%	0.97%	0.74%	0.49%	0.19%	0.10%
Demand node (Beylikdüzü,Büyükçekmece,Çatalca,Silivri) served by supply node (Büyükçekmece Dam)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	5.50%	4.27%	3.06%	2.27%	1.62%	1.00%
12.32%	7.62%	9.34%	6.12%	average	5.19%	3.79%	2.69%	1.94%	1.31%	0.80%
				low	4.88%	3.32%	2.32%	1.61%	1.00%	0.40%
Demand node (Arnavutköy,Bağcılar,Güngören,Sultangazi) served by supply nodes (Sazlıdere, Terkos, , Istrancalar, Kazandere, Pabuçdere Dams)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	1.27%	1.13%	0.87%	0.66%	0.33%	0.20%
6.44%	4.87%	3.59%	1.51%	average	1.20%	1.00%	0.77%	0.56%	0.27%	0.15%
				low	1.13%	0.88%	0.66%	0.47%	0.20%	0.10%
Demand node (Avcılar,Başakşehir,Esenyurt,Küçükçekmece) served by supply nodes (Büyükçekmece, Sazlıdere, Terkos, Istrancalar, Kazandere, Pabuçdere Dams)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	3.06%	2.15%	1.43%	0.75%	0.28%	0.15%
7.28%	5.34%	4.84%	6.30%	average	2.88%	1.91%	1.26%	0.65%	0.23%	0.12%
				low	2.71%	1.67%	1.08%	0.54%	0.17%	0.08%

Demand node (Beşiktaş,Fatih,Sarıyer) served by supply nodes (Alibey, Terkos, Istrancalar, Kazandere, Pabuçdere, Ömerli, Darlık Dams and Melen River)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	0.48%	0.38%	0.21%	0.07%	-0.09%	-0.06%
0.12%	0.12%	0.92%	0.74%	average	0.46%	0.34%	0.18%	0.06%	-0.07%	-0.05%
				low	0.43%	0.29%	0.16%	0.05%	-0.05%	-0.04%
Demand node (Gaziosmanpasa) served by supply nodes (Alibey, Sazlıdere, Terkos, Istrancalar, Kazandere, Pabuçdere Dams and Melen River)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	0.86%	0.68%	0.46%	0.23%	0.12%	0.10%
9.11%	6.26%	4.95%	1.27%	average	0.81%	0.61%	0.40%	0.20%	0.10%	0.07%
				low	0.76%	0.53%	0.35%	0.17%	0.08%	0.05%
Demand node (Beykoz) served by supply nodes (Ömerli, Elmalı Dams and Melen River)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	2.21%	1.74%	1.16%	0.71%	0.25%	0.15%
3.05%	2.64%	2.10%	0.37%	average	2.08%	1.55%	1.02%	0.61%	0.20%	0.10%
				low	1.96%	1.35%	0.88%	0.50%	0.15%	0.05%
Demand node (Bahçelievler,Bakırköy) served by supply nodes (Buyukçekmece, Sazlıdere, Terkos, , Istrancalar, Kazandere, Pabuçdere, Ömerli, Darlık Dams)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	0.31%	0.23%	0.11%	0.06%	0.04%	0.030%
1.45%	1.35%	2.07%	0.70%	average	0.29%	0.20%	0.10%	0.05%	0.03%	0.020%
				low	0.27%	0.18%	0.09%	0.04%	0.02%	0.017%
Demand node (Adalar) served by supply node (Ömerli and Darlık Dams)										
1990-1995	1995-2000	2000-2007	2008-2015	scenarios	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2100
				high	-0.21%	-0.17%	-0.11%	-0.06%	-0.01%	-0.01%
-0.85%	-0.89%	-5.87%	1.57%	average	-0.20%	-0.15%	-0.10%	-0.05%	-0.01%	-0.01%
				low	-0.19%	-0.13%	-0.09%	-0.04%	-0.01%	-0.01%

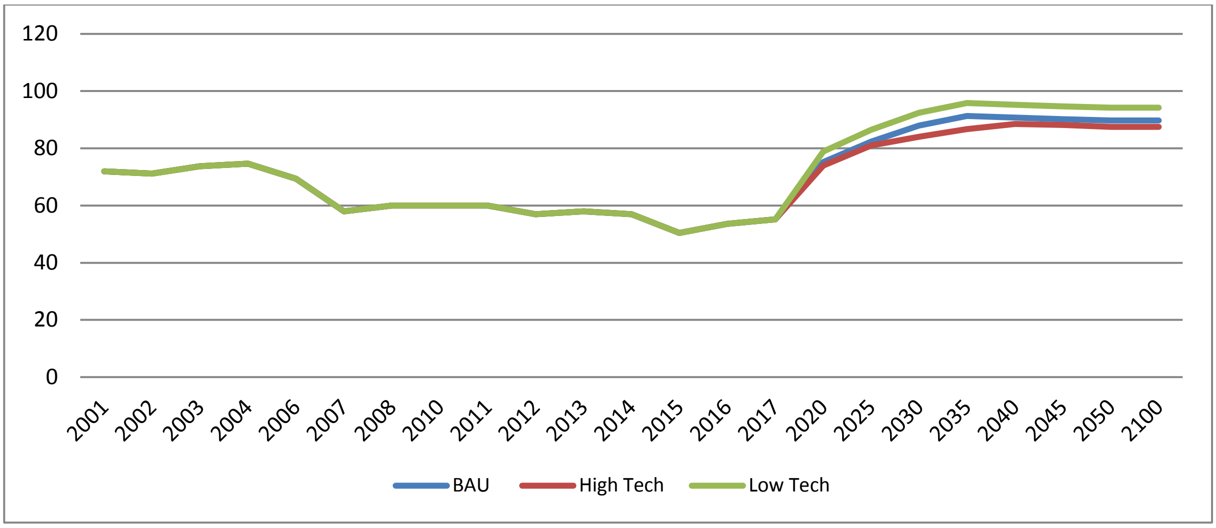

Figure 1. Water use data (past and projected data for 3 main scenarios) (m^3/cap/year).

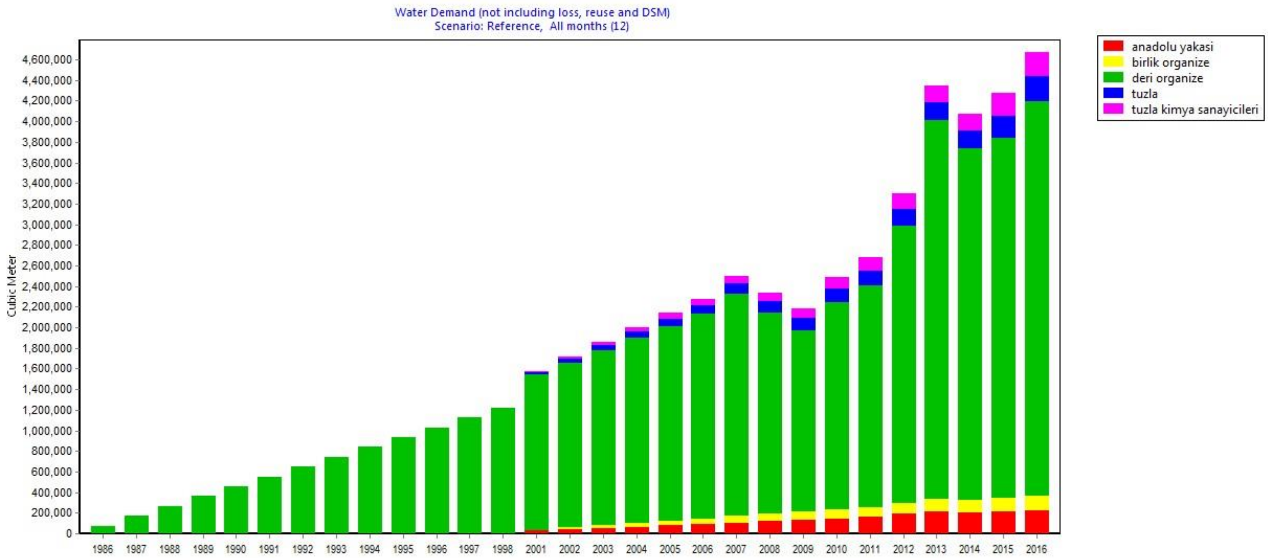

Figure 2. Observed industrial water demand in Istanbul (1986-2016).

