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System dynamics for monitoring urban water consumption management: a case study

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Abstract

With continued water resource shortages and population growth rate especially in the big cities, it is necessary for managers to aim of providing high quality water for public as well as protecting the water resources. Planners and water managers must focus on obtaining a complete understanding of the available water resources and potential impacts in order to meet current and future water demands. Investment in long term strategy for water problems is a fundamental step to avoid and reduce water crises in the future. Water problems involve different values of social, economic and environmental interests; applying new systems based water management tools could provide the means to consider and assess all the complex issues. It is crucial to obtain suitable tools to deal with multiple and dynamic problems of water and simplify the various aspects related to the water resources management. These tools could facilitate a closer linkage between decision-making process with regard to sustainable planning and long-term water management and also maximise the effectiveness of water managers' decision processes. Aronson (1998) believed that the character of systems thinking makes it extremely effective on the most difficult types of problems to solve: those involving complex issues, those that depend a great deal dependence on the past or on the actions of others, and those stemming from ineffective coordination among those involved.

Water consumption management is one of the most complicated subjects in planning of urban areas. As the complexity of water management increases there is a need to develop a systematic approach to investigate the requirements of water management. System thinking offers the water consumption managers the ability of assessing, predicting and planning for availability and use of water. This method is a suitable tool to deal with multiple and dynamic problems of water and could simplify the various aspects related to the water resources management. Saysel (2007) expressed that the water resources planning and management requires analytic methods to guide decision making on development, use and consumption of water resources. System dynamic provides a flexible structure as to establish a framework for learning water resource systems and water management problems. System dynamics with systemic feedback modelling can monitor water supply-demand flow of urban areas in order to support decision over long term policy.

The purpose of this paper is to develop a methodology for monitoring water consumption that highlights possible water saving strategies. The paper presents the process of building a system dynamics model of water consumption management using the VENSIM software. The model provides a formal causal-descriptive framework along with computer simulation for the analysis of dynamic, complex and socio-economic water consumption problems, which includes feedback loops and dynamic relationships over the time. In particular, the computer simulation methodology provides an experimental platform for the water consumption

problems of Tehran, the capital city of Iran, and illustrates engagement of managerial roles with the society to establish the water efficiency strategies. The water management system has been affected by the past and present conditions of the city such as rapid urbanisation, industrialisation, and population growth. The household consumers are responsible for 70 percent of the total water consumption of Tehran that indicates the importance of water saving strategies in this mega city (Bidhendi et al, 2008). These current circumstances may create a water crisis in the city in the future, and therefore seriously influence the water management system. In addition, the city will need extra water resources, which have to be mainly provided by the strategic actions taken by the consumption management.

This paper outlines the necessity of careful consideration and control of water demand as a vital component of the integrated water resources management. The proposed system dynamic model facilitates water management planning with consideration of cultural and technical aspects in order to maintain the water consumption at the optimal point. The data input is derived from the statistical figures reported by the authorities. Finally, the model provides water strategic whilst changing water consumption behaviour in terms of public awareness, low volume water fixtures, price setting and water loss control. The paper mainly focuses on the effects of public awareness and culture on the water demand.

1. Introduction

Improving the efficiency of water use is a key for decision makers in water resources management. On the other hand the complexity of water resources makes it difficult for managers to assess the efficacy of the decisions. Consequently, it is essential to employ modelling approaches to deal with water problems and improve decision making in this area. System dynamics is a powerful methodology for managing complex feedback systems based on computer simulation modeling technique for understanding, and discussing complex issues and problems. Saysel (2007) expressed that the water resources planning and management requires analytic methods to guide decision making on development, use and consumption of water resources. He mentioned the systems methodologies as a flexible framework for learning about water resource systems and management of water resource problems. Saysel (2007) indicated System Dynamics (Systemic Feedback Modelling) of offering the appropriate principles and methods for long term policy analysis and design. Therefore the System Dynamics modelling is an approach which can be use to improve the efficiency of water use in an urban area.

