Sustainability **2015**, *7*, 11050-11067; doi:10.3390/su70811050

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

A Framework for Sustainable Urban Water Management through Demand and Supply Forecasting: The Case of Istanbul

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Academic Editors: Tan Yigitcanlar and Md. Kamruzzaman

Received: 30 March 2015 / Accepted: 3 August 2015 / Published: 13 August 2015

Abstract: The metropolitan city of Istanbul is becoming overcrowded and the demand for clean water is steeply rising in the city. The use of analytical approaches has become more and more critical for forecasting the water supply and demand balance in the long run. In this research, Istanbul's water supply and demand data is collected for the period during 2006 and 2014. Then, using an autoregressive integrated moving average (ARIMA) model, the time series water supply and demand forecasting model is constructed for the period between 2015 and 2018. Three important sustainability metrics such as water loss to supply ratio, water loss to demand ratio, and water loss to residential demand ratio are also presented. The findings show that residential water demand is responsible for nearly 80% of total water use and the consumption categories including commercial, industrial, agriculture, outdoor, and others have a lower share in total water demand. The results also show that there is a considerable water loss in the water distribution system which requires significant investments on the water supply networks. Furthermore, the forecasting results indicated that pipeline projects will be critical in the near future due to expected increases in the total water demand of Istanbul. The authors suggest that sustainable management of water can be achieved by reducing the residential water use through the use of water efficient technologies in households and reduction in water supply loss through investments on distribution infrastructure.

Keywords: water supply; demand; time-series forecasting; ARIMA; urban water sustainability; Istanbul

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1. Introduction

In 1995, the former World Bank Vice-President Ismail Serageldin claimed that "*the wars of the next century will be about water*" [1]. Whether this hypothesis comes true or not, we are living in a world becoming constrained by water and the human beings are facing with serious social and economic problems related to accessibility of clean water resources. Despite occupying as little continental surface as 2%, more than 50% of the world population today lives in cities and this number is expected to reach 70% in 2050 [2]. In the future, cities will continue to play a major economic role, as well as contribute to further environmental degradation through water resource consumption, climate change and pollution [3,4]. Sufficient water supplies with a reasonable cost will continue to become one of the top agenda items for city decision-makers due to overcrowded cities and the climate change threats the water supply for most of the cities in Turkey. Opposite to common beliefs, Turkey is not a water rich country and the World Water Foundation (WWF)'s recent report on the water footprint of Turkey shows that country might be faced with serious water shortages by 2030 due to rising population, consumption, industrialization, and agricultural production [5]. In this regard, the use of forecasting models for understanding the long-term sustainability of water demand and supply becomes necessary.

In the literature, forecasting models are widely used in environmental studies to understand the level of pollution and identify the potential risks for depletion of the limited resources supplied by the ecological systems. As commonly used forecasting techniques, traditional methods such as time series, regression and an autoregressive integrated moving average (ARIMA) as well as soft computing techniques such as fuzzy logic, genetic algorithm, and artificial neural networks are being extensively used for a time-series demand forecasting [6–8]. Especially for urban water demand modeling, the ARIMA model has performed more accurately than time-series and multiple regression methods when forecasting demand based on climate variables [9]. ARIMA models are extensively used in time-series forecasting, especially in water and energy forecasting [10,11]. For instance, Praskievicz and Chang [12] used daily and monthly data from 2002 to 2007 to conduct a statistical analysis of seasonal water consumption in Seoul, South Korea. Significant improvement of the modeling of seasonal water use was achieved by developing the ARIMA models, which account for autocorrelation in the time series and explain up to 66% of the variance in water use. Ediger *et al.* [13] developed forecasting model for production of fossil fuel sources and compared the performance of two forecasting techniques: regression analysis and ARIMA. In other study, Ediger and Akar [14] used the ARIMA and seasonal ARIMA (SARIMA) methods to estimate the primary energy demand in Turkey. The authors concluded that the ARIMA forecasting of the total primary energy demand appears to be more reliable than the summation of the individual forecasts. Unakıtan and Türkekul [15] also assessed annual time series data for energy consumption using the ARIMA model. Erdoğdu [16] studied on the future growth of gas demand in Turkey and developed a forecasting model using an ARIMA framework. However, time-series ARIMA forecasting considers only the past values without showing determinants explicitly. In addition, this method is found to be suitable when climatic and socio-economic data are not available. Hence, the accuracy of ARIMA forecast may be limited due to the presence of high correlations among determinants and nonlinear relationships between water demand and its determinants [17].

Due to the aforementioned limitations of linear time series forecasting techniques, non-linear models are also used in demand forecasting in environmental studies. For instance, in predictive models for forecasting hourly urban water demand, artificial neural networks, projection pursuit regression, multivariate adaptive regression splines, compare a series of predictive models for forecasting water demand. Consequently, the results which obtained are nearly reliable in comparison by common forecasting models [18]. In other work, 39 multiple linear regression models, 9 time series models, and 39 artificial neural network models were developed to forecast the water demand and their relative performance was also compared. The neural network showed a better performance for prediction of daily summer water demand compared to multiple linear regression and time series analysis [19]. In other research, the performance of regression, time series, and neural network models are analyzed for short-term peak water demand forecasting. The significance of climatic variables such as rainfall and maximum temperature on water demand management is also investigated. The artificial neural network models consistently outperformed the regression and time-series models developed in this study [20]. To forecast urban annual water demand, Huang *et al.* [17] proposed a combination of models including wavelet transform (WT) and kernel partial least squares-autoregressive moving average (KPLS-ARMA). The combined models are applied to understanding the nonstationarity and forecasting the annual water demand of Dalian City, China. The results showed that the performance of combined WT, KPLS and ARMA outperforms other forecasting models. In other work, artificial neural network and ARIMA models are used for energy consumption forecasting. Four main factors were considered, including population, gross domestic product, exports, and total visitor arrivals. The results indicates neural network models release acceptable forecast accuracy when single predictor is considered but the forecast accuracy of artificial neural network does not improve extremely as the number of predictors increase [21].