APPENDIX B: RESERVOIR STORAGE VOLUMES OF SCENARIOS UNDER PLANNED FUTURE INFRASTRUCTURAL CHANGES SCENARIO

Reservoir Storage Volumes under Planned Future Infrastructural Changes Scenario (Figures 1.1-1.14)

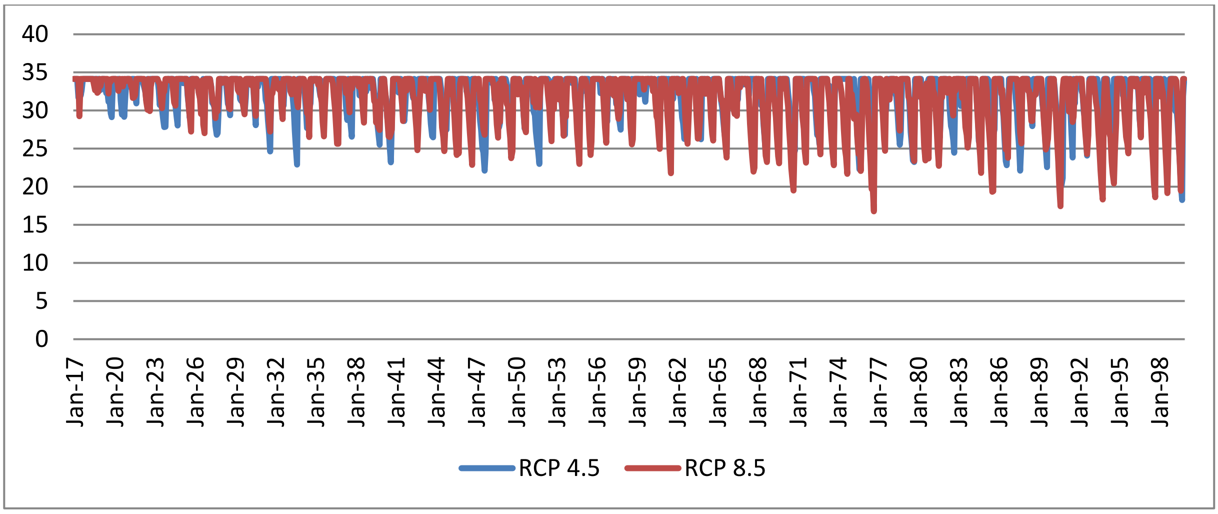

Fig 1.1. Storage Volume of Alibey Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

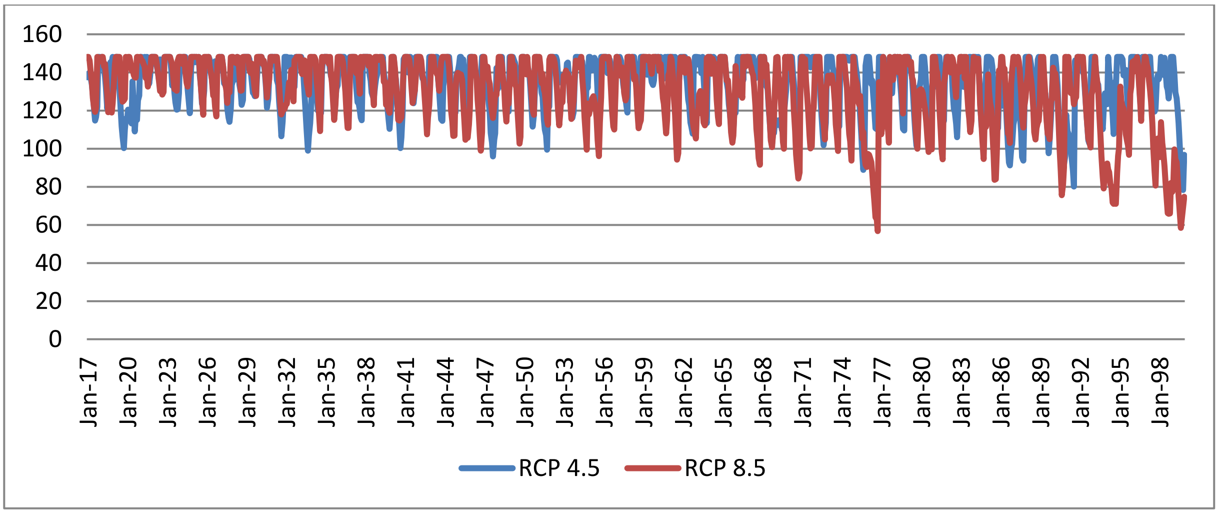

Fig 1.2. Storage Volume of Büyükçekmece Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

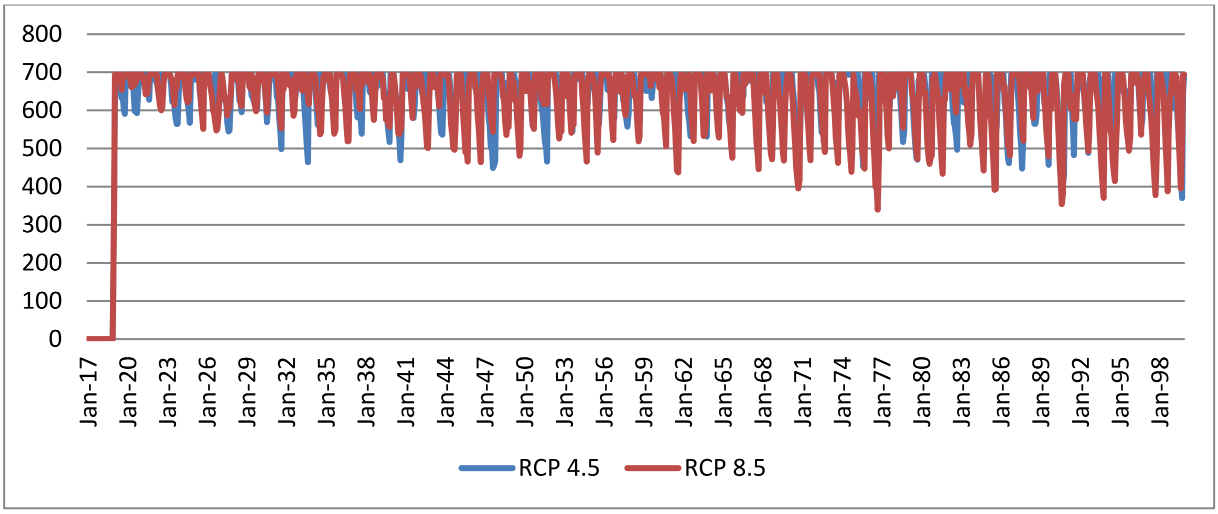

Fig 1.3. Storage Volume of Cumhuriyet Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

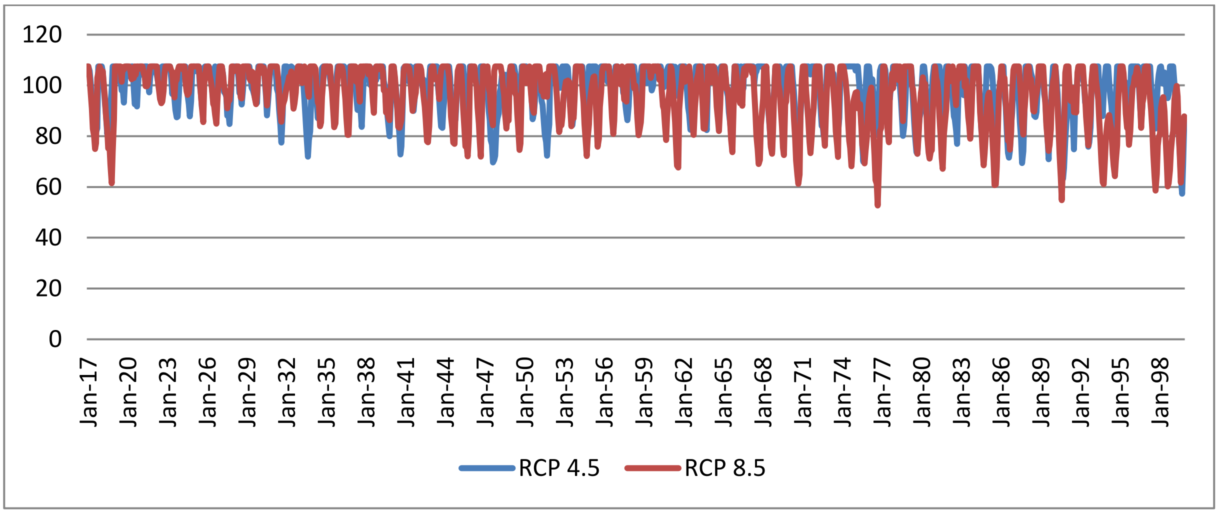

Fig 1.4. Storage Volume of Darlık Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

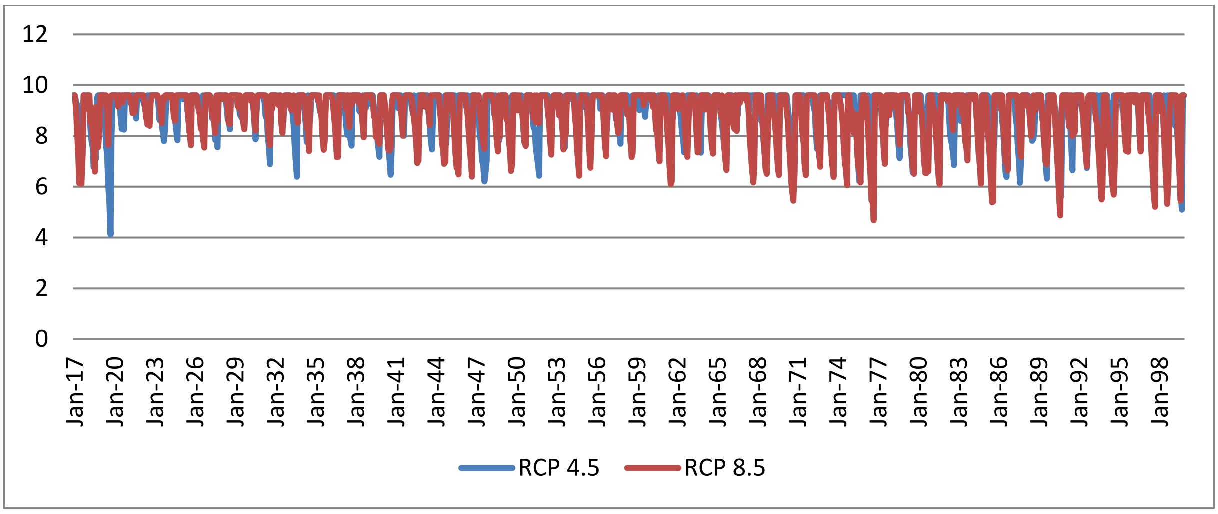

Fig 1.5. Storage Volume of Elmalı Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