Tehran, the capital of the Iran is the 18th most populated city in the world and has accommodated almost 20 percent of the Iranian population. Tehran is experiencing perhaps the fastest urban development of all Asian cities and is facing water-related problems. Mahmoudi (2006) indicated that Tehran has been faced with serious water-related challenges as it is not constructed close to any large river; thus its water resources are very limited. The population growth together with the unfavorable water consumption pattern among Tehran citizens (above 300 liters per day which is two times greater than world average), have caused a decrease in amount of available water per capita from above 1,000 m3 in 1956 to almost 500 m3 in 2001. The result was the critical condition in available water for Tehran citizens in 2001. The water management of the city is a big challenge which depends on the recognising different factors and values such as environmental, economic, political, social and cultural values. There is an urgent need to prevent the occurrence of a more intense water crises in the region by both reviewing past behaviour in water management and seeking innovative approaches. Saysel (2007) highlighted that past experience in water resources management show that, many water development projects built on engineering expertise and hydrosystems analysis concepts had failed due to human-social agency and plus ecological impacts and uncertainty. Consequently, regarding to the water consumption the specific culture and behaviours of people in the society should be identified. It is necessary for decision makers to consider people and their relationship with water as a factor to reach a sustainable water management and water efficiency. People's water use habits could be hard to change, therefore wise strategies will be needed to be introduced and put forward (Tajrishy, Abrishamchi, 2005; World Bank, 2004, Jahani and Reyhani, 2006, Vojdani, 2002, Bagheri and Hjorth 2007, Mahmoudi 2006). The recent water crisis in Tehran indicates the necessity of careful consideration and control of water demand as an important component of integrated water resources management. Confronting the water crisis requires some changes of values from both decision makers as well as people. Bidhendi et al. (2008) expressed that the household consumers are responsible for 70 percent of the total water consumption of Tehran. Tehran residents should be made aware of water's importance for the city's existence. Tehran is a dry land and depended on the water support from the other cities and areas. For reaching a balance between water resources and water demand, decision makers should comprises planning and controlling water uses considering technical, economic and social measures. The appropriate water management planning with consideration of cultural and technical methods could lead the water consumption of Tehran to the optimal point. The UK's Environment Agency (2001) suggests that socio-economic change may result in large increases or large decreases in demand for water, depending on changes in population, GDP, uptake of water saving technology, leakage control and social attitudes towards water use and the environment.

The purpose of the study is to develop a methodology for monitoring of water consumption and to highlight the importance of the value of water saving strategies. The study illustrates the process of building a system dynamics model of water consumption management in Tehran using VENSIM software. The model provides a formal causal-descriptive framework linked to computer simulation method for the analysis of dynamically complex socio-economic of water consumption problems.

2. System Dynamics and urban water management

System dynamics is an approach for understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. System dynamics is a powerful methodology for managing complex feedback systems based on computer simulation modeling technique for framing, understanding, and discussing complex issues and problems. System dynamics originally developed to help corporate managers improve their understanding of industrial processes and was created during the mid-1950s by Professor Jay Forrester and was applied almost exclusively to corporate/managerial problems. Saysel (2007) believed that the water resources planning and management requires analytic methods to guide decision making on development, use and consumption of water resources. He indicated System Dynamics (Systemic Feedback Modelling) of offering the appropriate principles and methods for long term policy analysis and design.

3. Causal Loops Diagrams for monitoring urban water problems

Optimising the water resources management can be done by different ways, system dynamic was selected for this study because it makes the complex systems easy to understand. VENSIM software was used to build a system dynamics model to observe the association of water consumption and water supply of Tehran. The causal loop diagrams or feedback loops are beneficial in modelling the system structures. Figure 1 provides the basic model structure of water causal-loop diagram. As it can be seen the diagram consists of two feedback loops. The first positive feedback loop represents interaction between water demand and water supply: the higher the water demand, the higher the water supply, then higher the demand, completing the reinforcing loop. The second feedback loop represents interaction between water supply, water consumption strategies and water consumption behaviour. The higher the water supply causes unintended consequence behaviour such as increase in water demand, completing the reinforcing loop.