In this research, the water supply and demand forecasting model is built based on the ARIMA method. Although several techniques including neural networks and multivariate regression analysis are used in the literature for time-series forecasting, with a given limited water demand and supply data for the period between 2006 and 2014, the authors used ARIMA in their analysis. As discussed initially, ARIMA forecasting is extensively used in urban water demand forecasting. However, there is still an important knowledge gap on the use of forecasting models for urban water supply and demand, simultaneously. This research used ARIMA for both demand and supply forecast covering the period between 2015 and 2018 and tried to estimate the long-term viability of urban water management practices in Istanbul looking at the gap between demand and supply. To address these research objectives, first, data including water demand categories and supply sources are collected. Then, the ARIMA forecasting model is developed based on a time-series real data obtained from the Istanbul Metropolitan Municipality. In this regard, this paper has the following research objectives:

(1) analyze the water demand of Istanbul based on five consumption categories such as residential, commercial, industrial, agriculture, park and gardens and others,

(2) analyze the water supplied to Istanbul based on different supply sources such as pipeline, dams and underground,
(3) present the share of the water demand categories, supply sources, and water losses between period of 2006 and 2014,
(4) evaluate the sustainability of water supply polices for until 2018 by looking at the gap between water supply and demand,
(5) highlight policy areas need urgent attention in order to sustain the current urban water management practices and provide a vital guidance and analytical framework for city water planners for future.

The rest of the paper is organized as follows. First, the data collection process is described and the ARIMA forecasting model is briefly explained in a step-by-step manner. Next, the findings are presented for water demand categories and supply sources as well as forecasting results for the period covering 2015 and 2018. Finally, the findings are summarized and the future work is pointed out.

2. Data Collection

This work is based on a real dataset obtained from the Istanbul Water Supply and Sewage Administration (ISKI) which is governed by the Municipality of Metropolitan Istanbul [22]. Since the data for demand and supply was available starting from the 2006, the initial dataset covered the period between 2006 and 2014. The dataset is first divided into two main categories: water demand and water supply. Each category is then divided into several sub-categories based on water demand type and supply source. First, the water demand data account for the total annual amount of water used by the following consumption categories (see Table 1):

Table 1. Water demand categories and their descriptions.

Demand Categories (*)	Description of Each Category
Residential	The amount of annual water used by households (invoiced water expense).
Commercial	The amount of annual water used by commercial facilities such as hospitals, schools, banks, hotels, offices, *etc.*
Industrial	The amount of annual water used by industrial facilities such as power plants, textile factories, cement plants, *etc.*
Outdoor	The amount of annual water used outdoor activities such as garden irrigation and/or parks.
Agricultural	The amount of annual water used for agricultural irrigation in rural areas.
All other unspecified	All other unspecified annual water use categories.

(*) The amount of demand categories is presented in terms of meter cubes (m^3).

Second, the water supply represents the total annual amount of water supplied to city which includes the following supply sources (see Table 2):

Table 2. Water supply sources and their descriptions.

Supply Sources (*)	**Description of Each Supply Source**
Pipeline and Regulator	The amount of annual water supplied by the Yesilçay and Melen regulators.
Dams	The total annual water supplied by dams such as Alibeyköy, Büyükçekmece, Darlık, Istrancalar, Kazandere, Ömerli, Pabuçdere, Elmalı, Sazlıdere and Terkos. This is the largest water supply source for the city.
Underground	The amount of annual water withdrawal from the underground reservoirs.

(*) The amount of water supply sources is presented in terms of meter cubes (m^3).

3. Methods

In this research, the ARIMA is utilized as reliable technique to forecast the demand and supply of water in Istanbul and consequently estimate the sustainability of demand and supply in the long run. The ARIMA is a commonly used time-series forecasting methodology in environmental studies [23,24]. The general model introduced by Box and Jenkins includes autoregressive as well as moving average parameters, and implicitly contains differencing in the formulation of the model [25]. In general, the three sorts of parameters in the model are known as: the autoregressive parameters (p), the number of differencing passes (d), and moving average parameters (q). In general, the ARIMA method consists of five main iterative procedures which are listed as follows:

(1) Stationarity checking and differencing,
(2) Model identification,
(3) Parameter estimation,
(4) Diagnostic checking, and
(5) Forecasting

ARIMA has been emanated from the autoregressive model (AR) and the moving average model (MA) and the integration of the AR and MA result in the ARIMA model, which was introduced in 1926, 1937, and 1938, respectively [13]. Although this technique has been extensively used for a time series forecasting, ARIMA model requires instruction in statistical analysis as well as appropriate knowledge of the field of application. Furthermore, the accessibility of an easy to use but adjustable specialized computer program is essential [26]. Therefore, one of the software which is used for developing ARIMA forecasting model is the R statistical software package.

In the ARIMA forecasting, the first step starts with creating statistical control charts to illustrate the trend of data before running the ARIMA. Hence, an initial step in analyzing time series data is running I-MR charts which show the control limits on the chart based on the mean of the moving range (the absolute difference between each consecutive pair of points). If there is no independence between the points, we have the so-called condition autocorrelation which there is little difference in each consecutive pair of points. Moreover, we used first autocorrelation (ACF) and partial autocorrelation (PACF) to understand the correlations between data at different points in time lagged by one or more periods. In the next step of constructing the ARIMA model, the data needs to be stationary. In other words, there should be no trend in the process either upwards or downwards [13,14]. To achieve this condition, certain stability in the process mean needs to be achieved which the differencing data. Next, we run first autocorrelation (ACF) and partial autocorrelation (PACF) to understand the correlations of differencing. The autoregressive part of the ARIMA model predicts the value at time *t* by considering previous values in the series at time *t-1*, *t-2*, *etc.* The moving average (MA) uses past residual values which show the differences between the actual value and the predicted value based on the model at time *t*, so that the ARIMA model allocated (p ,d, q), which are named as the number of different passes, moving average parameters, and autoregressive parameters, respectively [21,23]. After checking the data and identifying the aforementioned parameters, we run the R-software to forecast a set of factors: (1) water demand of city; (2) water supply; and (3) water supply without the pipeline projects for the period between 2014 and 2018. The visual check of the accuracy of forecasts is used for determining whether or not the current exponential smoothing model fits the data. Hence, the precision of the forecasting are evaluated by different methods. In this paper, we simply used the Mean Absolute Percentage Error (MAPE) for testing the ARIMA model performance. MAPE represents the accuracy as a percentage and value is simply calculated using the following formulation [27]:

$$\frac{1}{n}\sum_{t=1}^{n}\left|\frac{At-Ft}{At}\right| \quad (1)$$

where A_t is the actual value, F_t is the forecast value and n is the number of data points.