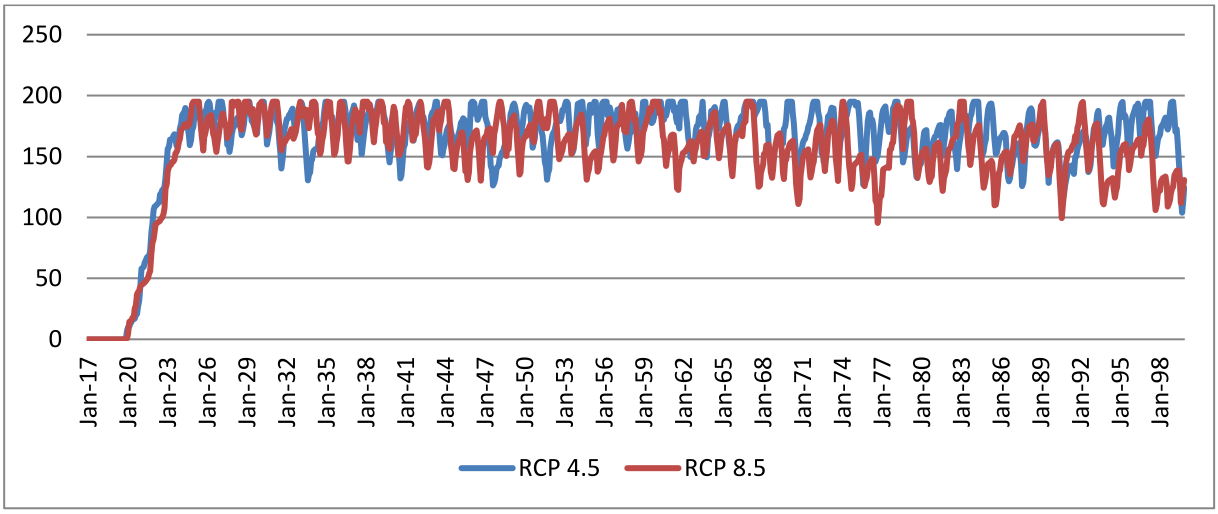

Fig 1.6. Storage Volume of İsakoy Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

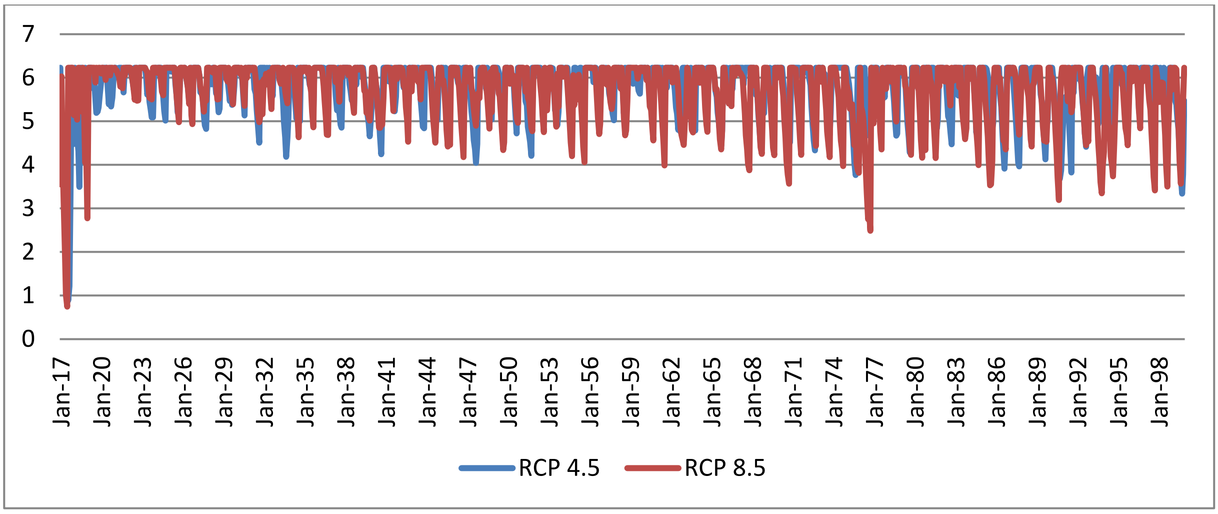

Fig 1.7. Storage Volume of Istrancalar Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

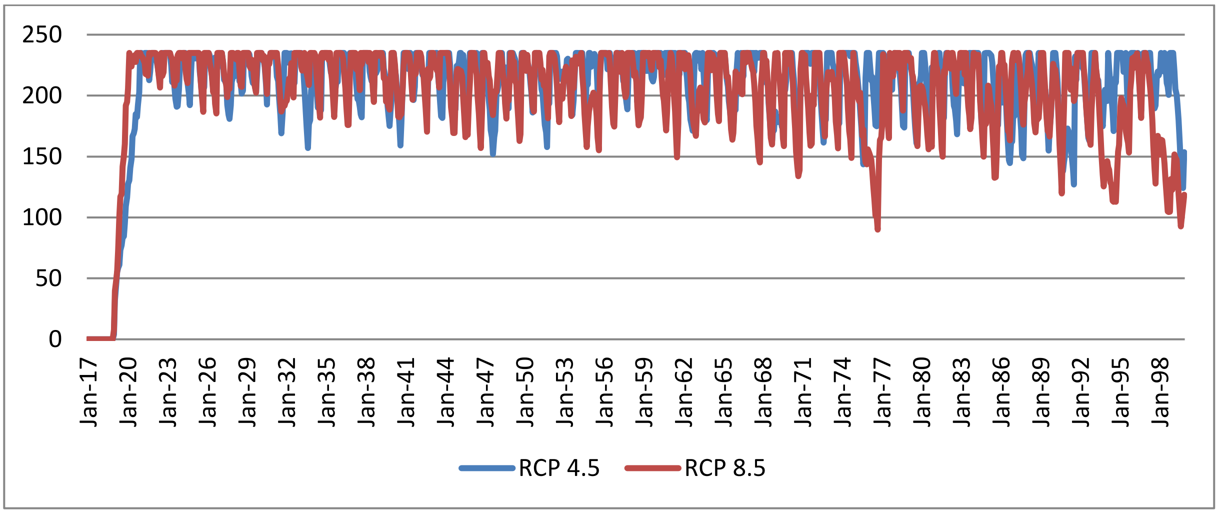

Fig 1.8. Storage Volume of Karamandere Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

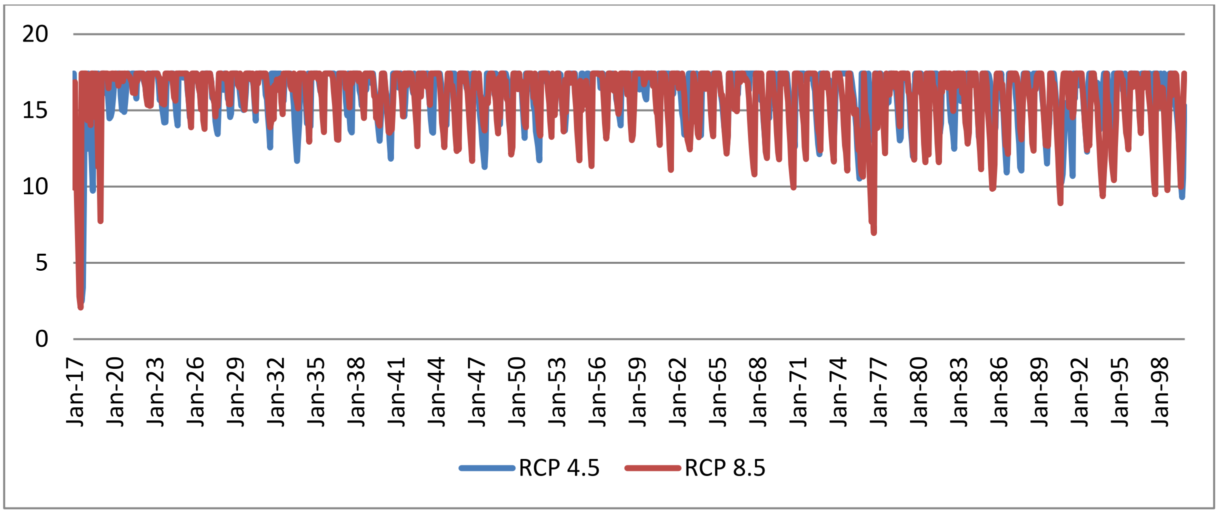

Fig 1.9. Storage Volume of Kazandere Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

