Sustainability and determining the optimal population based on water resources in Mashhad, Iran

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Abstract: This study first evaluates Mashhad's water resource sustainability, employing sustainable urban development models proposed by Haughton. Second, it determines the optimal number of population in 2016, both with and without the Dousti and Ardak dams. Results show that the Mashhad plain possesses only 2% of the total province groundwater although 65.97% of the urban provincial population live there. Furthermore, 92.7% of surface water comes from the Dousti dam, which is located 220 km from Mashhad, and only 30% of domestic sewage is recycled. Using Haughton's theory of urban metabolism, Mashhad is thus not a sustainable city, as, including the Dousti and Ardak as water sources (dependence out of hinterland), it has a surplus population of 550,459 and excluding them, a surplus of 1,192,660 people.

Keywords: Ardak dam; Dousti dam; Haughton's theory; independent city model; Iran; Mashhad; optimal population; re-designing cities model; sustainability; water resources.

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1 Introduction

It is expected that, by 2030, 60% of the global population will live in urban areas, (United Nation, 2012) and providing for the resulting higher demand for water is one of the challenges associated with the increased rate of urbanisation (Srinivasan et al., 2013; Nair et al., 2014). There are particular challenges in arid and semi-arid regions where climate change exacerbates water scarcity (Field et al., 2014; McDonald et al., 2011). As water is an essential natural resource, national policies must support water resources management and planning because of the threat from climate change and population growth (Shinde, 2003, Whitler and Warner 2014). The water shortage crisis is the biggest challenge countries and governments will face in the near future because "water is the key for sustainable development" (UNESCO, 2014).

After the concept of sustainable development was introduced (Brundtland Commission, 1978), models of sustainable cities were developed in which urban planners had to concentrate their goals on creating cities with lower energy inputs and lower pollution outputs (Turner, 1996). Hutton's studies on models of sustainable urban development have been very useful as each of these models suggests different strategies in relation to water and wastewater networks, including the model for redesigning cities and that of the independent city (Williams et al., 2000). Clearly, for water resource management, cities must move toward sustainable urban forms that emphasise resource recycling and population decentralisation.

With an average annual rainfall of 250 mm, Iran is a dry country with limited resources. In the next 30 years drought conditions in Iran will worsen, and, in the years 2011, 2025, 2032, 2034, 2035 and 2039, most places in Iran will face severe and extremely severe droughts (Khazaneh dari et al., 2009). Razavi Khorasan Province (RKP), with an annual rainfall of 210 millimetres, is one of the regions that face water scarcity (Statistics for RKP 2012). Mashhad, the capital and largest city in the province, is in the Mashhad Plain. It is the second largest city in Iran and has a population of 2,766,258. Moreover, it is the second most popular religious centre in the world and, in addition to its own population, receives about 20 million pilgrims and tourists annually (Mashhad's Jahad Daneshgahi Research Deputy, 2011). Obviously, such an unprecedented growth in population affects all facilities. One of the most important of these is the provision of drinking water, which has met innumerable problems. In summer, the warm air and pilgrim population increase water demand and, hence, water scarcity becomes more apparent (Velayati, 1997).

In 1966, using the Mashhad plain to provide water was forbidden by the Water Office of Power Ministry (Behzadi, 1970). This caused Mashhad to become dependent on areas outside its sphere of influence to provide water. The city must be guided towards a sustainable form to reduce its dependence on surrounding regions and to achieve sustainable management of water resources. Solutions for these urban water problems require development and implementation of new paradigms, not just analyses (Seto and Satterthwaite, 2010). For this purpose, the goal of the first stage of this research is related to the sustainability of Mashhad in relation to water resources, emphasising Hutton's urban metabolism. In the second stage, the optimum population in 2016 is determined based on two options of the water and sewage organisation of Mashhad (WSOM). These options consider providing required water and per capita water consumption.

1.1 Water and urban planning

The growth of urbanisation has resulted in severe water shortages (Olli and Pertti, 2001, Tomohiro et al., 2006, Unalan, 2011). Water security forms an important part of economic, environmental, social, and national security, especially in arid and semi-arid regions (Knapp, 1995). In general, arid and semi-arid regions face more serious water shortages than other regions. Kathleen et al. (2010) stated, "Is there really a capacity for urban development based on water resources?" It is necessary to move towards urban planning, sustainable urban development, and optimum urban population based on water resources.