4. Results and Discussion

In this paper, the results are presented in two sub-sections. In the Section 4.1, water demand and supply characteristics of Istanbul are described in details. In the Section 4.2, a time-series ARIMA forecasting results are discussed for both demand and supply categories.

4.1. Water Demand and Supply Analysis

4.1.1. Total Water Demand and Percentage Contribution of Demand Categories

In this section, the total water demand between 2006 and 2014 is analyzed. The results show that residential water consumption is higher than all other consumption categories. This consumption category is followed by commercial activities whereas industrial, parks and gardens, agriculture categories and others are found have a lower contribution to total water demand. Among these categories, only residential consumption has shown a steady increase between 2006 and 2014, and the remaining categories have an increasing and decreasing trend. Between 2006 and 2014, the net water demand shows the highest amount in 2013 and 2014 while the minimum amount of water demand is observed in 2008. The total residential water use has a little fluctuation between 2006 and 2010 ranging between 3.86×10^8 m^3 and 3.96×10^8 m^3. Furthermore, the total water demand related to commercial activities is found to be the largest in 2008 and 2010, and after 2010, the total commercial water use has showed a declining trend. Overall, the total amount of water consumed in Istanbul reached to peak in 2013 and 2014 at 5.84×10^8 m^3 and 5.82×10^8 m^3, respectively.

In addition, the percentage contribution of all water demand categories for the period between 2006 and 2014 is analyzed. The results indicate that residential water consumption is responsible for approximately 80% of total water demand with an exception of 2008. For this year, the share of residential water use is found to be responsible for nearly 70% of total water use, and 15% of total water demand is attributed to the commercial activities. On the other hand, the percentage share of industrial and agriculture activities are less than 1% of total water demand in 2013 and 2014. This finding clearly showed that the water demand of Istanbul is largely dominated by household use and industrial and agriculture activities have a lower impact on the net water demand of the city. Although Marmara region has the largest industrial facilities in Turkey, the industrial sectors are not water intensive as compared to residential consumption. When compared to other cities, Istanbul is found have a high unit price of water which makes Istanbul unaffordable city for water intensive industrial production. Therefore, it is important to note that reducing the residential water use can be the most critical policy strategy to minimize the net water footprint of the city in the future.

4.1.2. Total Water Supply and Percentage Contribution of Supply Sources

Sakarya and Melen regulators (pipeline projects), dams, and underground represent the main water supply sources. The results showed that the largest amount of water supplied to city is obtained from the dams. Starting from 2011, the Sakarya and Melen regulators have become the second important water supply source after the dams. The amounts of water obtained from these two regulators have steadily increased between 2011 and 2014. In addition, starting from 2010, there is an increasing trend for the water supplied to city for both dams and regulators. After dams and Sakarya and Melen regulators, Pabuçdere, Kazandere and Istrancadere are the most important water supply sources for Istanbul. Based on the results, in 2014, the highest amount of water is supplied to city with a value of 9.24×10^8 m^3 while the least amount of water is supplied in 2006 with a value of 7.32×10^8 m^3. This result indicates that there is approximately 25% increase in the net amount of water supplied to city between 2006 and 2014.

In addition, the percentage share of each water supply source for the period during 2006 and 2014 is presented. The results clearly show that dams are the main water supply source of the city. For instance, in 2006, more than 95% of the water is supplied by the dams. The share of water obtained from the underground reservoirs is always less than 5% of total water supply. Starting from 2011, the share of water supplied by pipeline projects has started to increase and almost 25% of total water is supplied by the Sakarya and Melen regulators. Between 2010 and 2014, the percentage share of water supplied by dams has steadily decreased and there has been an increasing share of water obtained from the pipeline systems. The findings of city water supply indicate that water supply of Istanbul is largely dominated by dams and regulators. These facts might bring several important risks in the long run. For instance, the water level in dams in Istanbul is able to show significant fluctuations over the last decade that can create a risky condition for city water supply. In addition, the water is supplied by regulators are obtained from the neighbor city Sakarya and a conflict related to water trading between these cities may put a risk for meeting the total water demand in the future.

4.1.3. Total Water Coming and Supplied to City *versus* Water Demand

Figure 1a presents the net amount of water coming to city, supplied to city, and water demand between 2006 and 2014. This analysis will be important to understand the gap between incoming water *versus* supplied water and water demand. The results show that in 2006 and 2010, the difference between incoming water and supplied water was minimum at 6.45 × 10^7 m^3 and 7.35 × 10^7 m^3, respectively. In other words, for 2006 and 2010, the amount of water coming to city just met with the supply requirement. Starting from 2010, the gap between incoming and supplied water has steadily increased until 2014. For this year, the difference between incoming water to city and water supplied to city is found to the largest compared to other years. When compared to 2014, the net water surplus (difference between incoming water and water supplied to city) is found to be 9 times more than the surplus in 2006. The construction of Sakarya and Melen regulators has played a significant role in this result. Especially, starting from 2011, there has been a growing water supply to city from these regulators. Overall, the amounts of incoming water, supplied water, and demand have shown a steadily increasing trend after 2009.

In addition, the trend for total water supply and demand and the gap between them are also investigated. In this research, the difference between the net water supplied to city and water demand is called a water loss. The findings show that the difference between demand and supply was lower in 2008 compared to other years. Starting from 2009, the supply and demand gap, in order words water loss, has started to increase and reached to its maximum value in 2014. Compared to 2006 levels, the total water loss is found to be around 1.5 times more in 2014. In 2013 and 2014, the net water loss is calculated as 3.26 × 10^8 m^3 and 3.42 × 10^8 m^3, respectively. On the other hand, the difference between supply and demand is found as 2.34 × 10^8 m^3 in 2006.

Figure 1b also presents the water demand, supply and incoming water to city without Sakarya and Melen regulators. This analysis is important to understand the trend without these pipeline projects and see whether city-planners are able to meet supply and demand requirements without these investments. The findings showed that the difference between incoming water and water supplied to city are lower in 2009 and 2010. After 2009, the amount of water supplied to city has grown continuously until 2014. Especially, the incoming water has reached its peak in 2014 and the gap between incoming water and supplied water is found to be the largest in 2014. When compared to Figure 1a, the total incoming water to city is lower; however incoming water amount is still able to meet the supply requirements. As presented in Figure 1a, in 2014, the total incoming water is 1.6 times more than the water supplied to city whereas this ratio is found as 1.2 times when there is no Sakarya and Melen pipeline projects for the city (see Figure 1b). However, to see the long-term sustainability of the incoming water, the ARIMA forecasting results are presented in the Section 4.2.