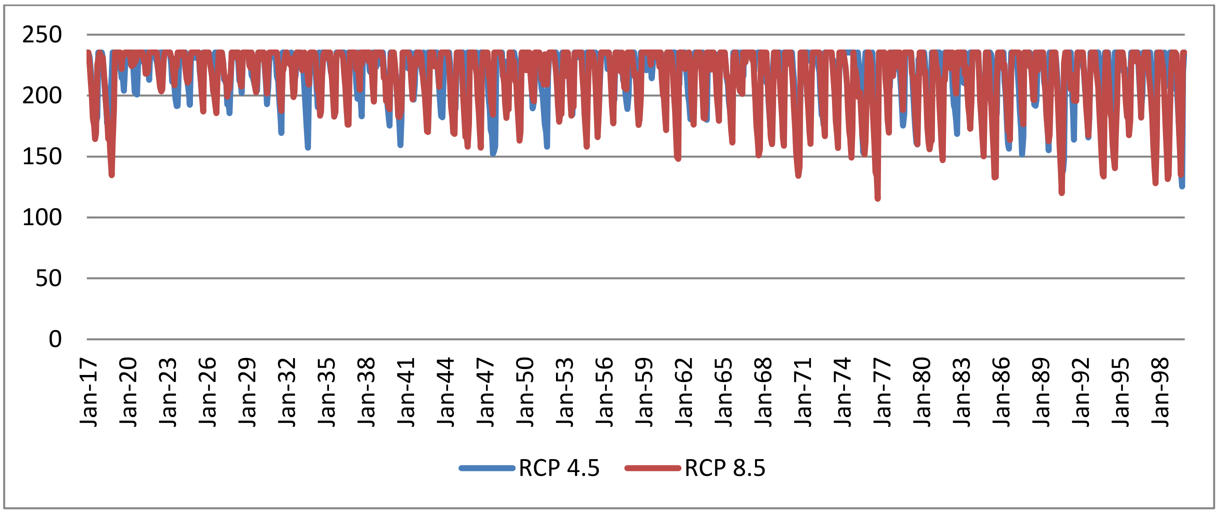

Fig 1.10. Storage Volume of Kazandere Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

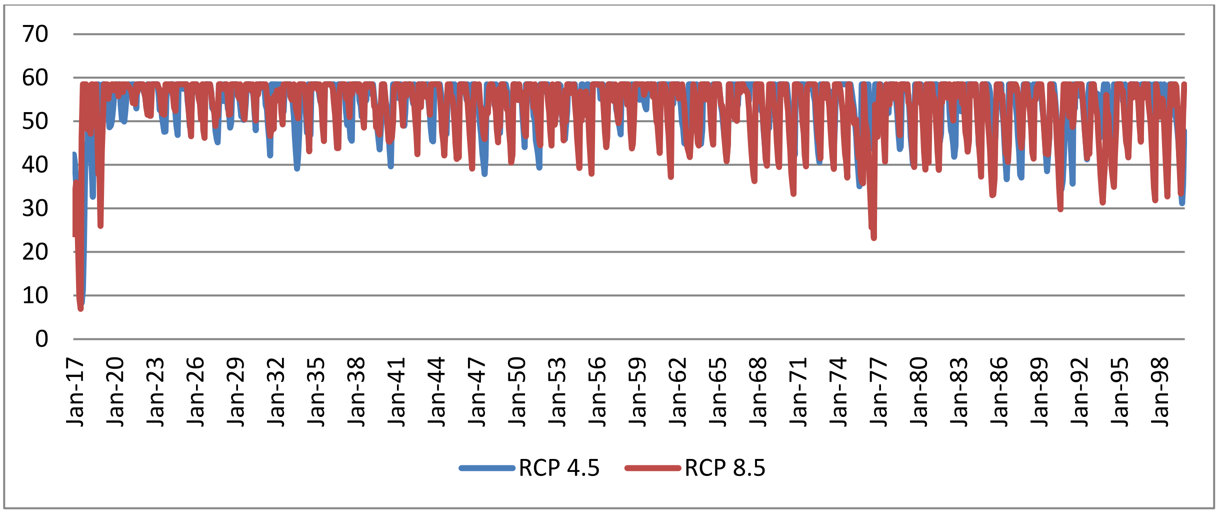

Fig 1.11. Storage Volume of Pabuçdere Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

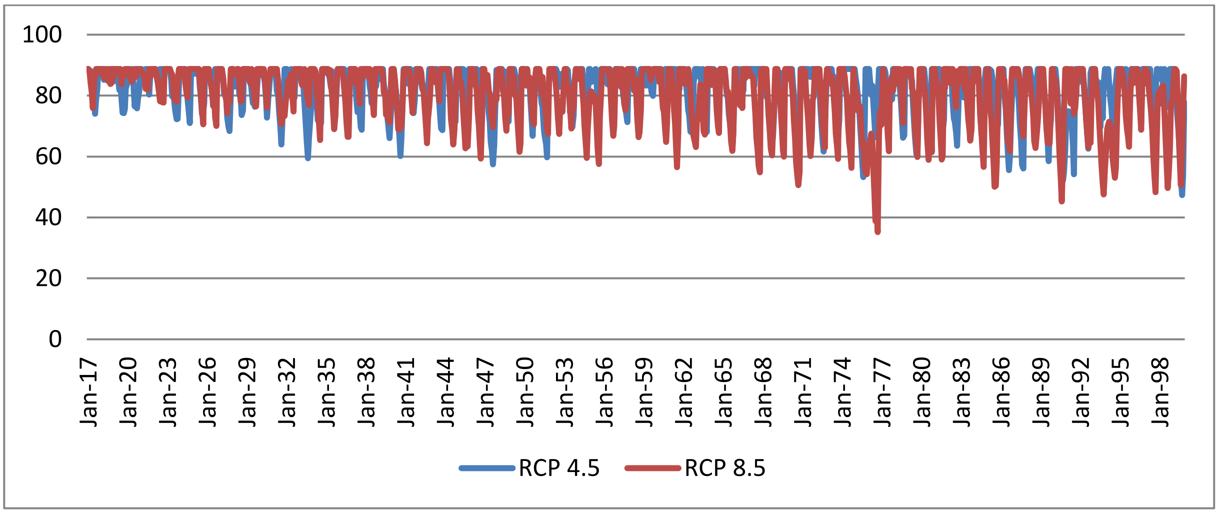

Fig 1.12. Storage Volume of Sazlıdere Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

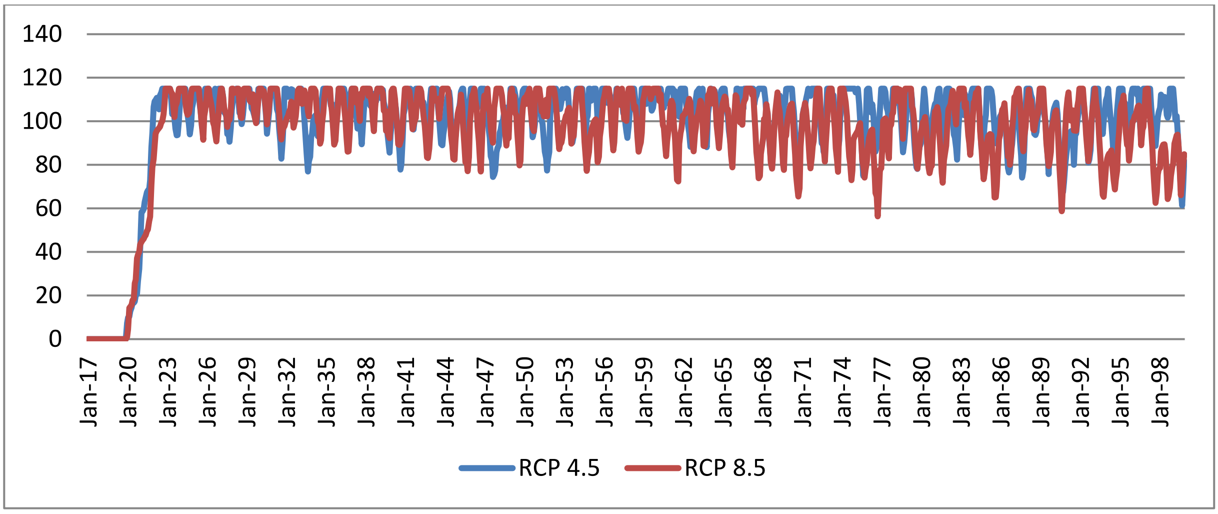

Fig 1.13. Storage Volume of Sungurlu Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

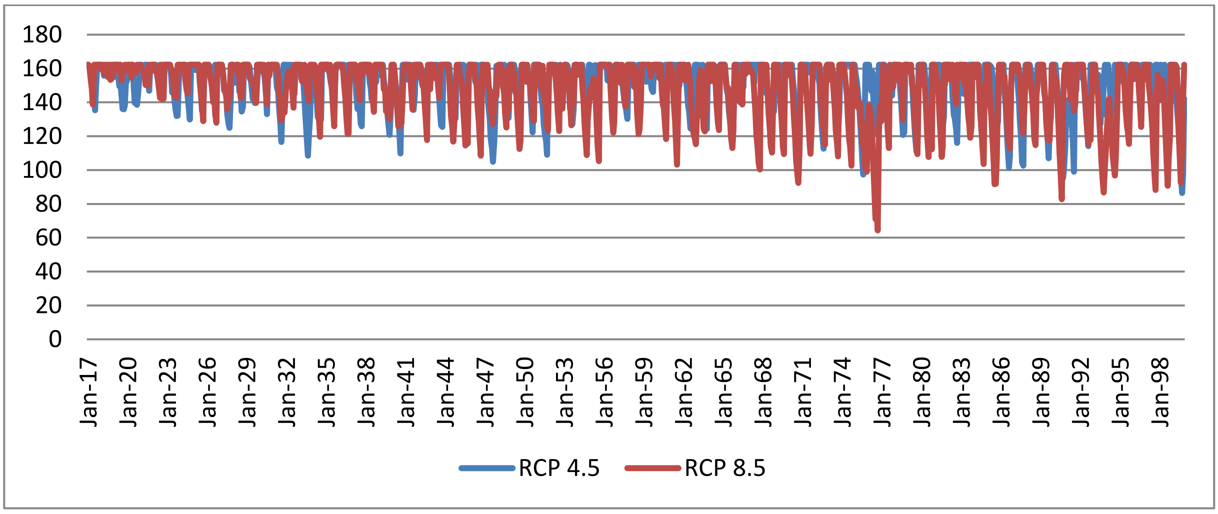

Fig 1.14. Storage Volume of Terkos Reservoir under both RCP 4.5 and RCP 8.5 scenarios (million m^3 / month).

