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Research Paper

Water Resources Management by Simulation under Virtual Water Scenario in Agricultural Sector, Case Study: Hirmand Catchment, Iran

Ali Sardar Shahraki [a,], Javad Shahraki [b] and Seyed Arman Hashemi Monfared [c]*

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Abstract

Due to the frequent drought periods, water consumption increase, and competition of different water-using sectors, the Hirmand catchment is in a critical water status in the Sistan Region. This threat has been intensified in recent years. To cope with this problem, we must pay more attention to different types of water use such as virtual water as a water saving method. The present study calculates virtual water demand of agricultural products in the Sistan Region in the cropping year of 2013-2014 using water evaluation and planning (WEAP) system. Furthermore, impacts of the implementation of the virtual water scenarios are predicted on water resources and consumption over the 2015-2030 period. Results show that tomato and alfalfa have less virtual water demand despite their high water requirements due to their high production yield. Furthermore, wheat and barley have the highest virtual water demand. Also, the results of the WEAP model reveal that in the virtual water scenario, the mean annual water demand is lower than the current account (61% for net efficiency, 17% for current efficiency). Consequently, unmet demand will be reduced about 383 million m^3. Therefore, given the prevalence of drought in the region, it is appropriate to implement this scenario to protect water resources. Hence, it is highly recommended to orient planning and investment in agricultural development projects of the Sistan Region with the concept of virtual water.

Keywords:
Virtual water, agricultural sector, water resource management, simulation, Hirmand catchment

[a] Assistant Professor, Department of Agricultural Economics, University of Sistan and Baluchestan, Iran
[b] Associate Professor, Department of Agricultural Economics, University of Sistan and Baluchestan, Iran
[c] Associate Professor, Department of Civil Engineering, University of Sistan and Baluchestan, Iran
* Corresponding author's email: a.s.shahraki@eco.usb.ac.i

INTRODUCTION

As water resources become further emphasized due to growing levels of total demand (agricultural, urban, and environmental sectors), the management of this scarce resource has gained strategic significance (Abbaspour et al., 2009; Shahraki et al., 2012). More than 90% of the total water withdrawal in Iran is consumed for irrigation in the agricultural sector (Ardakanian, 2005). To manage water resources in an efficient way, decisions need to be improved at three levels. The first is the consumer level, where technology and price play key roles. At the second level, a selection has to be made on how to manage and allocate water resources to the different sectors in catchments or river basins. Governments allocate water to serve specifics goals, presumably at the expense of other alternative goals. Water allocation can be more or less efficient depending on the amount allocated to its different uses. Hence, at the third level, researchers discuss water allocation efficiency (Hoekstra & Hung, 2005).

In this context, virtual water is one of the water efficiency indicators emerged as s a new concept in recent years to attract water planners and experts' attention at the regional, national and international levels. At the global level, water efficiency can be increased by trading virtual water through the wet and dry areas. Virtual water is defined as the water consumed in the production process of a crop. Not only is virtual water produced in agriculture but it also affects industry and service sectors. Virtual water refers to the amount of water used during the growth and production process and also embedded in this manner. Thus, trade of agricultural products at the place of production in different areas of internal and external is along with the virtual water trade at national and international level. Nowadays, according to the integrated water resources management, the concept of virtual water can play a significant role in efficient management and allocation of limited water resources (Allan, 1998).

One of the most important watersheds in Iran is the Hirmand cross-border catchment shared between Iran and Afghanistan with a substantial role in people's lives in the Sistan Region (Sardar Shahraki et al., 2018). Local livelihood highly depends on the Hirmand discharge. Sistan plain has an arid climate and it has been suffering from water resource crisis due to the very low rainfall (50 mm/year) and high evaporation rates (4000-5000 mm), its complete dependence on the Hirmand river, and the droughts of the last two decades with extensive negative impacts on the local economy, agriculture, employment, and environment (Rashki et al., 2012). Agriculture in the region has faced high volatility in the amount of cultivated area and production performance over the last decade (Shahraki & Sardar Shahraki, 2014).