Bagheri, and Hjorth, (2007) believed that in any complex system, some kind of self-organizing mechanisms are working to keep the system in balance. They mentioned that the system dynamics approach, the critical balancing or negative feedback loops in a system need to self-correct the system by adjusting reinforcing or positive feedback loops. These are demonstrated by an 'R' (for reinforcing loop) on the diagram. Viability Loops (VL on the diagram) are described by Hjorth and Bagheri (2005) as the balancing factor of dynamic system. Considering viability loop could highlight the ways of tackling the problems of the reinforcing mechanism. As can be seen in Figure 1 the water conservation strategies as a Viability Loop can have negative effect on the reinforcing feedback loops of water supply and demand which cause the unfavourable water consumption of the consumers.

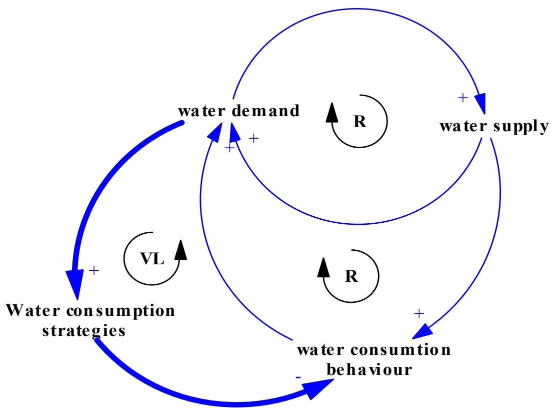

Figure 1. Causal loop diagram of the feedback mechanism with added a Viability Loop.

For visualising the water problems situation the dynamic feedback structures of the water system are built up by using the Causal loop diagram. This diagram highlights the dynamic situation of the water systems (those which are the intended focus of this study) and allows recognition of the reinforcing mechanisms of the system and their viability loops.

Figure 2 demonstrates some dynamics mechanisms in the water systems. As it can be seen the usual mechanism in water system of an urban area aims to provide the water demand of the city through increasing water supply which as the result encourage the more demand and the more use of the water resources. The reinforcing loops of R1, R2 and R3 present the effect of consumers' unfavourable water use and the population growth on the water system which caused by applying the short term strategies. Therefore the necessity of planning for long term water efficiency strategies of water consumption is highlighted. System needs to be balanced through the managerial strategies. The effective water consumption strategies could have positive feedback on the social, economic and environmental issues of the water supply with less costly dams and fewer transfer systems.