Reservoir Storage Volumes as Melen River is the backup source vs main source with the planned infrastructural changes (Figures 2.1- 2.14)

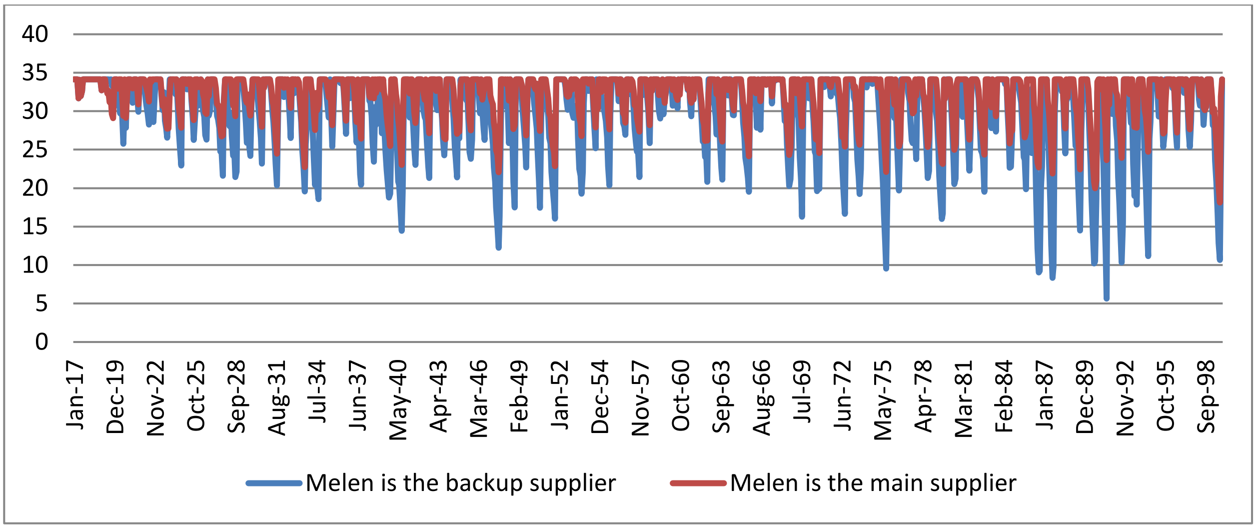

Figure 2.1. Storage Volume of Alibey Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

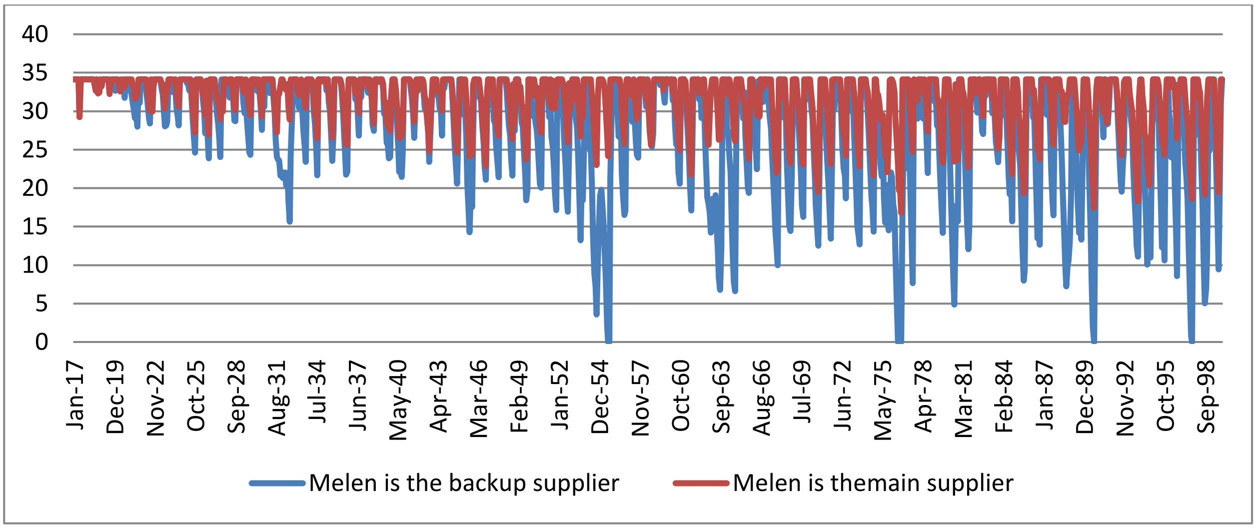

Figure 2.2. Storage Volume of Alibey Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

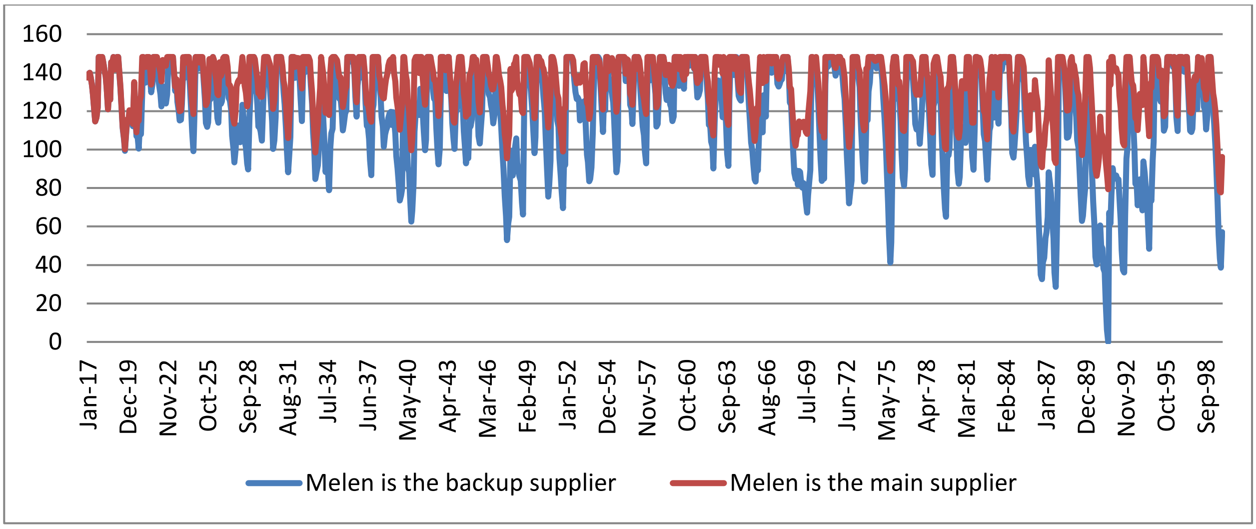

Figure 2.3. Storage Volume of Büyükçekmece Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

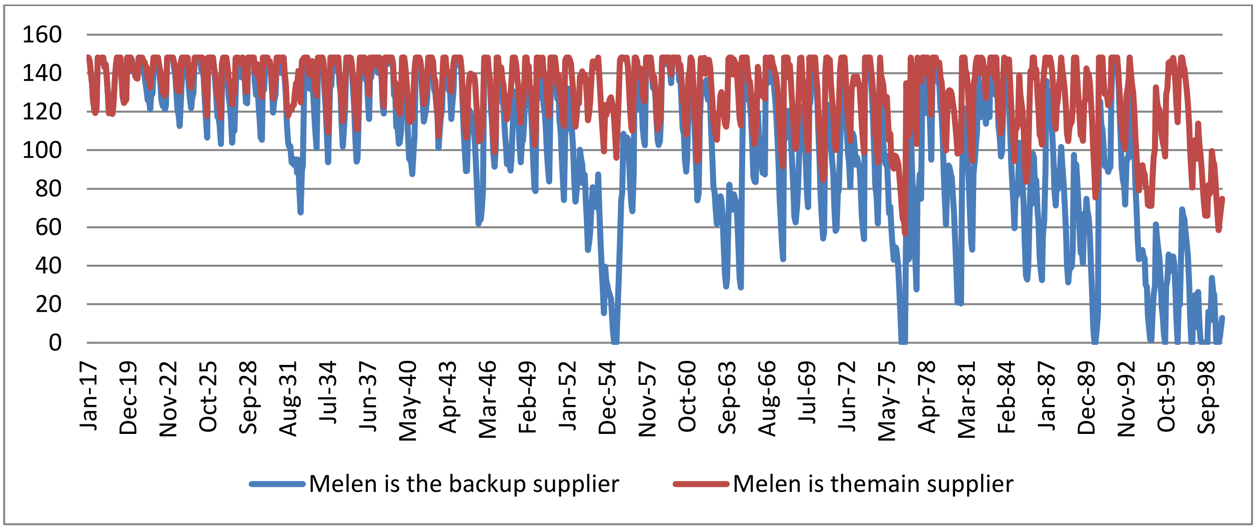

Figure 2.4. Storage Volume of Büyükçekmece Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