In addition to water shortage, other threatening factors such as mismanagement, lack of knowledge, fierce competition of the domestic and environment sectors with the agriculture sector over water resources, erosion, etc., have been the reasons for less production and underdeveloped agriculture of the region. In recent years, an extensive investment has been made in the agricultural sector in the Sistan Region and many facilities have been created in the context of development projects for the supply, transmission, and distribution of water. But it seems that the projects had been unable to achieve their main goals appropriately. Therefore, it is necessary to review agricultural administrative affairs and attempt to enhance irrigation efficiency. By using virtual water, one can improve irrigation efficiency and agricultural development.

Due to drought conditions in the Sistan Region, irrigation management based on virtual water projects can help to save water in this area. In this sense, the goal of the present study is to simulate the Hirmand basin and water resources management by using the concept of virtual water for agricultural development in the Sistan Region.

Various studies have been conducted on virtual water. For example, to quantify the flow of virtual water trade between nations, Hoekstra and Hung (2005) investigated international trade of agricultural products over 1995-1999. Their results indicated that 13% of the water consumed for production in the world was not used for domestic use; rather, it was virtually exported. In the studied years, the US, Canada, Thailand, Argentina, and India were the largest importers of virtual water. Iran has imported, on average, 29.1 year^{-1} gm^3 of virtual water. Nineteenth countries were the most important regions for virtual water.

Zimmer and Renault (2003) estimated virtual water trade between nations in 2000 at 1340×10^9 m^3. Oki and Kanae (2004) examined virtual water trade and global water resources. Their results showed that the trade saved virtually 450 billion m^3 of water. Ramirez and Rogers (2004) investigated the flow of virtual water trade and its relationship with trade liberalization. Their results revealed that Japan, Mexico, Russia, Korea, and Egypt were the main importers of virtual water in the studied year, respectively. Hanasaki et al. (2010) estimated the status of virtual water import and export of agricultural and livestock commodities on a global scale by using a hydrological model.

Studies show that the concept of virtual water is interesting to researchers. However, these studies have examined virtual water application in present or past time periods. Therefore, it is necessary to investigate virtual water effects on water resources and water usage in the future, for which simulation models are needed. These models try to guide decision-makers by informing them about the impact of development projects and water supply and demand (e.g. virtual water) on a catchment. Simulation models determine what will happen if a management policy is applied.

Water supply should be secured for all demands, especially when it comes to meeting the basic human needs of the communities that have been deprived for a long time. Nonetheless, water should not be simply released to meet the increasing demands of the agriculture, service, and industry sectors and other productive demands; rather, care should be given to satisfy the requirements of aquatic ecosystems and ecological reserves (Lévite et al., 2003).

Models such as River Basin Simulation Model (RIBASIM), Water balance Model (WBalMo), Model Simulator (MODSIM), MIKE Basin, Multi-Sectoral, Integrated and Operational Decision Support System (MULINO-DSS), and Water Evaluation and Planning System (WEAP) have been used for planning purposes in the basins or water quality and sedimentation transport, river flow routing, evaluation alternative water allocation policies and water demand analysis (Mugatsia, 2010).

WEAP is a model that has been used for the simulation of water resource systems in numerous studies. Examples of studies in that the WEAP model has been applied include Hollermann et al. (2010), Vonk et al. (2014), Li et al. (2015), Dimova et al. (2014), Yaqob et al. (2015), Sardar Shahraki et al. (2016), Condom et al. (2011), Choi et al. (2010), and Mounir et al. (2011). In the present study, virtual water demand of agricultural crops is examined in the Sistan Region, Iran in the cropping year of 2014. The contribution of the study is the prediction and evaluation of the implementation of virtual water scenario in the medium term (horizon 2030) by using the WEAP model at the Hirmand catchment In Iran.

METHODOLOGY

Different stages of virtual water demand are presented below. It is followed with an explanation of the WEAP model.