With the increase in the number and density of urban population, required water resources must be provided from outside urban borders (Lundqvist et al., 2003). However, this violates sustainable development which favours controlling city size and prefers controlling urban borders to providing water from far away. Sustainable development is one of the prominent development paradigms at the local and regional levels (Castro, 2004). It emphasises concentrated development, preservation, and revival of water resources (Denver Regional Council of Governments, 2007), and in future it will be viewed as a paradigm that prevents resource destruction (Pruneau et al., 2014).

Following the concept of sustainable development, that of sustainable city and its multiple models was introduced. Many models of sustainable cities have been suggested, but this concept has not been investigated theoretically (Jones and MacDonald, 2004). Models of sustainable cities are based on economic, social, and environmental foundations. Research has shown that several city forms can be sustainable (Flint, 2004; Jenks and Jones, 2010). Hutton's studies on models of sustainable cities, each of which shows a different strategy in relation to water and wastewater networks, have been very useful.

1.2 The model for re-designing cities

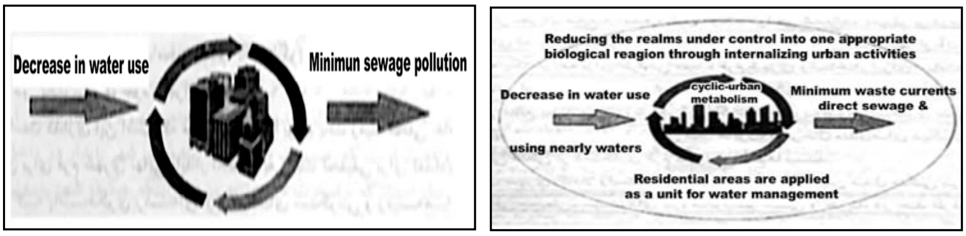
This model is based on energy productivity and population density in urban areas and concentrates on urban development associated with reduced urban metabolism and energy flows, the focus being inside the city. Flows, including food, energy, and water entering the city must be recycled. It is possible to reduce these flows, and hence decrease environmental pollution, by reorganising energy flows (Meijer et al., 2011). These changes are usually accompanied by increased density. This model raises many of the basic assumptions related to compact cities (Williams et al., 2000). Concentrated development reduces surface water and water pollution by 30% and 40%, respectively (US Environmental Protection Agency, 2004).

1.3 The model of an independent city

This model emphasises reduced dependence on external resources so that the urban spheres of influence decrease. It concentrates on circular metabolism through which the inflow and outflow of resources are related. The sphere of influence is reduced to a suitable bioregion inside which resource flows are reduced. The basic principles of this model are the use of small-scale technologies, recycling materials, and demand management (Williams et al., 2000). Figure 1 shows Hutton's sustainable urban models.

These models do not specify urban borders, but each model provides various technological, economic, and social settings within which use of lands and buildings must be planned and managed. Some urban forms can be sustainable so that the two suggested models also emphasise the compact city pattern (Williams et al., 2000). The environmental advantages of this pattern include protection of green spaces and reduction of environmental waste, reduced emission of greenhouse gases and decreased water pollution. This pattern strikes a balance between the environment and development and protects open spaces, vulnerable environments, and water resources (Litman, 2005). Although the idea of compact cities has been criticised, this pattern has attracted great interest and support with regards to environmental issues (Jenks et al., 2005; Lee et al., 2014; Nabielek, 2012).