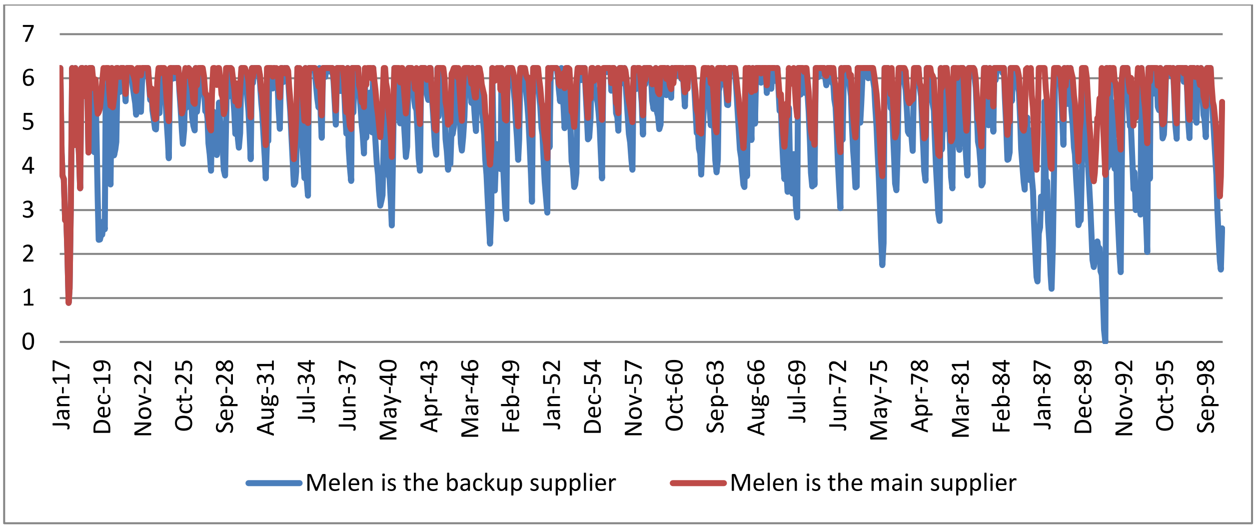

Figure 2.5. Storage Volume of Istrancalar Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

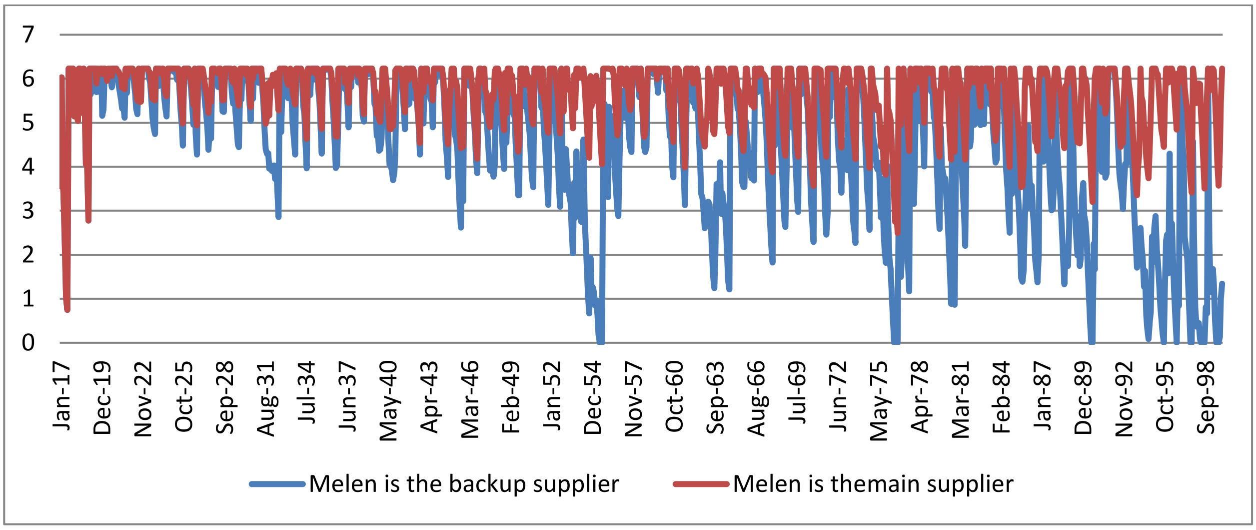

Figure 2.6. Storage Volume of Istrancalar Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

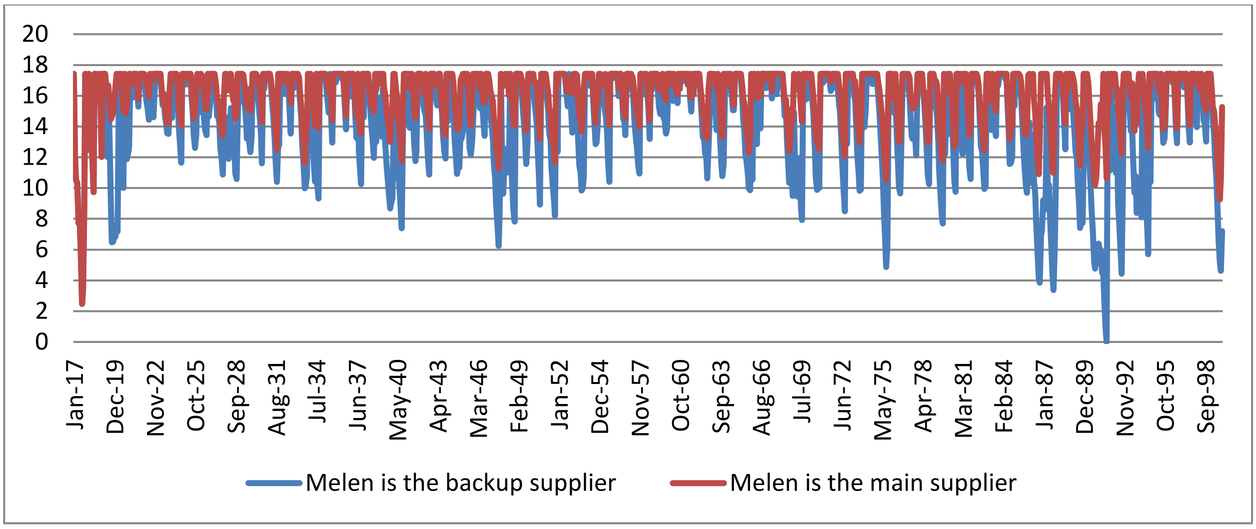

Figure 2.7. Storage Volume of Kazandere Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

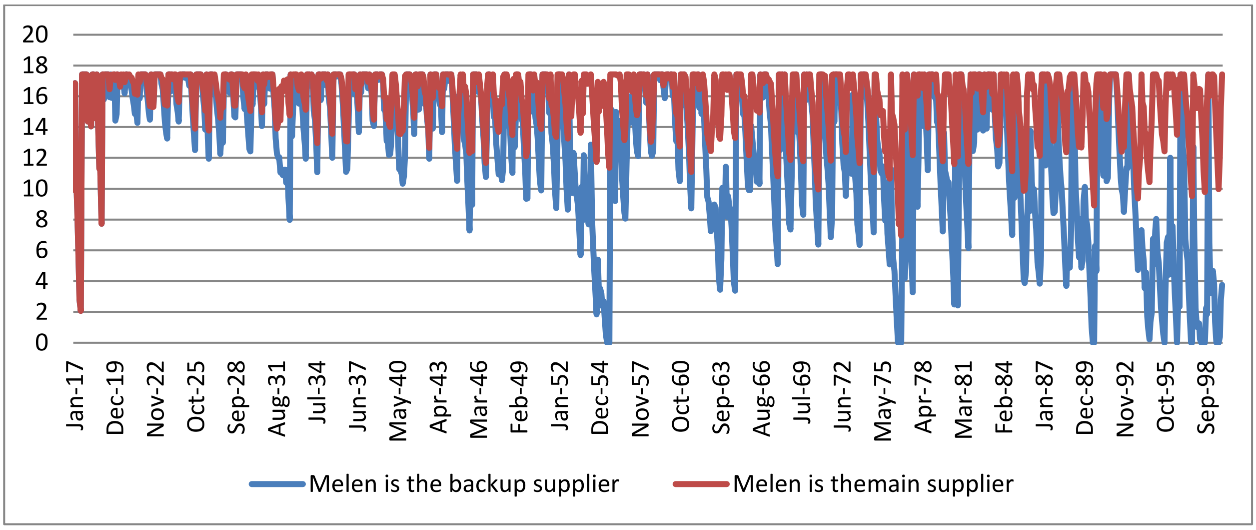

Figure 2.8. Storage Volume of Kazandere Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