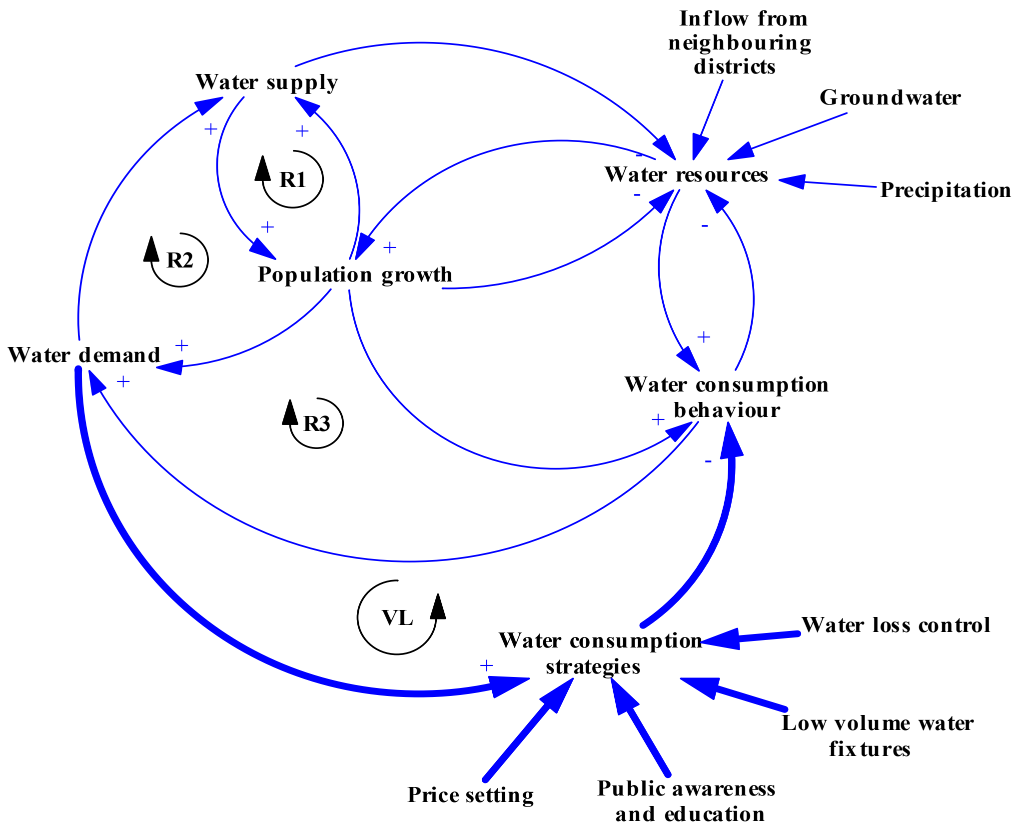

Figure 2. Causal loop diagram of the feedback mechanism and viability loop of Water consumption management strategies.

For changing water consumption behaviour of people it is necessary to consider the record and evaluation of the consumption patterns and the public relations with water and their opinion about different aspects of water services. Changing water consumption behavior could be applied through the water saving strategies of: public awareness and education, price setting (water metering), low volume water fixtures and water loss control (leakage detection).

4. Case study

Over the recent years Tehran has been facing a lot of water related problems. Water shortage is one the most apparent problem of the city. Despite this problem the residents of the city are overusing the water. Tajrishy and Abrishamchi, (2005) stated in the year 2020, the volume of water consumption in Tehran is projected to reach 1,400 million m^3.Which comparing to available water of 900 Mm^3 indicates in the near future, Tehran will need the extra water that has to be provided by the strategic actions taken by the consumption management. For future water resource and water consumption predictions and therefore, the development of the water policies of Tehran, recognition of available water resources, population growth and the water demand of the city are necessary.

5. Population

Tehran has more than seven million permanent residents and two million non–resident commuters, constituting the largest population base in Iran and it is the eighth largest city in the world (Mahmoudi, 2006). Population has rapidly grown from 2,000,000 in 1960 to 7,797,520 in 2006, and sill is rising (Table1).

Name	Status	Capital	Census 1986	Census 1991	Census 1996	Census 2006
Tehran	City		6,042,584	6,475,527	6,758,845	7,797,520
Iran	Country	Tehran	49,445,010	55,837,163	60,055,488	70,495,782

Table 1. Population of Iran and capital city of Tehran (Census 1986 to 2006)
http://www.citypopulation.de/Iran-Tehran.html#Land

6. Water resources

The water supply for Tehran is mainly provided by springs from the Alborz Mountains (located in the north of Tehran). Water is supplied to Tehran from both surface and groundwater (almost 300 wells located in the city) resources. The present surface water resources as can be seen in Figure 3 are: Karaj River, Jajrood River and Lar River.