Figure 1 Haughton's suggested models, (a) the model of re-designing cities (b) the model of an independent city



(a) (b)

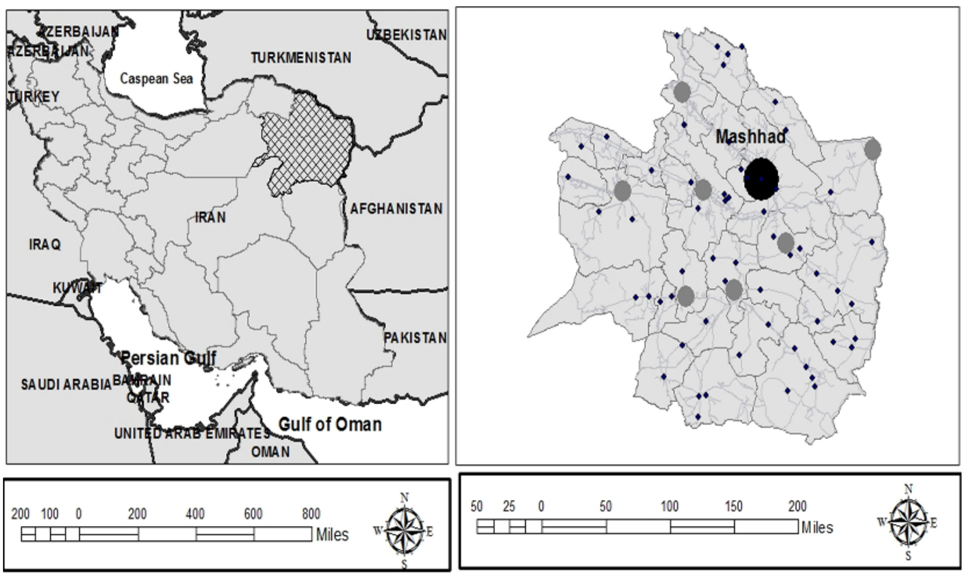
2 Methodology

This is an applied study with the following goals:

1 Evaluating the sustainability of Mashhad in relation to water resources. Hutton's urban models are used for this.

2 Determining the optimum population of Mashhad in 2016 based on the two options of WSOM. These two options are related to provision of required water and per capita water consumption.

Figure 2 The stance of Mashhad in the available spatial structure of settlement system in RKP



A nested mixed methods research design is employed in which qualitative data supports quantitative analyses. Sustainable urban forms were first investigated in library studies, and Hutton's studies in relation to urban water and wastewater networks were found. Qualitative research and document analysis were then utilised to determine the situation of water resources in the province, the Mashhad plain, and Mashhad. Following that, the necessity of introducing strategies for achieving sustainable development is raised.

In addition to being the political capital of the province, Mashhad has a religious status and is the social and economic centre of the region. This has led to a considerable increase in population. The population of Mashhad is 12 times more than that of the second main city in the province. Therefore, RKP has a single-centre spatial structure with Mashhad as the centre. Figure 2 presents the location of Mashhad in the spatial structure of the province.

Concentration of industrial, educational, investments activities should not be centralised as this will influence population absorption and reduce migration.

3 Result

3.1 Water condition in RKP and Mashhad plain

RKP has four main watersheds. The Mashhad plain is in the 9,909-square kilometre Qara-Qom watershed. As for groundwater utilisation, of the 37 plains in this province 12 are in critical condition and water utilisation is prohibited, 22 are not in critical condition but water utilisation is prohibited, and three are free plains. The Mashhad plain is one where water utilisation is prohibited. 2% of the groundwater resources of the province are in the Mashhad plain, but 65.97% of the provincial population lives there, and Mashhad is the largest urban area (Mashhad's Jahad Daneshgahi Research Deputy, 2011).

Underground water in Khorasan plains, including the Mashhad plain, is semi-fossil water, and only part is renewable, and the rest remains out of the water cycle for a very long time (Velayati, 2013). The first notice concerning prohibition of water utilisation in plains such as the Mashhad plain was issued in 1966, but utilisation has not stopped, and an increasing number of wells have been drilled.

There are 26 operational dams in RKP (five of them in the Mashhad plain). Because of the increased population in Mashhad and the Mashhad plain, and due to the negative water balance of groundwater in the plains (Hosseini and Baqeri, 2012), discussion on a project of water transfer from the Dousti dam to Mashhad started in 1993. This water transfer is against the direction of the topography slope and has entailed high costs. The project was intended to transfer 130 million cubic metres of water annually for drinking water and industry in Mashhad. From the implementation of the Dousti dam project to the end of 2012, to complete the transportation line, ring and dam tanks has cost 49 million dollars.