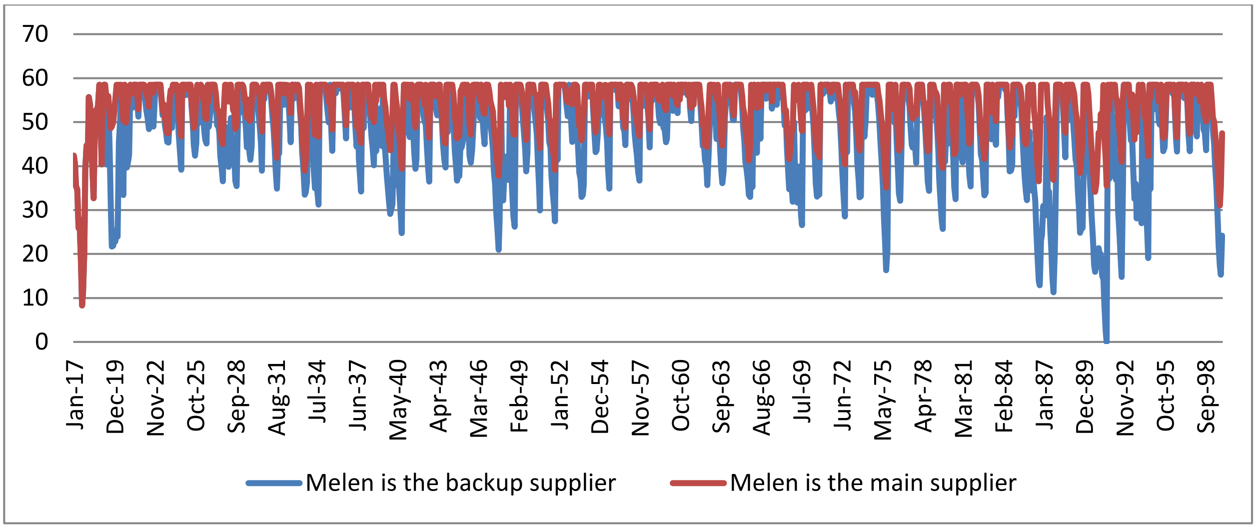

Figure 2.9. Storage Volume of Pabuçdere Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

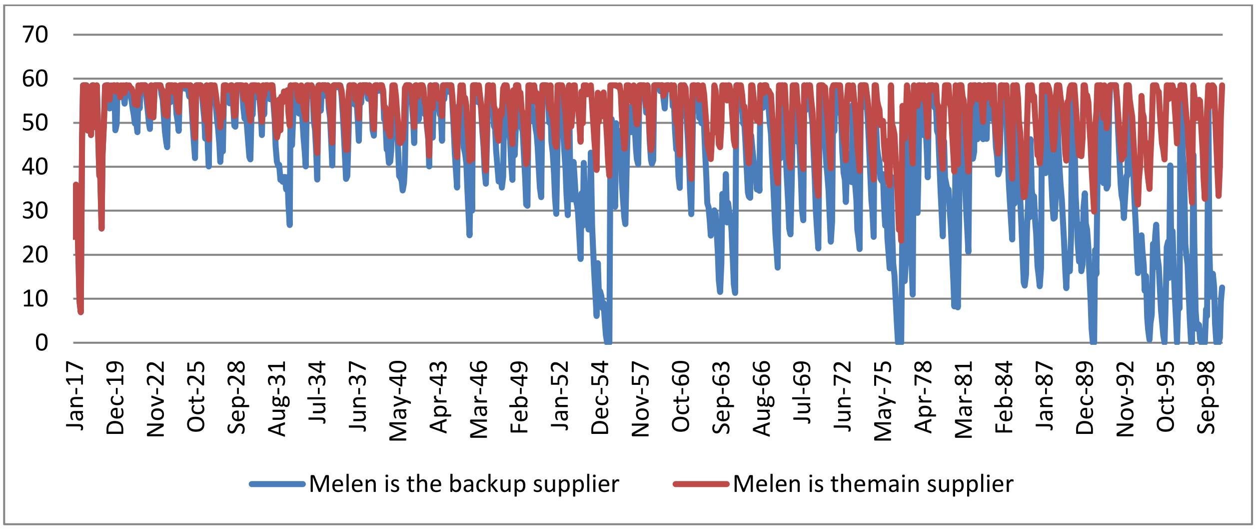

Figure 2.10. Storage Volume of Pabuçdere Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

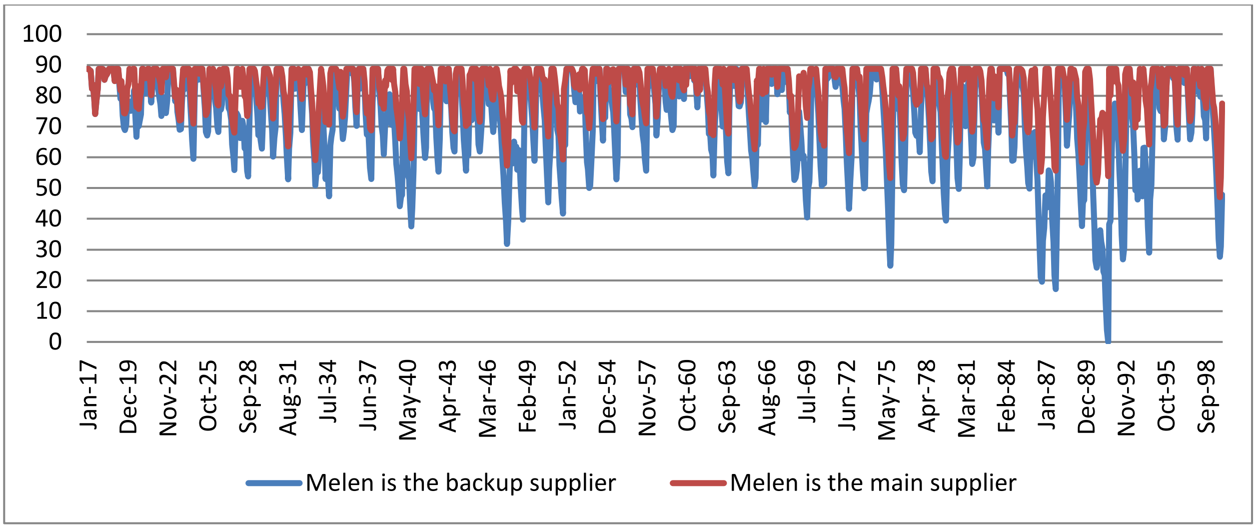

Figure 2.11. Storage Volume of Sazlıdere Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

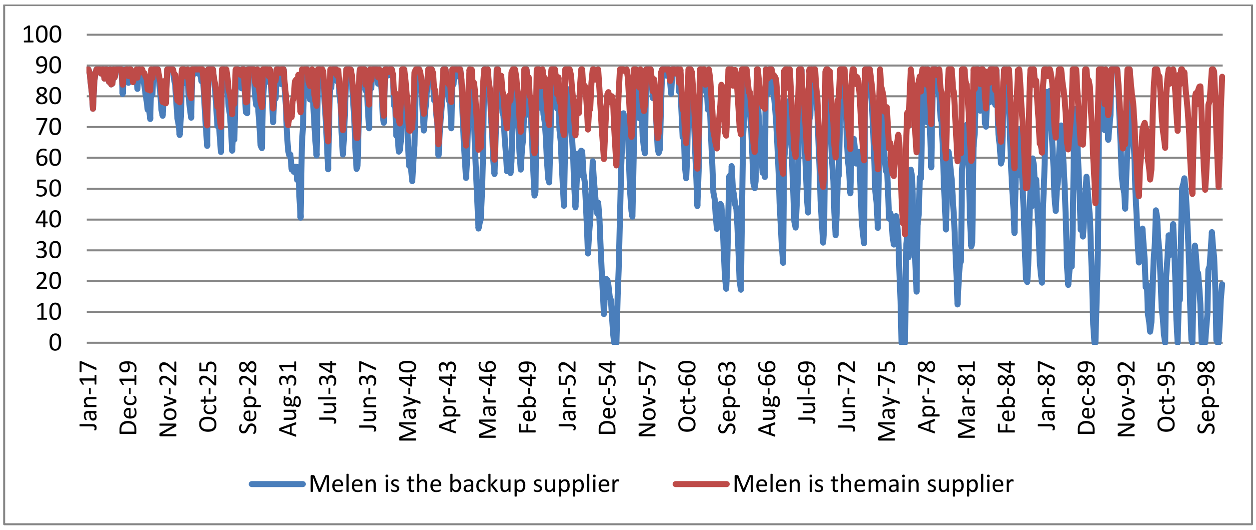

Figure 2.12. Storage Volume of Sazlıdere Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

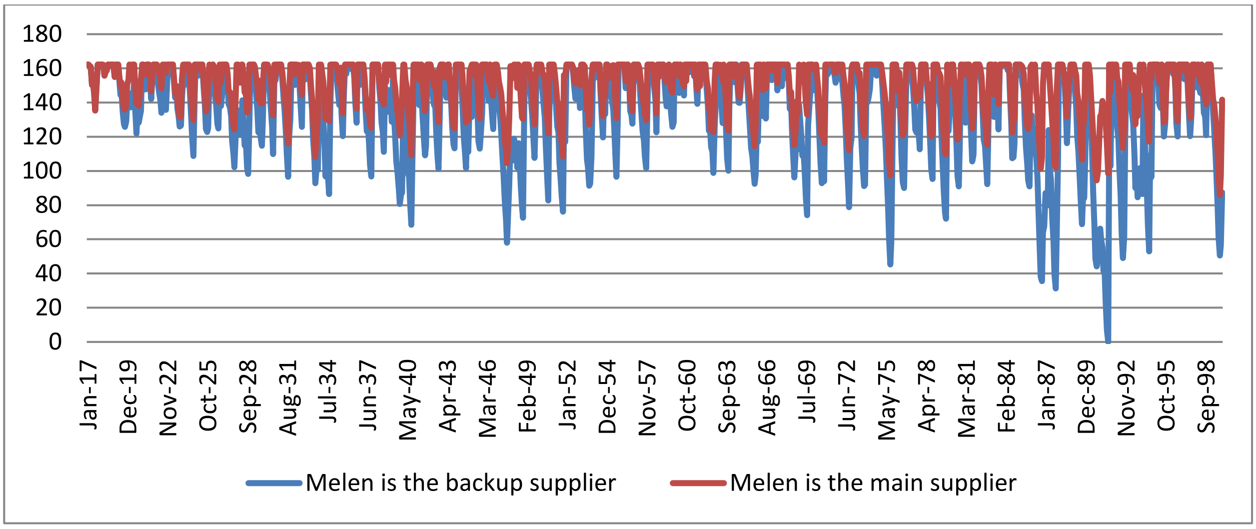

Figure 2.13. Storage Volume of Terkos Reservoir when Melen River is the backup source vs main water supply source under RCP 4.5 scenario (million m^3 / month).