Virtual water model (VWM)

Average water demand of a certain crop has been estimated separately for each respective nation on crop water requirements and crop yields on the basis of FAO data:

$$SWD_c = {CWR_c}/{CY_c}$$

in which *SWD* is the particular water demand (m^3ton^{-1}) of crop *c*, *CWR* is the crop water requirement (m^3ha^{-1}), and *CY* is the crop yield ($ton\ ha^{-1}$). The crop water requirement *CWR* is estimated from the accumulated crop evapotranspiration ET_c (in mm day^{-1}) in whole the growing period. The crop evapotranspiration ET_c is produced by multiplying the crop coefficient *Kc* in the reference crop evapotranspiration ET_0 as below:

$$ET_c = K_c \times ET_0$$

The concept of 'reference crop evapotranspiration' was first raised by FAO to study the evaporative demand of the atmosphere, independent of crop type, management practices and crop development in the agriculture sector. Climatic parameters are the only factors affecting ET_0. The reference crop evapotranspiration ET_0 is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed fixed crop surface resistance of 70 s m^{-1}, an albedo of 0.23, and a crop height of 12 cm. This reference crop evapotranspiration closely resembles the evapotranspiration from a wide surface of actively growing, completely shaded ground green grass cover of uniform height supplied with adequate water (Smith et al., 1992). ET_0 is computed on the basis of FAO's Penman–Monteith equation (Smith et al., 1992; Allen et al., 1994, 1998):

$$ET_0 = \frac{0/408\Delta(R_n - G) + \gamma 900/(T+273)U_2(e_a - e_d)}{\Delta + \gamma(1+0/34U_2)}$$

Based on the above equation, ET_0 is the reference crop evapotranspiration (mm day-1), Rn is the net radiation at the crop surface ($MJm^{-2}\ day^{-1}$), G is the soil heat flux ($MJm^{-2}\ day^{-1}$), T is the average air temperature (°C), U2 shows the wind speed measured at the height of 2 m (m s^{-1}), ea represents the saturation vapor pressure (kPa), ed is the actual vapor pressure (kPa), ea_ed are the vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa $°C^{-1}$), and describes the psychometric constant (kPa $°C^{-1}$). The crop coefficient serves as an accumulation of the physiological and physical differences between the reference crop and a certain crop. The crop coefficient accounts for relative aerodynamic resistance and the actual crop canopy to the hypothetical reference crop.

WEAP model

FAO crop requirements assuming a demand site are computed with agro hydrological processes and simplified hydrological such as rainfall agriculture, crop growth emphasizing irrigated, precipitation and evapotranspiration. Clearly, non-agricultural crops can be included as well. Figure 1, depicts the flowchart of the models used in the present study.

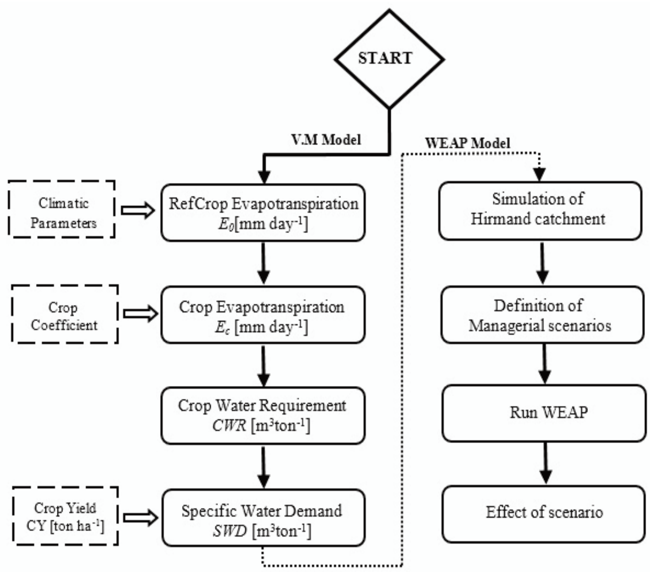


Figure 1. Schematic of the simulation methodology

Some scenarios should be defined in the study area for the simulation of water resources. The selected scenarios of water demand management in this study are selected as follows:

Scenario 1 (SC1): This scenario is the default scenario (reference scenario) and represents the status quo with past management and indeed is used as the basis for comparison with other scenarios. In other words, if the Hirmand catchment considers to be managed under the current situation and past policies, what will be the status of the water resource of the catchment by 2030?

Scenario 2 (SC2): Virtual water net ($SC_{2.1}$); Virtual water with an efficiency of 36% ($SC_{2.2}$). Table 1 shows the site specifications of water demands and supplies in the Sistan Region.