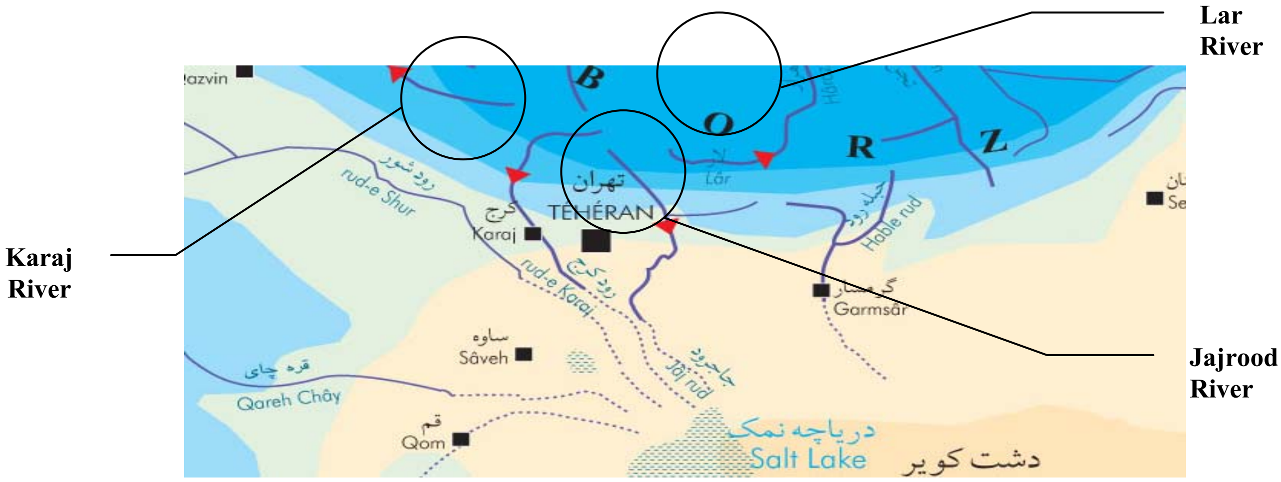

Figure 3. Geographical location of Tehran water resources

As shown in the Table 2 the total of 890 Million Cubic Metres (MCM) per year of water supply of Tehran are provided by Rivers of Karaj, Jajroud, Lar and Wells of Tehran.

Rivers and Wells of Tehran	Capacity to supply water (MCM per year)
Karaj River	340
Jajroud River	160
Lar River	140
Western Tehran Wells	100
Eastern Tehran Wells	100
Central Tehran Wells	20
Tehran southern towns Wells	30
Total	890

Table 2. Proportion of water supplied by groundwater and surface water MCM per year for Tehran

7. Water demand

Karamouz et al. (2004) mentioned that Tehran metropolitan area is one of the mega cities of the world and has annual domestic water consumption close to one billion cubic meters. Despite the water shortages of the city, the average combined per capita consumption (pcc) of water is above 300l/p/d which is the twice world average of water consumption. Tajrishy and Abrishamchi, (2005) mentioned that during recent years water consumption in Tehran has risen above 350 litres/person/ day.

Table 3, presents the daily water usage per person, total daily water usage and total yearly water usage for Tehran.

	1965	1975	1985	1995	2000	2005
Daily water usage litres/person	**97**	**160**	**250**	**335**	**350**	**365**
Daily water usage per capita m3	**0.097**	**0.16**	**0.25**	**0.335**	**0.35**	**0.365**
Total daily water usage m3 (1000)	**262**	**720**	**1500**	**2211**	**2520**	**2847**
Total yearly water usage m3 (1000)	**95630**	**262800**	**547500**	**807015**	**919800**	**1039155**

Table 3. Daily water usage per person, total daily and yearly water usage of Tehran from 1965 to 2005.

8. System dynamic model of Tehran water consumption

Based on Tehran water consumption a system dynamic model was built, which characterises between Level (Stock) and Rate (Flow) and Auxiliary variables (Figure 4). Stock Variables represent the circumstances and situation of system. Flow variables represent the situation changes of the system. Stocks could change values through their flows. A model structure could be identified by locating relevant stock and flow variables.