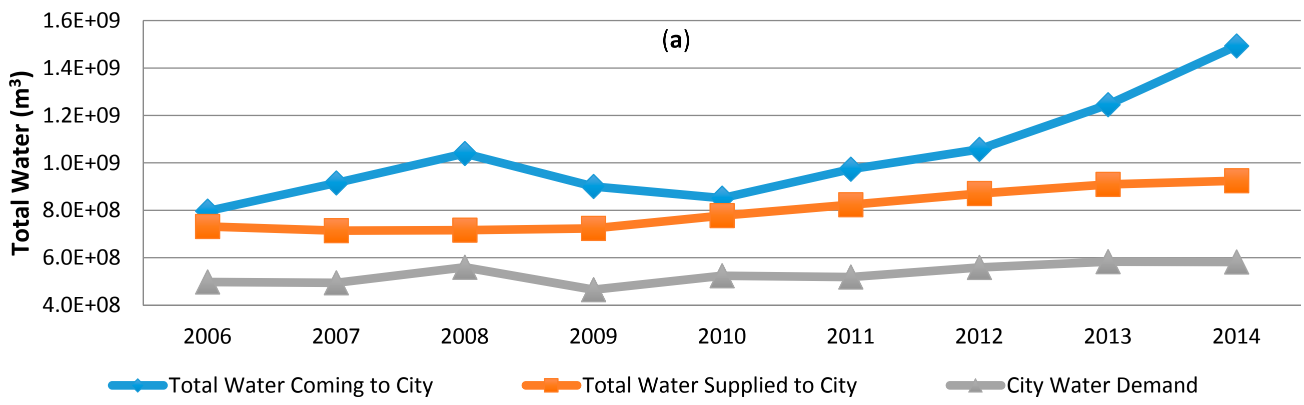


Figure 1. *Cont.*

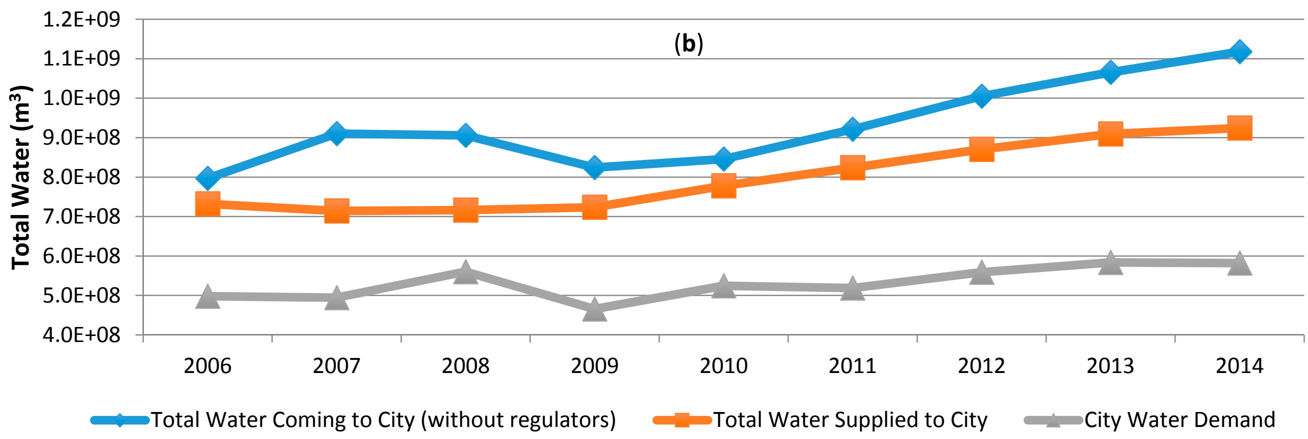


Figure 1. Water supply and demand between 2006 and 2014 (m^3). (**a**) With Sakarya and Melen regulators; (**b**) Without Sakarya and Melen regulators.

4.1.4. The Net Water Loss Analysis

In this section, the net water loss of water supply is analyzed considering the gap between the amount of demand and water supplied to city between 2006 and 2014. In addition, three important metrics such as water loss to demand ratio, water loss to supply ratio, and water loss to residential demand ratio are presented.

First, Figure 2a presents the trend of water supply, demand and loss between 2006 and 2014. This analysis revealed important insights regarding the time-series change of water supply and demand as well as water loss. The results indicate that the total water loss has a minimum value in 2008 at 1.56×10^8 m^3. After 2008, the total water loss has shown a growing trend until 2014. Similar to water loss, the net amount of water supplied to city also has an increasing trend after 2010. Interestingly, in 2014, the gap between demand and supply is found to be the largest with a comparison with other years. Figure 2b also shows the two important ratios such as *water loss to supply ratio* and *water loss to demand ratio*. First, the *water loss to supply ratio* is calculated by dividing the net water loss to net water supplied to city. The results showed that in 2013 and 2014, almost 35% of total supplied water is lost in the system. The water loss to supply ratio is found to be minimum in 2006, 2007 and 2008; however starting from 2010, there has been an increasing trend in the loss ratios.

In addition to water loss to supply ratio, the *water loss to demand ratio* is analyzed between 2006 and 2014. This ratio accounts for the net water loss against total water demand for the city. This ratio is found to have a minimum value in 2006, 2007, and 2008. On the other hand, after 2010, the water loss to supply ratio is found to be nearly 60% of total water demand of city. Similar to water loss to supply ratio, the highest value is observed in 2014 (see Figure 2b). Finally, Figure 2c depicts the *water loss to residential demand* ratio which is calculated by dividing the net water loss into the net residential water demand in city during 2006 and 2014. The results showed that this ratio was too high for some years. For instance, in 2014, the total water loss accounts for approximately 75% of total residential consumption in Istanbul. In other words, the city wasted 75% of household water use in the supply network. The value of this indicator is found to be the lowest in 2008 and stable between 2011 and 2014 accounting for over 70% of household water demand (see Figure 2c).