Table 1
Sites Specifications of Demand and Supply Water in the Sistan Region

$Reservoir_1$	Inflow of the Sistan River enters this reservoir. Total storage is 660 MCM and dead storage is approximately 320 MCM. It is the main source of water for agriculture, urban uses and wetlands demands.	**Sistan & Paryan River**	Initially the Sistan River flows enter $reservoir_1$ and the surplus water will be used to meet the Zh.Agr and Zb.Agr demands. Finally, the Sistan River releases into Hamoon wetland. The Paryan River provides Agr_3 water demand.
$Reservoir_2$	Surplus water of reservoir1 enters this reservoir. Total storage is 820 MCM and the inactive zone is approximately 200 MCM.	**$City_6$**	Population of this city is 3,300 people; Annual water use rate is 46.01 m^3/person
$City_1$	Population of this city is 600,000 people; Annual water use rate is 55.56 m^3/person	**Rural**	Population of this area is 266,000 people; Annual water use rate is 54.75 m^3/person
$City_2$	Population of this city is 142,000 people; Annual water use rate is 58.02 m^3/person	**Zh.Agr**	Cultivated area is about 49,000 ha; Water use rate[b] is 8750 m3/ha
$City_3$	Population of this city is 14,000 people; Annual water use rate is 53.34 m^3/person	**Zb.Agr**	Cultivated area is about 54,000 ha; Water use rate[b] is 8450 m^3/ha
$City_4$	Population of this city is 6,700 people; Annual water use rate is 57.37 m^3/person	**M.Agr**	Cultivated area is about 32,000 ha; Water use rate[b] is 7950 m^3/ha
$City_5$	Population of this city is 72,000 people; Annual water use rate is 47.97 m^3/person	**Lake**	Total area is about 400,000 ha, Water rights approval[c] 60MCM/Year

[a] Million m^3;
[b] This rate is obtained according to the dominant cropping pattern of each area;
[c] This water rights are determined for 2,500 hectares of Hamoon wetlands.

In the Sistan Region there are three agricultural sectors, seven drinking water sectors (six urban and one rural) and a demand for the Hamoon wetlands sector. The priority of water allocation in this region is in the order of drinking, agriculture, and wetland. In Figure 2, conceptual schematic of the Hirmand catchment and water situation of the Sistan Region is shown for supply and demand water sites by using WEAP software.

RESULTS AND DISCUSSION

The features of the crops in three agricultural subsections in the Sistan Region are presented in Tables 2-4 in terms of crop type, cultivated area, water requirement, yield, and virtual water calculation (net efficiency and current efficiency (36%)) for the 2013-2014 cropping year.

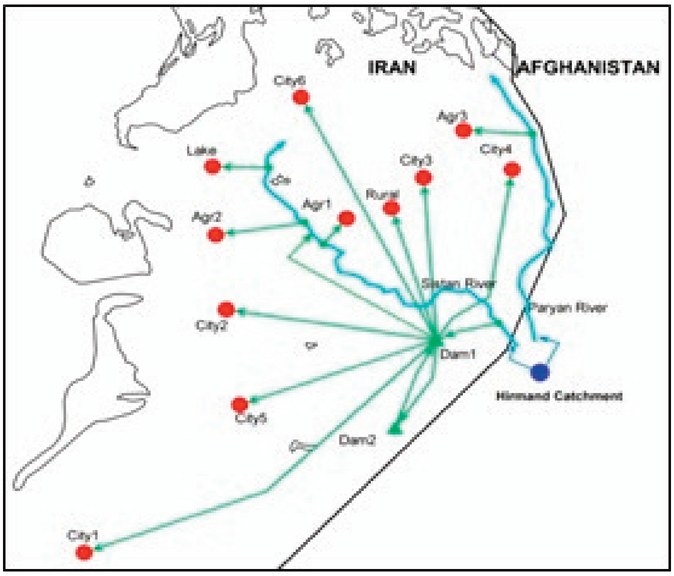


Figure 2. Schematic illustration of Hirmand catchment

Table 2
The Features of Crops and Demand for Virtual Water at Agricultural Subsection Zb.Agr In The 2013-2014 Cropping Year