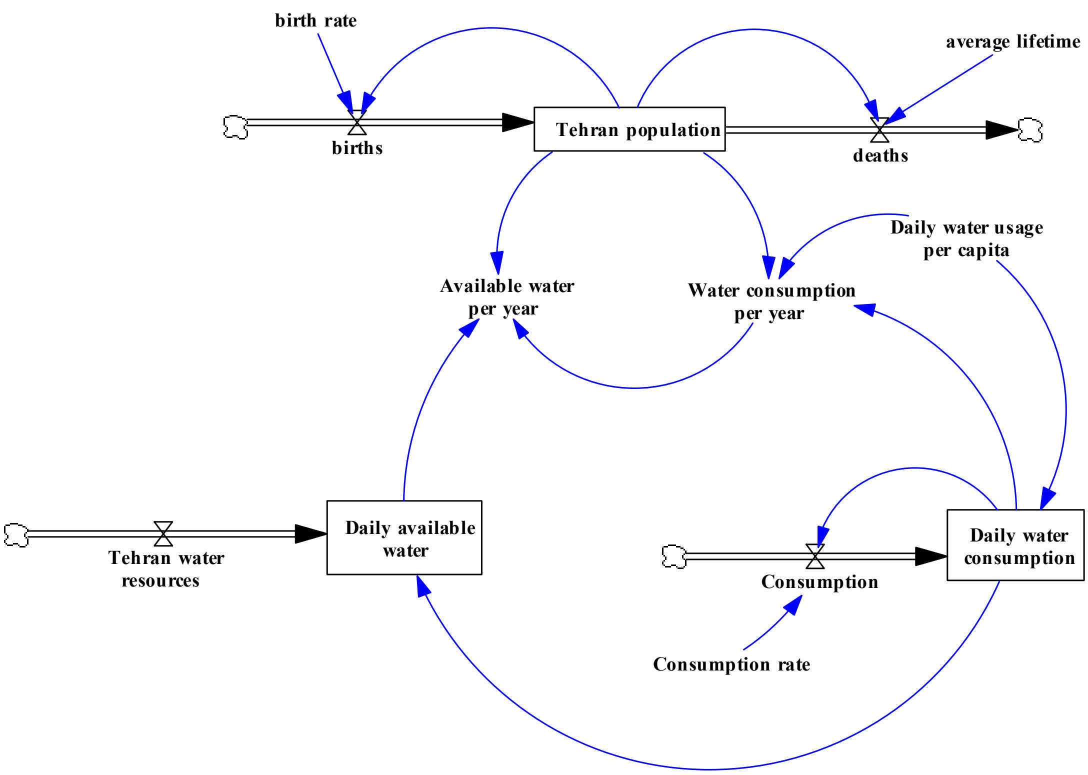

Figure 4. The system dynamic model of Tehran water consumption

The data input needed to assemble the model was used from the statistical figures reported by other studies and also authorities which are presented in Tables1, 2 and 3. The initial values in the model are based on Table 3, for year 2000 information such as total water demand per capita of 920 Mm^3 (million cubic metre) per year and 350 dm^3 (cubic decimeter) or 0.35 m^3 residential use per capita per day. The model is considers mainly the daily water consumption per capita by different scenarios. Two sets of assumptions were considered for testing the different water consumption behaviour of people as follow:

Assumption set 1:

- People of Tehran will continue to consume the water as the same as current use (350 dm^3).
- Water resources and water availability will remain unchanged.
- Population growth rate will remain the same.

Assumption set 2:

- People of Tehran decrease their demand of water as the world average of (150 dm^3) per day.
- Water resources and water availability will remain unchanged.
- Population growth rate will remain the same.

9. Results

The system dynamic model simulation was run over the water consumption of the city for year of 2000 to 2100. Simulation results are shown in the Figures 5 and 6 for water consumption and available water per year respectively. Figure 5 shows the increase of the water consumption until the next century for both assumptions however the Figure indicates that water consumption would be much less by consideration of assumption 2. Figure 6 presents the decrease in the available water of the city. This Figure implies that there will be less water if residents continue to consume water as much as they consume now.

The results highlighted the value of the consumption management for the city that could have a great effect on saving water. Model simulation and output graphs provide a strong visual method to compare the results of different policy. The model output graphs produced from different behaviour water consumption to show the importance of people engagement in water management. Study considered by two different assumptions, one with no change in water consumption behaviour (same as current use) and another one with change in water consumption behaviour (reduce the consumption). Model simulations signify the importance of change in the consumption behaviour of the residents for saving water.