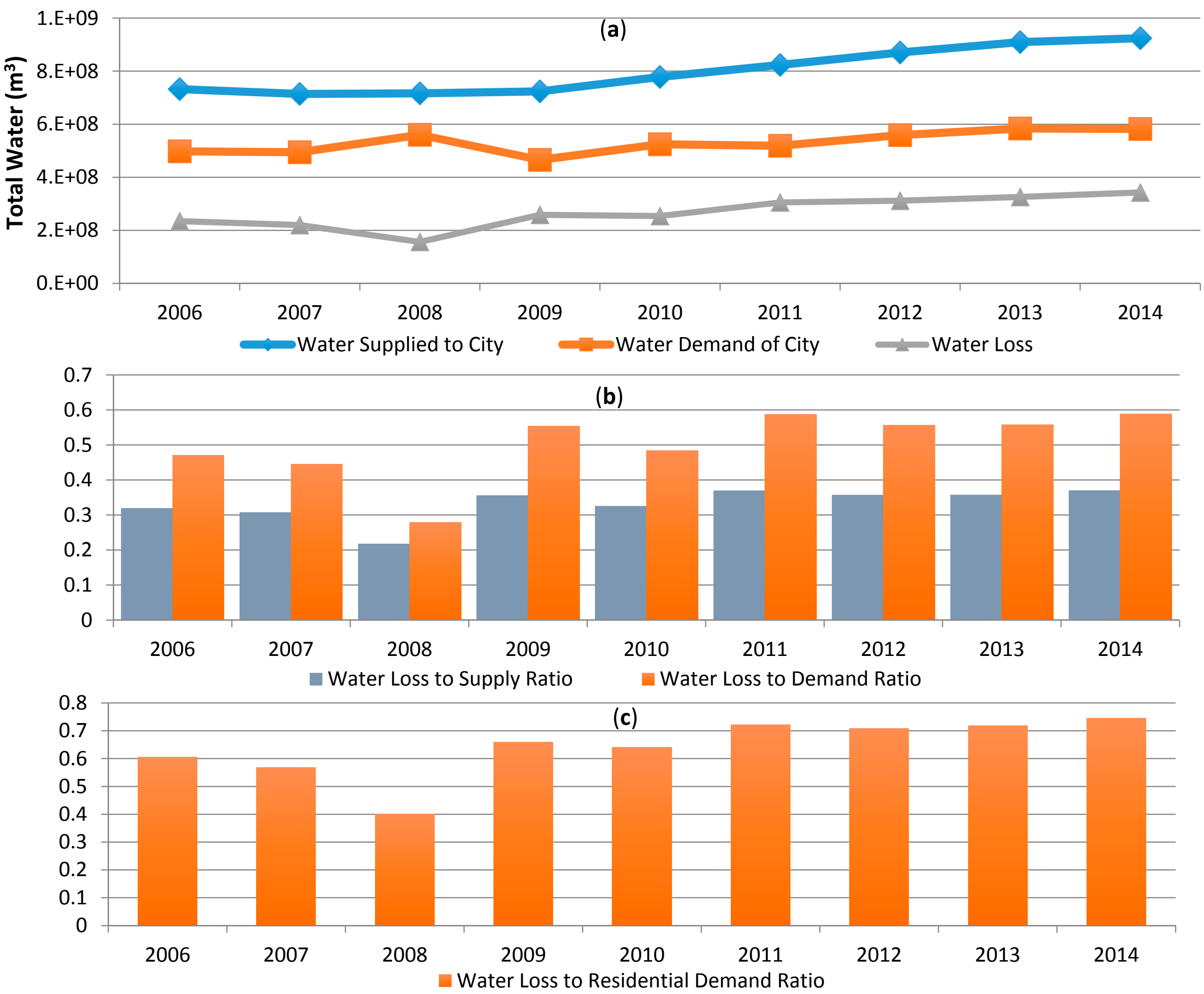


Figure 2. Water supply, demand and loss characteristics between 2006 and 2014. (**a**) Water supply, demand and loss (m^3); (**b**) Water loss to supply ratio and water loss to demand ratio; (**c**) Water loss to residential demand ratio.

4.2. ARIMA Demand and Supply Forecasting Results

After analyzing the water demand categories, supply sources and water loss amounts, it is important analyze the future of water demand and supply and the gap between these parameters in the long run. Therefore, the authors developed the ARIMA based time series forecasting model covering the period between 2015 and 2018. First, Figure 3a presents the testing data for ARIMA fit *versus* actual data between 2007 and 2014. The results showed that ARIMA model outputs and actual data have a good fit for the testing period. To understand the error between ARIMA outputs and actual data, the mean absolute percentage error (MAPE) is used as a statistical error check parameter. The MAPE results are presented in Table 3 for three estimates: demand, supply, and supply without pipeline projects. Based on the study findings, MAPE is calculated as 6.30 for demand forecast.

Table 3. MAPE values of demand and supply forecasts.

	Demand	Supply	Supply Without Pipeline Projects
MAPE	6.30	2.57	5.82

After testing the ARIMA model, the forecasting results are presented in Figure 3b. The forecasting results are illustrated for three estimates: upper limit, normal forecast and upper limit. This illustration helped us to reflect inherent uncertainties for forecasting outcomes. According to results, in 2018, the total water demand of city reached 7.72×10^8 m^3 for the upper limit forecast, 5.82×10^8 m^3 for the normal forecast, and 3.91×10^8 m^3 for the lower limit forecast. For the upper limit demand forecast, the net water consumption is expected to increase 1.32 times when compared to 2014 levels. For normal forecast value, this value is found to be similar to the water demand in 2014. Between 2015 and 2018, the upper limit forecast of water demand is ranged between 6.77×10^8 m^3 and 7.72×10^8 m^3.