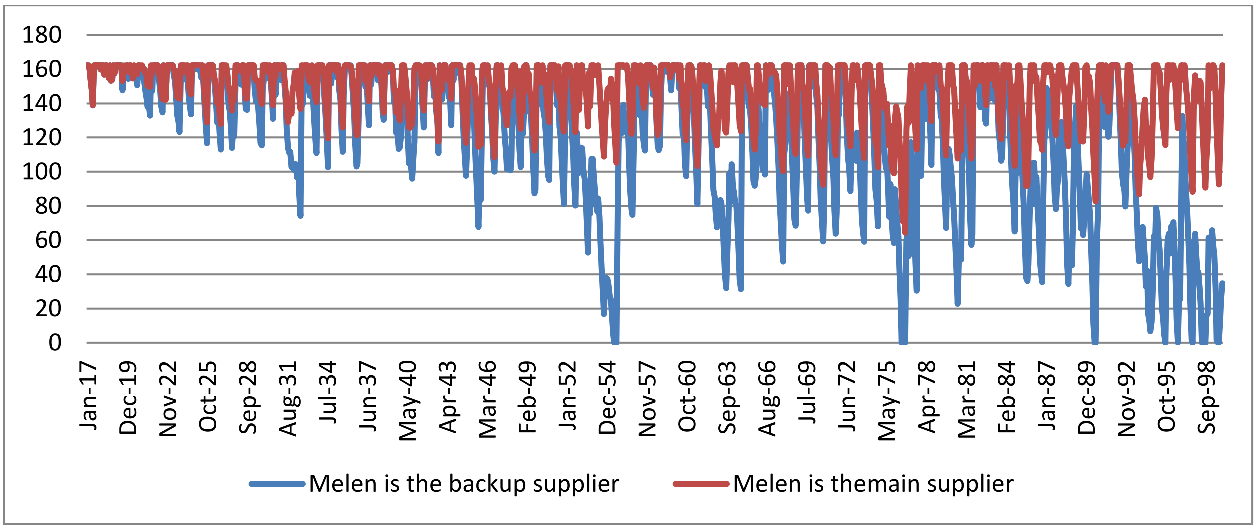

Figure 2.14. Storage Volume of Terkos Reservoir when Melen River is the backup source vs main water supply source under RCP 8.5 scenario (million m^3 / month).

APPENDIX C: UNMET WATER DEMAND OF MUNICIPALITIES WITH THE CURRENT WATER SUPPLY SOURCES

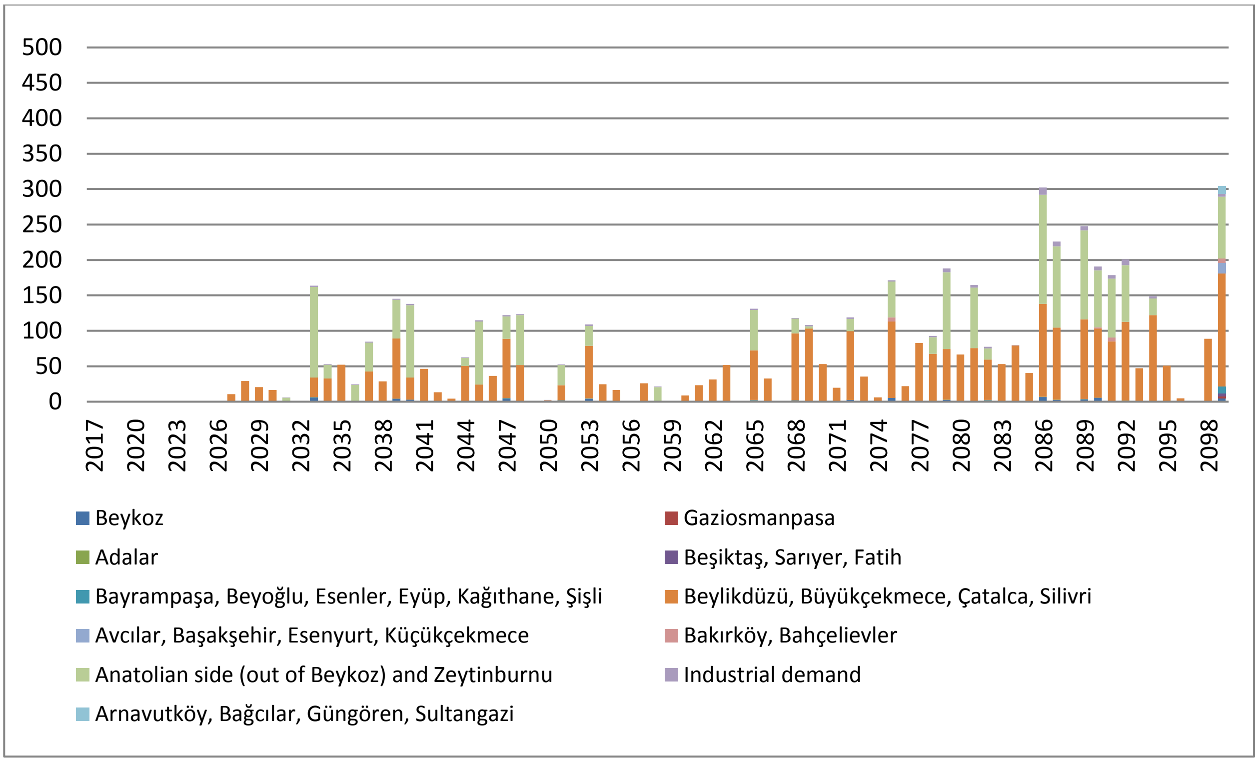

Fig 1.1. Unmet water demand with demand nodes under RCP 4.5 scenario (million m^3 / month).

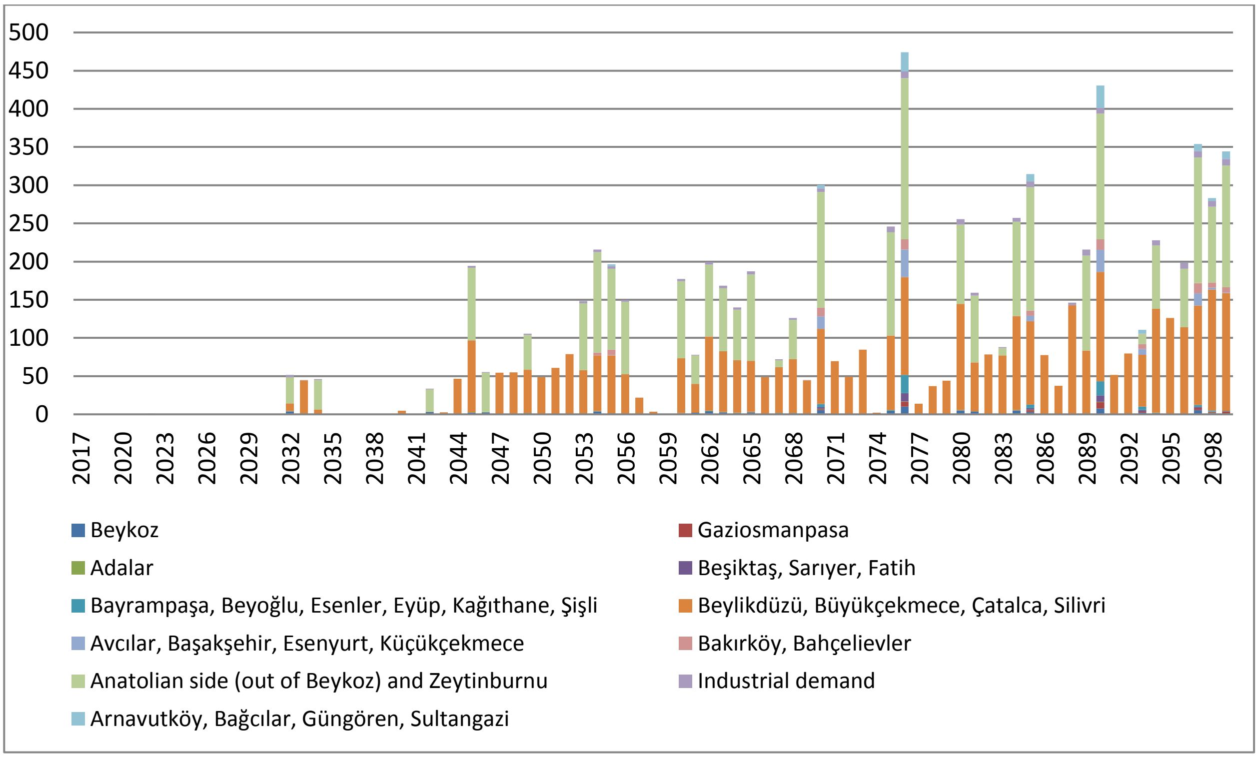

Fig 1.2. Unmet water demand with demand nodes under RCP 8.5 scenario (million m^3 / month).