Studies show that 64.8% of the urban population in this province lives in plains with a critical water situation, and 54.2% of the urban areas, 67.1% of the rural population, and 60.2% of the rural areas of the province also are in these plains. Based on the Falcon Mark index, which evaluates access to water based on per capita renewable water, most of the Province faces undesirable conditions with respect to access to water (less than 500 cubic metres per person, with different severity of water shortage in various regions) (Mashhad's Jahad Daneshgahi Research Deputy, 2011). In all, the present situation of water resources in the province and in the Mashhad plain is unstable, and a prolonged drought under current conditions could be hazardous for residents.

3.2 Water conditions in Mashhad

In the past, more than 90% of water consumed in Mashhad was supplied from groundwater resources in the Mashhad plain. However, these resources currently face a strong negative water balance. Therefore, if the present situation continues, the city will always be under critical conditions due to limited water resources, especially during the period of highest water consumption (Monfared and Hosseini, 2005).

Since 2008, the Karde, Torogh, and Dousti dams have provided 60% of the water for Mashhad. The Torogh dam is located 25 km southeast of Mashhad, the Karde 35 km north of Mashhad, and the Dousti dam 75 km south of Sarakhs city (220 km from Mashhad). In the first five months of 2014, 42% of supplied water was from surface water resources and the dam. The Dousti, Karde, and Torogh dams contributed 92.7%, 3.1%, and 4% of dam water, respectively.

At present, because of climate change, the variable flow regime of the Harirud River, and the construction of the Salma dam in Afghanistan, water in the Dousti dam is at 25% capacity (half of this belongs to Turkmenistan). There is evidence that the dam is drying up and will not be a reliable water supply source in the long-term (WSOM, 2014). The production and transfer costs of one cubic metre of water in Mashhad amount to 24 cents, but the domestic consumer pays 10 cents per cubic metre (41% of the total costs) (WSOM, 2014).

Table 1 Production and deficit capacity of Mashhad between the years 2013 and 2036

Deficit production	*Production capacity*	*Maximum daily water need (cubic metres per second)*	*Year*
1.052	13.272	11.222	2013
–0.108	13.272	13.38	2016
–1.708	13.272	14.98	2021
–3.198	13.272	16.47	2026
–4.568	13.272	17.84	2031
–5.568	13.272	19.14	2036

In Table 1, the production and deficit capacity of Mashhad between the years 2013 and 2036 is shown. It is noteworthy that in this column, Ardak dam has also been considered as one of the water resources (Toos Ab Consulting Engineers, 2013).

Considering the climate change conditions, production capacity in Table 1 has been considered constant. It is assumed that more groundwater will be extracted, or water imported from Tajikistan. As shown in the table, Mashhad faced a water shortage in 2016 even with the water from the Ardak dam. With the per capita renewable water of 264 cubic metres, Mashhad faces the most severe water scarcity, and strategies must be adopted to protect natural resources and achieve sustainable development.

3.3 The plan for providing water to Mashhad

The regional water and wastewater company of RKP has studied and executed many projects to introduce strategies for solving water shortages. The most important of these are presented below:

3.3.1 Replacing the wastes of sewage refineries with resources of surface and underground agriculture waters

Preliminary studies on the wastewater network project in Mashhad began in 1989 and implementation started in 1993. The project was supposed to be completed in 2011 but was postponed to 2015. Due to city development, this project has not been completed and it cannot be predicted when it will be.

At present, 6,500 km of pipeline is required to collect wastewater in Mashhad, 35.6% of which (2,315 km) have been laid and the remaining 64% (4,185 km) are yet to be laid (WSOM, 2014). Based on available information, 35% of the wastewater collected in the first five months of 2014 was recycled (WSOM, 2014). Results indicate that about one third of the produced wastewater is recycled and extensive activities are required in this area. Three wastewater treatment plants are currently operating, and Table 2 lists their characteristics.