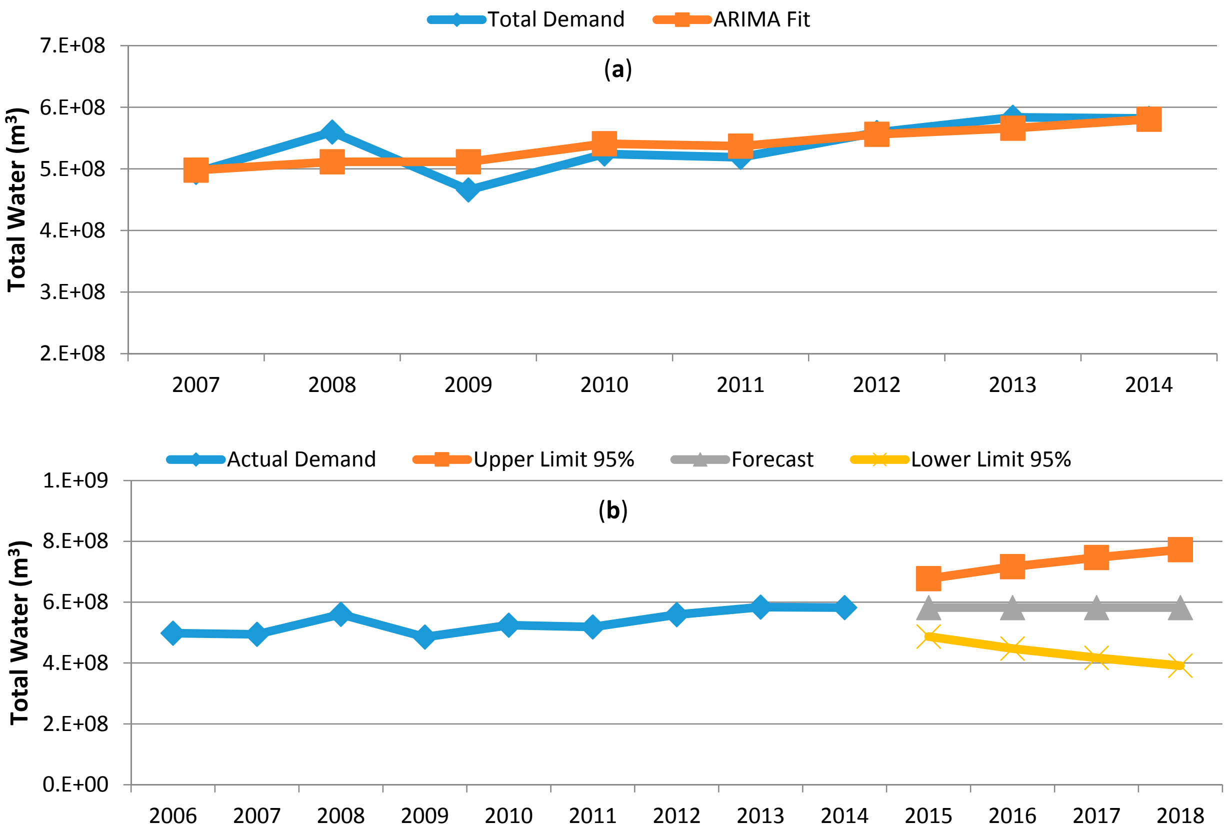


Figure 3. ARIMA forecasting results for water demand (m^3). (**a**) Actual demand *versus* ARIMA fit; (**b**) Demand forecasting data for upper, normal and lower limits.

In addition to water demand forecasting, the water supply forecasting results are also presented in Figure 4. Similar to demand forecasting, first, the ARIMA fit *versus* actual supply data between 2007 and 2014 is illustrated. The findings showed that the ARIMA forecast and real data have a good fit and little fluctuations are observed between actual data and ARIMA outputs. To estimate the error between ARIMA fits and actual data, MAPE is utilized. According to the findings, MAPE is calculated as 2.57. Hence, it is observed that water supply forecast has a better performance than the water demand forecast for testing data (see Table 3).

After testing the ARIMA model for supply data, the forecasting results are also illustrated in Figure 4b. Similar to water demand forecast, the forecasting results are visualized for three estimates such as upper limit, normal forecast, and upper limit. Based on the results, for the year 2018, the total water supplied to Istanbul is expected to reach to 1.11 × 10^9 m^3 for upper limit forecast, 1.02 × 10^9 m^3 for normal forecast, and 9.25 × 10^8 m^3 for lower limit forecast. For the upper limit supply forecast, the net water supply is expected to increase 1.21 times in comparison with the net supply in 2014. When we look at the normal forecast value, it is observed that this value is found to be 1.1 times more than the water supply in 2014. Between 2015 and 2018, the normal forecast of supply is ranged between 9.48 × 10^8 m^3 and 1.02 × 10^9 m^3.