Crop	Cultivated area (ha)	Water requirements (m^3/ha)	Yield (kg/ha)	Virtual water (Net) (m^3/kg)	Virtual water (efficiency 36%) (m^3/kg)
Wheat	10306	5360	1679	0.31	8.87
Barley	896	5000	1647	0.33	8.43
Bean	49	3440	1000	0.29	9.56
Sunflower	15	7000	1500	0.21	12.96
Sesame	6	7360	1000	0.14	20.44
Onion	51	7490	30000	4.01	0.69
Tomato	26	10710	30000	2.80	0.99
Melon	280	4500	15000	3.33	0.83
Watermelon	506	7330	16000	2.18	1.27
Cucumber	4	3760	13000	3.46	0.80
Alfalfa	216	22440	18000	0.80	3.46
Corn	12	6590	23000	3.49	0.80
Sorghum	1300	3462	63207	18.26	0.15
Medicinal plants	6	1500	1000	0.67	4.17
Garden crops	1413	11000	8000	0.73	3.82
Sum	15086	106942	224033	27.83	77.26
Average	1005.73	7129.47	14935.53	2.73	5.15

According to Table 2, wheat had the highest acreage in Zb.Agr. In fact, it accounted for 62% of the total cultivated area. The lowest cultivated area was for cucumber. Sorghum had the highest yield in this subsection. The lowest yield was related to beans, sesame, and medicinal plants.

According to Table 3, garden crops had the highest cultivation area and tomato had the lowest cultivation area in Zh.Agr. In addition, sorghum and sesame had the highest and lowest yield, respectively.

Table 3
The Features Crops and Demand for Virtual Water at the Agricultural Subsection Zh.Agr in The Crop Year 2013-2014

Crop	Cultivated area (ha)	Water requirements (m^3/ha)	Yield (kg/ha)	Virtual water (Net) (m^3/kg)	Virtual water (efficiency 36%) (m^3/kg)
Wheat	11485	5360	2407	2.23	6.19
Barley	2764	5000	1850	2.7	7.51
Bean	274	3440	1200	2.87	7.96
Sunflower	1	7000	1500	4.67	12.96
Sesame	2	7360	500	14.72	40.89
Onion	101	7490	30000	0.25	0.69
Tomato	0.5	10710	30000	0.36	0.99
Melon	1400	4500	25000	0.18	0.50
Watermelon	1200	7330	34000	0.22	0.60
Cucumber	0.5	3760	13000	0.29	0.80
Alfalfa	695	22440	35000	0.64	1.78
Corn	183	6590	31000	0.21	0.59
Sorghum	1930	3462	40000	0.09	0.24
Medicinal plants	5	1500	1000	1.5	4.17
Garden crops	11787	11000	8000	1.38	3.82
Sum	31828	106942	254457	32.31	89.69
Average	2121.86	7129.46	16963.8	2.15	5.98

Table 4
The Features of Crops and Demand for Virtual Water at the Agricultural Subsection M.Agr in the 2013-2014 Cropping Year

Crop	Cultivated area (ha)	Water requirements (m^3/ha)	Yield (kg/ha)	Virtual water (Net) (m^3/kg)	Virtual water (efficiency 36%) (m^3/kg)
Wheat	9161.33	5360	1595.67	3.36	9.33
Barley	1162.33	5000	1335	3.75	10.40
Bean	178	3440	900	3.82	10.62
Sunflower	15.33	7000	1066.67	6.56	18.23
Sesame	3.33	7360	1000	7.36	20.44
Onion	150.33	7490	23116	0.32	0.90
Tomato	8.67	10710	18333.33	0.58	1.62
Melon	2058.33	4500	17900	0.25	0.70
Watermelon	1494.33	7330	21366.67	0.34	0.95
Cucumber	4	3760	14000	0.27	0.75
Alfalfa	01.67	22440	20833.33	1.08	2.99
Corn	239.33	6590	41666.67	0.16	0.44
Sorghum	1655.33	3462	30266.67	0.11	0.32
Medicinal plants	2.33	1500	833.33	1.8	5.00
Garden crops	1403.67	11000	8000	1.38	3.82
Sum	17938.31	106942.00	202213.34	31.14	86.51
Average	1195.89	13367.75	25276.67	2.08	5.77

In M.Agr, the highest and the lowest cultivated areas were related to wheat and medicinal plants, respectively. In this subsection, the highest yield was for corn and the lowest for medicinal plants. The greatest demand for water in all three subsections was related to alfalfa. Regarding water requirements and yields in all three subsections, the highest and the lowest demand for virtual water were observed in sesame and sorghum, respectively.