Table 2 The characteristics of refineries in Mashhad

Row	*Refinery*	*The regions under control*	*Current capacity* (*cubic metre per day*)
1	Parkandabad1	The western part of Mashhad, including Qasem Abad	15,000
2	Parkandabad2	Western development regions of Mashhad	60,000
3	Olang	Eastern part of Mashhad	25,000

Notes: Total: 100,000. The amount of produced water per day: 615,485.78 cubic metres.

70% of the water used in Mashhad is lost as wastewater. Therefore, there is a considerable volume of water that can be recycled but, unfortunately, no suitable use is made of it. There are 180 hectares of green spaces in Mashhad irrigated with urban water and treated wastewater. One of the strategies for reducing urban water consumption is to use wastewater effluents to irrigate green spaces. The cost of treating one cubic metre of wastewater is 20% of that of using well water. Therefore, WSOM is conducting study projects to complete wastewater transmission lines and increase capacities of the water treatment plants. Moreover, WSOM has the goal of reducing per capita urban water required for green spaces to zero.

3.3.2 Transporting water from Dousti dam

The Dousti dam is located 220 km from Mashhad and its water is shared between Iran and Turkmenistan. It was constructed to transfer 130 million cubic metres of water to Mashhad to meet some of the water demands. By 2012, the cost of its construction reached 49 million dollars (Velayati, 1997). Because of the variable flow regime of the Harirud River, the construction of the Salma dam in Afghanistan, and climate change conditions, this dam is not a reliable long-term water supply source (WSOM, 2014).

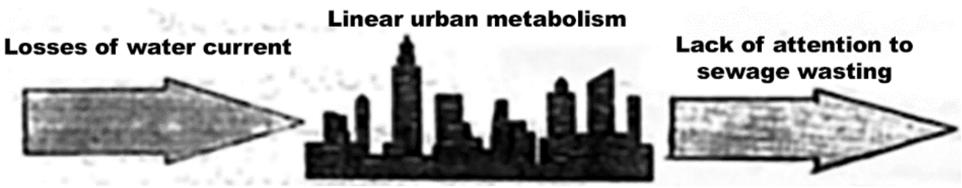
3.3.3 Transporting water from Ardak dam

The Ardak dam is situated 70 km northwest of Mashhad and, under optimum rainfall conditions, will provide 12 million cubic metres of water annually for Mashhad. Water transfer from Ardak was supposed to be completed in 2011, but this has not happened due to delays in operations and the project will probably become operational in 2016 (WSOM, 2014). By the end of 2012, six million dollars were spent on this project.

3.4 Assessing the sustainability of Mashhad and determining the optimal population

After considering study results of studies, water sources, and wastewater recycling, and after comparison with the principles of Hutton's sustainable urban metabolism models, the governing urban model in Mashhad can be seen to be an urban model completely dependent on external resources. This model relies on externalising the surplus environmental costs, open systems, non-compliance with water management, linear metabolism and purchase at the level of the current capacity This model considers the city as a node that attracts resources from outside realms for urban consumption. The model is a very open system that squanders resources and ignores more efficient resource management (Williams et al., 2000). Figure 3 shows the governing urban model in Mashhad.

Figure 3 The governing urban model in Mashhad



Note: The model completely dependent of external resources.

Therefore, the current conditions in Mashhad violate the principles of sustainable development, and urban managers and planners must move towards sustainable urban forms to reduce dependence on areas outside its spheres of influence. Under such conditions, supply and demand for water can be harmonised and matched only by conducting careful population studies and planning.

Perhaps the best way for preventing a regional and national crisis in Mashhad and moving towards sustainability and sustainable management of water resources is to reduce its size and spheres of influence, decentralise population within Mashhad, and move from a single-to a multiple-cantered structure in RKP.

Although population decentralisation, especially within a county like Mashhad, has its own problems, the policy on land preparation is based on the balanced development of settlement areas in the province to prepare the ground for reduced migration to Mashhad. Of course, if decentralisation is not carried out and droughts continue, WSOM has proposed a project to transfer water 500 km from Tajikistan to Mashhad. This completely violates the principles of sustainable development, may influence Iranian foreign relations, and entails very high costs.