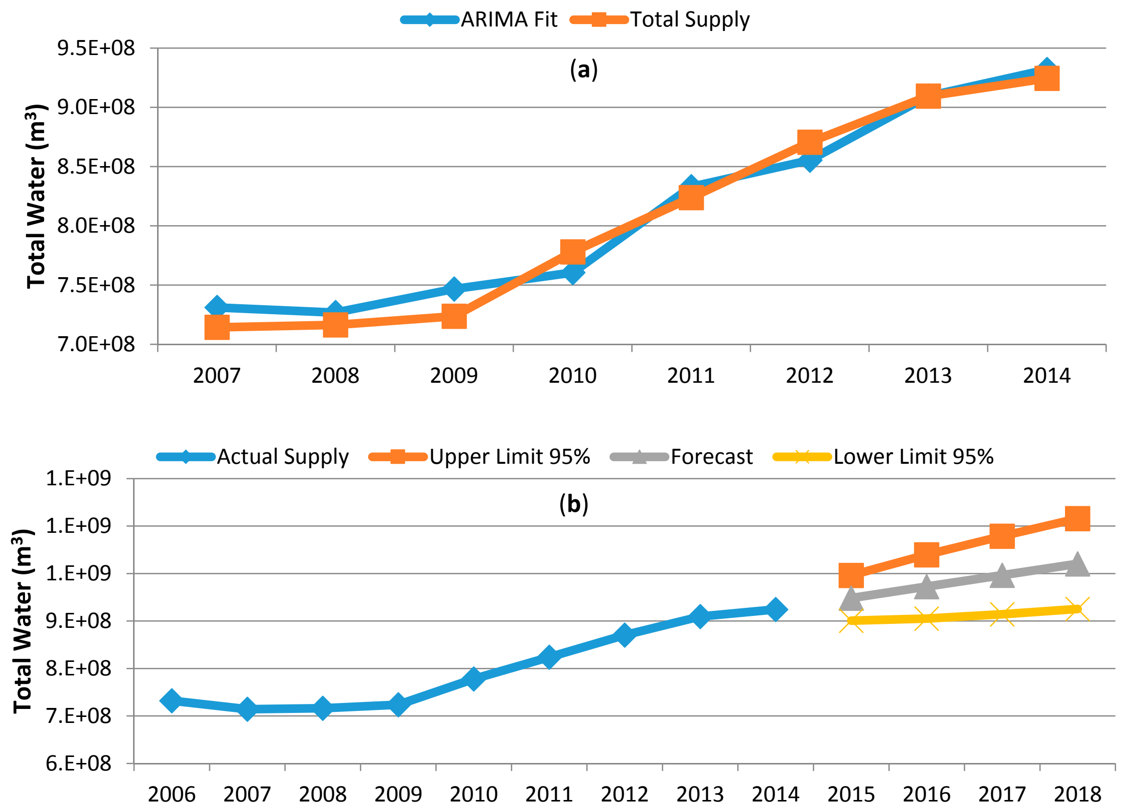
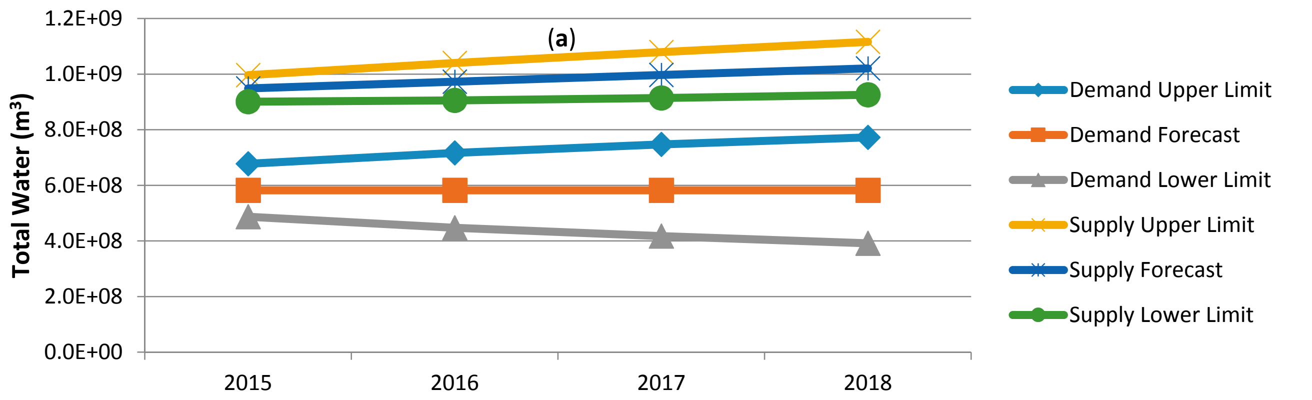


Figure 4. ARIMA forecasting results for water supply (m^3). (**a**) Actual supply *versus* ARIMA fit; (**b**) Supply forecasting data for upper, normal and lower limits.

Figure 5a shows the water demand and supply forecasts for the period between 2015 and 2018. The forecasting results are presented for three estimates: upper limit, normal forecast, and lower limit. The results presented in Figure 5a are based on water supplied to city with the Sakarya and Melen regulator projects. The forecasting results showed that supplied water in 2018 is able meet the water demand in this year. This result is found to be valid for both upper and lower limit forecasts and in both conditions, water supplied to city is significantly greater than the water demand in Istanbul. In 2018, the lower limit forecast of supplied water is found to be 1.19 times higher than the upper limit forecast of water demand. Furthermore, the lower limit forecast of water supply is 1.58 times greater than the normal forecast of water demand. Therefore, it is likely to conclude that the city is not expected to have a water shortage to meet the demand if the water supply is not affected by unforeseen environmental and climatic conditions.

Although Figure 5a presents the estimates of water demand and supply amounts, it is still important to see the future of city water supply without pipeline projects. The findings revealed interesting insights and show that for upper limit forecasts, the water supply is found to be quite larger than water demand until 2018. On the other hand, upper limit demand forecast values are getting closer to lower limit supply forecast values. In 2018, the value of lower limit supply forecast is found to be 8.43×10^8 m^3 and the upper limit demand forecasting is calculated as 7.72×10^8 m^3 (see Figure 5b). Therefore, it is important to note that pipeline projects might be highly critical for meeting the increasing city water demand. Without these projects, the city may suffer from water shortage in the near future. This case might also bring unforeseen risks for sustainable supply of city water due to fact that any conflict between neighboring cities can result in serious disputes related to water trade between Istanbul and water exporter cities.



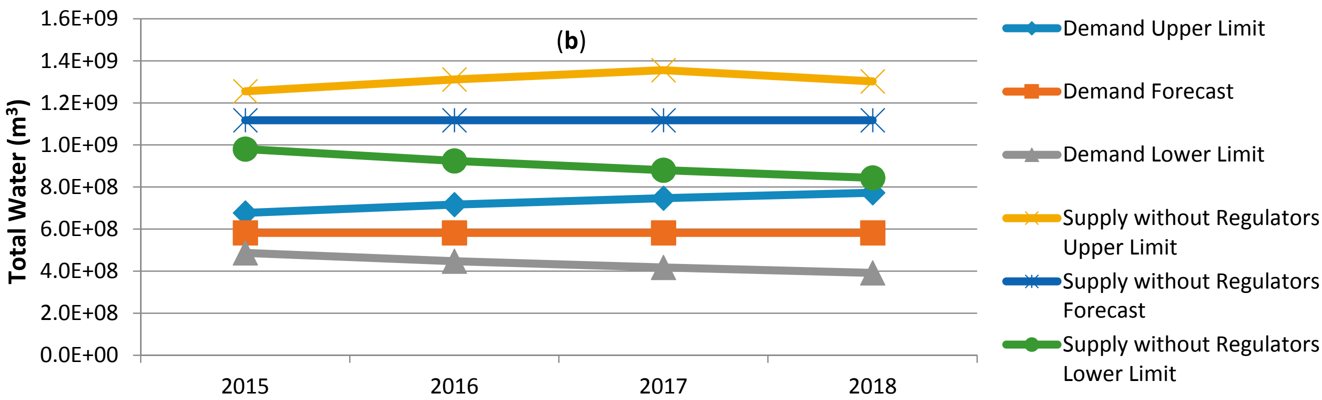


Figure 5. ARIMA forecasting results for water demand and supply. (**a**) Demand *versus* supply (m^3); (**b**) demand *versus* supply without regulators (m^3).