Table 5 shows the results of the WEAP model for total water demand in 2030 for different sections and two scenarios of reference and virtual water (net and current efficiency) separately. According to the results of virtual water scenario, the demands of domestic and environmental sectors will not change. But, water demand in $SC_{2.1}$ for Zb.Agr, Zh.Agr and M.Agr will be reduced to approximately 5300, 4100 and 3100 million m^3 in total of 16 years (2015-2030).

Also, the total demand of different sectors (sum of 16 years) is decreased from 20660.8 in the reference scenario to 8042.24 in $SC_{2.1}$ and 17139.36 in $SC_{2.2}$. On the other hand, unmet demand (sum of 16 years) in the reference scenario is about 44% for Zb.Agr and Zh.Agr and is about 28.4% for M.Agr. These figures are 32.11%, 31.02% and 0.2% in $SC_{2.1}$ and 41.88%, 41.92% and 23.49% in $SC_{2.2}$, respectively.

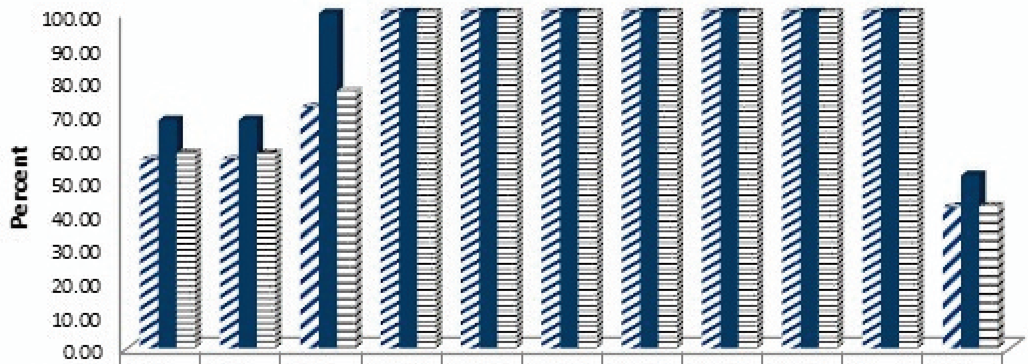
Therefore, in virtual water scenario, the amount of unmet demand is greatly reduced. Hence, unmet demand of about 91 million m^3 of water in the virtual water scenario is decreased compared to the reference scenario. Also, under virtual water scenario, more water will be made available to the lake. Recognizing the importance of drinking water allocation in the region and giving first priority to this sector, its demand was fully estimated (100%). When compared to the status quo, average water saving per year will be about 788 million m^3 in $SC_{2.1}$ and about 220 million m^3 in $SC_{2.2}$.

Table 5
The Output of WEAP Model in the Different Sectors Under Two Reference and Virtual Water Scenarios

Scenarios	Type of demand	Agriculture sector			Drinking sector							Environmental sector	Sum
		Zb.Agr	Zh.Agr	M.Agr	$City_1$	$City_2$	$City_3$	$City_4$	$City_5$	$City_6$	Rural	Lake	
SC1	A	7544.96	6860	4471.04	416	148.48	13.76	6.72	6.24	2.72	230.88	960	20660.8
SC2.1	A	2215.2	2768.88	1363.36	416	148.48	13.76	6.72	6.24	2.72	230.88	960	8042.24
SC2.2	A	6153.12	5453.44	3748	416	148.48	13.76	6.72	6.24	2.72	230.88	960	17139.36
SC1	B	3323.04	3024.64	1270.04	0	0	0	0	0	0	0	557.76	8175.84
SC2.1	B	711.52	859.04	3.04	0	0	0	0	0	0	0	466.24	2039.84
SC2.2	B	2577.12	2286.08	880.48	0	0	0	0	0	0	0	554.88	6298.56
SC1	C	471.56	428.75	279.44	26	9.04	0.86	0.42	0.39	0.17	14.43	60	1291.3
SC2.1	C	138.45	167.43	85.21	26	9.04	0.86	0.42	0.39	0.17	14.43	60	502.64
SC2.2	C	384.57	340.8	234.25	26	9.04	0.86	0.42	0.39	0.17	14.43	60	1071.21
SC1	D	207.69	189.04	79.41	0	0	0	0	0	0	0	34.86	510.99
SC2.1	D	44.47	53.69	0.19	0	0	0	0	0	0	0	29.14	127.49
SC2.2	D	161.07	142.88	55.03	0	0	0	0	0	0	0	34.68	393.66