The optimum population of Mashhad for 2016 is determined by considering the two options of the WSOM. These two options are related to the sources of water supply for 2016 (when Mashhad will face water shortages) and the annual water needs of Mashhad. They have been approved by Iran's Water and Wastewater Company, and consider water needs of pilgrims. Table 3 presents annual water needs of Mashhad in 2016.

Table 3 Annual water needs of Mashhad in 2016

Population (person)			*3,126,000*		
Consumption of water per capita (litre per day)	Domestic	Public	Commercial	Green environment	Losses
	143.6	10.8	13.7	2	48.1
			Total: 218		
Pilgrim per capita (litre per day)			75		
The average water needs of resident population (millions of cubic metres per year)			249.5		
Pilgrim need (millions of cubic metres per year)			8.6		
The total average of water need (millions of cubic metres per year)			258.1		

Option 1 Determination of the optimum population in 2016 based sources of water supply without considering the Dousti and Ardak dams (WSOM, 2014).

Table 4 Situation of water supply sources in 2016 without considering the Dousti and Ardak dams

Production	*(Millions of cubic metres per year)*	
The water provision plan of 2016	Wells	144
	Toroq dam	8
	Kardeh dam	3
	Springheads and subterranean	6.8
	Total (production capacity)	161.8

Table 4 indicates the situation of water supply sources in 2016 without considering the Dousti and Ardak dams.

The following steps are taken to determine the optimum and surplus populations based on option 1:

Step 1 The extent of water scarcity for the population of Mashhad is calculated first. For this purpose, the water needs of pilgrims (8.6 million cubic metres per year) is subtracted from water production capacity (161.8 million cubic metres annually), yielding 153.2 million cubic metres per year.

Step 2 The difference between the mean annual water needs of the resident population (249.5 million cubic metres per year) from the result obtained in step 1 (which is 153.2 million cubic metres) shows the annual water shortage for the resident population (96.3 million cubic metres annually).

Step 3 To determine the surplus population, the water shortage for the resident population (96.3 million cubic metres per year) is divided by 365 and then multiplied by 109, yielding 26 * 107 litres per day. Next, based on the per capita formula (per capita consumption of 218 litres per day), the surplus population is determined (1,192,660 people). Therefore, based on option 1, the optimum population for 2016 is 1,933,340 people. In this option, dependence of the region on external resources outside its spheres of influence is eliminated, but population decentralisation on a large scale will be required.

14 projects are being studied to be implemented in phase 2 to solve water scarcity based on this option if population decentralisation is not carried out. However, the studies show that these projects will entail very high costs (WSOM, 2014). Moreover, this option will cause dependence of Mashhad on external resources, which violates the principles of sustainability.

Option 2 Determination of the optimum population for 2016 based on the situation of water supply sources in this year taking into account the Dousti and Ardak dams (WSOM, 2014).

The situation of water supply sources in 2016 taking into account the Dousti and Ardak dams is presented in Table 5.

Table 5 The situation of water supply sources in 2016 (taking into account the Dousti and Ardak dams

Production	(*Millions of cubic metres per year*)	
The water provision plan of 1395	Wells	126
	Dousti dam	65
	Toroq dam	8
	Kardeh dam	3
	Ardak dam	5
	Springheads and subterranean	6.8
	Total (production capacity)	213.8

The following steps are taken to determine the optimum and surplus populations based on option 2:

Step 1 The extent of water shortage for the population of Mashhad is calculated first. For this purpose, the water needs of pilgrims (8.6 million cubic metres annually) is deducted from the production capacity (213.8 million cubic metres), which yields 205.2 million cubic metres.

Step 2 The difference between the mean annual water needs of the resident population (249.5 million cubic metres per year) and the result of the first step (205.2 million cubic metres annually) is calculated to determine the volume of water shortage for the resident population per year (which is 44.3 million cubic metres annually).

Step 3 To determine the surplus population, the quantity of annual water shortage of the resident population (44.3 million cubic metres) is divided by 365 and then multiplied by 109 to obtain the result (12 * 107 litres per day). Next, based on the per capita formula (per capita of 218 litres per day), the surplus population is determined (550,459 people). Therefore, based on option 2, the optimum population for 2016 is 2,575,541 people.