5. Conclusions and Recommendations

This research is a first and critical attempt towards understanding the present and future of water demand and supply capacity of Istanbul and developing a time-series demand and supply forecasting model for sustainability of urban water management policies. Although water continues to become a highly critical and scarce resource for cities, there is unfortunately a little research done for analyzing the long-term sustainability of urban water management in Istanbul. Especially, by investigating the main demand categories and supply sources, the findings will guide the city decision makers to identify main areas that need an urgent attention in the long run. In addition, forecasting the future water demand

and supply amounts, the decision makers will be able to assess the effectiveness of their water conversation and supply policies which can lead to management of the city water in a sustainable way. Hence, the methodology applied in this paper can be a practical framework for other metropolitan cities towards achieving sustainable urban water management. Overall, the findings of the current research highlighted the following points:

- ❖ The residential water consumption is found to be dominant accounting for approximately 80% of city water use. Hence, giving a high priority for reducing household water use and incentives for water efficient household equipment can be listed among the sound water reduction strategies. Specific to Istanbul, the water use related to industrial, commercial and agricultural activities are comparatively lower than residential use, and the importance of water reduction polices addressing these activities are not likely to diminish the net water demand of the city as much as policies addressing reductions in residential use. The water efficiency related targets can be achieved by using a range of water efficient components in toilets, showers, kitchen taps, basin taps, dishwashers, washing machines, and baths and the importance of using water efficient equipment and residential water conservation strategies and their impacts are widely discussed in the literature [28–30].
- ❖ The total water supplied to Istanbul is largely supplied by dams located in the city. This indicates that city's water supply is highly sensitive to changing climatic conditions and rainfall patters. As we are facing with dangerous climate change worldwide, the impacts of global climate change might affect the long-term sustainability of water supplied from the dams. This is because high temperatures and drought are able to bring water reserves to low levels in city dams. Although the municipality built pipeline projects in order to supply additional water to city from neighboring cities, this case can also create conflicts between Istanbul and water exporters. Political conflicts or unexpected water shortages in neighboring cities can be risk for Istanbul when supplying water from Sakarya and Melen regulators. The forecasting results also showed that the city might not meet with the future demand without these pipeline projects. Hence, it is likely to conclude that the water supply of Istanbul might be subject to important risks in the upcoming decades.
- ❖ The water sustainability metrics that are used in this research also revealed important insights regarding water loss characteristics of Istanbul. First, water loss to demand ratio showed that in 2011 and 2014, the total water loss accounts for around 60% of total water used in Istanbul. In other words, the city wasted more than 50% of the residential water due to deficiencies in the water delivery infrastructure. Although city planners seek to minimize the water use in households, the distribution loss remained another critical area needs an urgent attention to reduce the demand on clean water as well as additional water supply. Hence, reducing the water loss should be priority area for decision makers for sustainable future of the urban water and the significance of several water loss reduction strategies and investments are discussed in previous studies [31–33]. However, high upfront investment needs to improve the current water supply network and having historical ruins preventing new underground infrastructure projects are listed among the main obstacles for city decision makers.

- The authors urge that the water supply of water in Istanbul is primarily dependent on dams and therefore the amount of water stored in dams will be critical to supply enough water to city. Especially, the fluctuations in stored water in city dams are enormously high which can lead to problematic cases for certain periods. At this point, it is not sustainable for Istanbul to continue with its current water loss ratio ranging between 35% and 37%. In 2014, the Turkish government representatives proposed the first official regulation for water loss control. Starting from 2014, decreasing the water loss has become mandatory for the water utilities in Turkey. In addition, according to the 10th Development Plan of Turkey covering the period between 2014 and 2018, preventing water losses will be a main priority of Turkish government [34,35]. The findings of this paper revealed that water loss in distribution network is still high and continues to result in huge economic losses for the city. Although policies addressing residential water reduction are among the top agenda items in a sustainable urban water management, the investments for the renovation of the water distribution network infrastructure should also have a similar priority in order to minimize the net water consumption effectively.

It should be kept in mind that current research is based on the limited dataset covering the period from 2006 to 2014. Although this work is a first attempt toward developing water supply and demand projection model for Istanbul, there is obviously further research needs on working with the long-term data series and addressing uncertainties in water supply and demand variables. For instance, the supply of water is highly dependent on the rainfall patters and temperature increases that are expected to have considerable fluctuations over the next decade. In addition, rising investments through mega-projects such as construction of The Yavuz Sultan Selim Bridge, The Third Airport with 150 million passenger capacities and The New City Project have a strong potential for increasing the city population as well as demand for clean water in the near future. Hence, much more attention should be given to probabilistic forecasting methods in order to reflect the role of uncertainty in future supply and demand forecasts of water in Istanbul [6,36]. In addition, real time water demand and supply tracking and management of city water through information technology (IT) are likely to be inevitable in the future and the importance of the algorithm-based IT applications and knowledge-based urban development is highlighted in the previous studies [37,38].

Last but not least, the traditional forecasting models including multivariate regression analysis, ARIMA, as well as more advanced models including soft computing, expert systems and artificial neural networks are mostly utilized for both short and long-term water supply and demand forecasts. However, these forecasting models are usually looking at cause and effect relationship without considering the dynamic complex interactions between the parameters of water demand and supply such as income level, water demand rate, increasing temperature, *etc.* Therefore, for future research, the authors suggest to model the water supply and demand projections of Istanbul using the system dynamics approach. In this way, the model will be able to take into account the interactions among economic and social dimensions, offering a realistic platform for practical use for sustainable urban water management by city-planners [39–42].

Acknowledgments

This material is based upon work supported in part by the Istanbul Water and Sewage Administration (ISKI). The authors are grateful to ISKI Strategic Management and Planning Department Head, Mehmet Palan for his support in data collection process.

Author Contributions

Murat Yalçıntaş carried out the analysis including work related to data collection and contributed to writing of the manuscript. Melih Bulu supervised the research and contributed to the literature review and conclusion sections. Murat Küçükvar worked on the selection of the water supply and demand parameters and contributed the model development part of the manuscript. Finally, Hamidreza Samadi run the ARIMA forecasting model using the R-software and obtained the forecasting results. All of the authors contributed equally to this research. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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