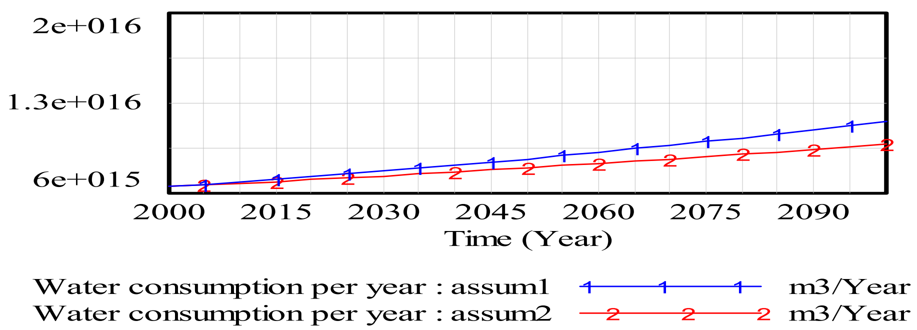

Figure 5.Comparison of assumption 1 and 2 of water consumption per year

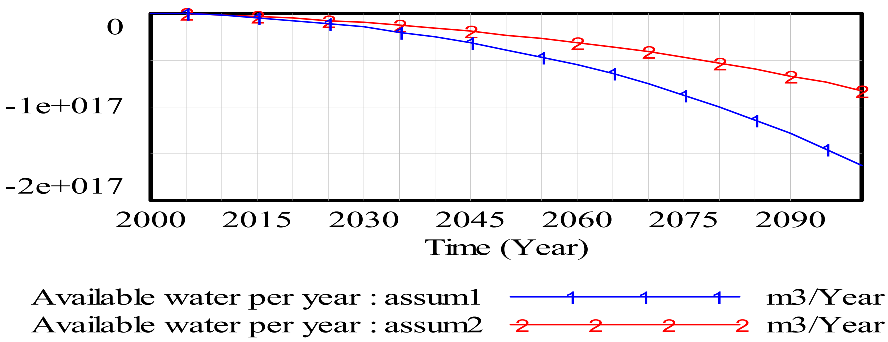

Figure 6. Comparison of assumption 1 and 2 of available water per year

10. Conclusion:

Water resource management systems in urban areas are affected by the past and present conditions which will continue to influence the water management through the future. The rationality implies an efficient and sustainable management of water resources to obtain the understanding of the available water resource and potential impacts in order to meet current and future demands. It is obvious water problems are very complex and they involve different values including social, economic and environmental interests. In this way the water management tools could provide the means to consider and assess the complex issues. The application of decision support systems as a tool could deal with multiple objectives and multi-purpose problems and simplify the various aspects related to the water resources management. Employment of decision support systems techniques enable predictions to be made by managers. This paper describes a simulation methodology, based on the combination of the water consumption and system dynamics that assists managers in predicting future behaviours.

In recent years, Tehran has experienced severe drought. And nowadays, people of the city should face the reality of less water resources. The current water problems of the Tehran can be linked to the lack of long-term policies strategy and the absence of serious attempts to formulate water management plans. It is necessary to establish a framework to consider appropriate strategies of water problems. It is necessary to establish the new models for engaging societies with the managerial roles. Understanding domestic water usage and people's attitudes towards consumption of water are the main strategies to reach water efficiency. System dynamics modelling as an approach can help managers to communicate with people by explaining the problems and illustrate the outcomes of suggested strategies. Applying system dynamics model could highlight and explain of the problems situation and make it easier to detect different situations. The case study demonstrated the benefit of water resource management communication with public. By visualising water problem (over consumption) and how to solve it (change behaviour). Two separate assumptions are considered for people water consumption, one 350 litres/day for per customer and the other for 150 litres/day per customer in the next 100 years. Data employed included; daily water consumption per person, available water for the city, and the population of the Tehran. Simulations generated using both assumptions were compared to water consumption and water availability. Results showed the increase of water consumption and decrease in the available water for the city. However the results indicated that by improving the water use efficiency (changing consumption behaviour) less water will be required in the future. The study showed the importance of creating a new culture of water use that could save water for the city. In addition the study highlighted the need of understanding the culture of water and causes of the high use of water. The challenge for water managers concern how to implement policies that stimulate the significant degree of behaviour change required. Water managers should try to build the public support for resource management strategies by raising public awareness of water problems. Further researches in this area would be essential because of the shortage and uncertainty of water resources.

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