Even with dependence on outside spheres of influence, Mashhad will face water shortages and surplus population. It must also be mentioned that the Dousti dam cannot be relied on in the long-term. In this option six projects are under study that must be implemented. Implementation of these projects will entail high costs and will violate the principles of sustainable development.

Of course, water supply system management must also be emphasised to minimise losses in water supply systems. Based on statistics for 2016, the predicted per capita water loss is 48.1 litres per day. The standard per capita loss is 35 litres per day, which must be achieved in Mashhad by 2041 (WSOM, 2014). Furthermore, although millions of pilgrims are a considerable economic support, they have led to increased annual demand for water. The monthly demand for drinking water in summer is 140% higher than the mean monthly demand during the year. Based on predictions, the population of pilgrims who stay in Mashhad for three days will reach 29,269,000 people by 2041. 20 to 80% of water shortage during 2021–2041 will be related to pilgrims.

The sum of the above factors, in addition to Mashhad being in an arid region, has caused water provision and distribution in this city to face critical and fragile conditions. Therefore, to plan and manage water resources, it must be emphasised that the extra population is the minimum figure which should be decentralised from Mashhad.

4 Conclusions

As the second most populous metropolis in Iran and the second largest religious site in the world, Mashhad has been faced with increasing population and tourists. This rising growth rate has led to increasing demands for water, and these conditions have made Mashhad an open system with linear metabolism. Increased demand has led to a mean annual drop in groundwater level of 13 metres in a 16-year period.

Mashhad has become dependent on areas outside its spheres of influence and on non-renewable resources to meet the increasing demand for water. The authorities have studied solutions to provide the required water and to prevent a regional and national crisis. These include the construction of the Dousti dam (which began in 1993). However, with growing urban development and continuing drought, this dam has not solved the water shortage problem. The water it now holds is a quarter of its capacity, and half of this belongs to Turkmenistan. Therefore, it is not a reliable long-term water supply source. The Ardak dam will entail considerable costs as for every kilometre of the pipeline required to supply water for Mashhad 2,403 dollars must be spent. The date for the completion of the project to substitute the effluents from wastewater treatment facilities cannot be predicted because of urban development and lack of funds. At present, only one-third of wastewater is treated. The other two proposed projects will increase the dependence of Mashhad outside its spheres of influence and thus violate the principles of sustainable development as this prefers controlling city size and preserving natural resources to providing water from places far away.

Mashhad is not a sustainable city based on Hutton's urban metabolism. The current development of the province and Mashhad is dependent on semi-fossil water resources only a part of which are renewable and the remaining part will be out of the water cycle for a long time. Therefore, in option 1 (not taking the Dousti and Ardak dams into consideration) and in option 2 (taking the Dousti and Ardak dam into consideration) 89% and 59% of the total produced water is extracted from groundwater resources, respectively.

Results show that, based on the two options of WSOM for providing required water in 2016, and taking pilgrim water into consideration, the city has a surplus population of 1,192,660 and 550,459 people based on options 1 and 2, respectively. The optimum populations of Mashhad based on options 1 and 2 are 1,933,340 and 2,575,541 people, respectively. Furthermore, it can be said that, even with dependence outside its sphere of influence, Mashhad will still have a surplus population. The Mashhad plain has 2% of the groundwater resources in the province but houses 65.97% of the population. At present the population in Mashhad is 12 times more than the second main city in this province.

The proposed solution for moving towards sustainability is decentralising the population within Mashhad and changing from a single to a multiple centred structure in RKP. The models proposed by Hutton must be used to guide the urban form from one that is completely dependent on external resources to sustainable urban forms. The model of redesigning cities raises many of the basic assumptions related to compact cities, especially the model of an independent city that emphasises reduced dependence on external resources, demand management, and wastewater recycling.

To utilise these models in Mashhad, the urban wastewater project must receive greater attention from responsible authorities. In general, decentralising population, upgrading people's culture regarding water consumption, managing water supply systems to reduce water loss, and increasing water prices, can be effective steps to improve the situation of water resources. Future researchers are recommended to study decentralising the population of Mashhad and directing the mono-central structure of RKP toward a multi-central structure.

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