Amounts are in million cubic meters.
A: Total water demand for 16 years (from 2015 to 2030) separately for different sectors under two reference and virtual water scenarios.
B: Total unmet demand for 16 years (from 2015 to 2030) separately for different sectors under two reference and virtual water scenarios.
C: Average total demand for each year (between 2015-2030) separately for different sectors under two reference and virtual water scenarios.
D: Average unmet demand for each year (between 2015-2030) separately for different sectors under two reference and virtual scenarios.

Figure 3, shows the average percent of met demand for different sectors under reference scenario (SC1) and virtual water scenario (SC2) over 2015-2030.



	Zb.Agr	Zh.Agr	M.Agr	City1	City2	City3	City4	City5	City6	Rural	Lake
SC1	55.96	55.91	71.58	100	100	100	100	100	100	100	41.90
SC2.1	67.88	67.93	99.78	100	100	100	100	100	100	100	51.43
SC2.2	58.12	58.08	76.51	100	100	100	100	100	100	100	42.20

Figure 3. Comparing the percent of met demand for different sections under the virtual water (SC_2) and reference scenarios (SC_1) over 2015-2030.

According to the results (Figure 3) compared to the reference scenario, the average satisfied demand is increased by 11.9%, 12% and 28% in SC2.1 and 2.16%, 2.17% and 4.93% in SC2.2 in Zb.Agr, Zh.Agr and M.Agr as compared to virtual water scenario over 2015-2030, respectively. In both scenarios, 100% of demand for drinking sector was supplied. Also, the increase in the amount of met demand in the environmental sector (Lake) is 9.5% in SC2.1 and 1% in C2.2 as compared to reference scenario.

CONCLUSION

In this study, virtual water demand was first estimated for various agricultural crops of the Sistan Region in the 2013-2014 cropping year. The Hirmand catchment was simulated using the WEAP model in order to assess the effect of implementing the concept of virtual water and to compare it with the current account. Results of the two main scenarios were analyzed. According to the results, the following recommendations can be drawn:

Calculating the water requirement for agricultural production in the region shows that there are crops with high water demands (e.g., tomato, alfalfa, corn, and garden crops). But, their special water demand (virtual water demand) is lower due to their high yield. It is suggested to enhance the yield of other crops through the improvement of production efficiency and water use efficiency.

Although it is important to optimize cropping pattern in the context of virtual water, according to the results, crops like sesame, wheat, and barley have the highest demand for virtual water. Therefore, given the drought conditions of the Sistan Region, we should aim to use crops with higher yield and lower water demand in the cropping patterns in order to contribute to the sustainability of water resources. Although the amount of water demand in virtual water scenario decreases when compared to the current account, relying on only this fact will lead to reducing the number of plants that are produced in the region and this will, in turn, lead to more unemployment. Therefore, it is necessary to adopt specific policies so that the challenges of limited water resources in the region are considered and also patterns are developed based on the lowest water requirement. As well, attention should be given to issues such as comparative advantage, employment, social profitability, and the long-term food security of the region.

Since the wetlands play a vital role in the ecological conditions in this region, their degradation will create social problems in addition to economic problems. According to the results, in the scenario of virtual water, more water demand will be supplied for the environmental sector (wetland) and unmet demands in this sector will be reduced. Hence, to protect wetland ecosystems, relevant organizations should seriously consider the adoption of this scenario.

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