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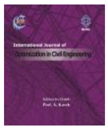

DETERMINING THE OPTIMAL POINT IN ARID BASINS USING WATER-ENERGY NEXUS APPROACH

M.M. Noruzi*, † and F. Yazdandoost
Department of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran

ABSTRACT

The excessive focus on water mounts a challenge to the sustainable development. Energy is another aspect that should be taken into account. *Nexus* approach is characterized by an equal emphasis on energy and water spheres. In arid areas, like the city of Kashan, Iran, non-conventional waters (e.g. desalinated and recycled waters) have been considered as an alternative resource of water. *Nexus* warns that alternative resources should be tapped in with consideration of the costs and environmental impacts of the energy. In this study, the allocation of demands and supplies in the basin are primarily modeled by *WEAP*. Then, the energy required to generate water is simulated by *LEAP*. Finally, using the *optimization* method, the desirable volume of non-conventional water is estimated. The results suggest that the maximum capacity of the non-conventional water is not necessarily the optimal point. Thus, despite high potentials for producing non-conventional water, caution should be practiced in setting proper limit for the production.

Keywords: nexus approach; recycling; desalination; optimal point; genetic algorithm.

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1. INTRODUCTION

The term *Nexus* approach indicates the inseparable link between water and energy. The Water-Energy *Nexus* suggests that any measure adopted to tap into one of these resources often have repercussions for other resources. In other words, the term water - energy *Nexus* covers all dimensions related to the use of water for energy production and energy for water production [1].

In the arid states in the Middle East, given high potentials of diversified energy sources, the aspect of *Nexus* approach focused on energy consumption for the water production has

*Corresponding author: Department of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran
†E-mail address: mnoruzi@mail.kntu.ac.ir (M.M. Noruzi)

gained more significance compared to water consumption for the purpose of energy generation. The Middle East states have no alternative but to use energy for water production. The *Nexus* approach to *energy for water* involves utilizing energy for the supply, transfer and treatment of water, desalination, wastewater collection, recycling, etc. For example, in California, the amount of energy used for water supply and transfer is 1.1 KW/m^3, water treatment is 3.03 to 4.23 KW/m^3, water distribution is 0.2 to 0.3 KW/m^3 and wastewater collection and recycling is 0.3 to 1.3 KW/m^3 [2]. For the production of non-conventional water source such as desalinated seawater and recycling water, 3 to 4 KW/m^3 and 0.3 to 3.6 KW/m^3 of energy is required, respectively [3].

To overcome water shortage in arid basins, the non-conventional waters such as desalinated or recycled waters have gained increasing attention. Non-conventional water production is an energy-intensive process. The elimination of water shortage using non-conventional water derived from desalination is a highly energy-intensive process compared to the conventional water [4].

There are still concerns whether tapping into desalinated or recycled waters is a proper strategy to alleviate water shortage. Thus, some argue that there should be a limit for the amount of non-conventional water generation. In some parts of Europe, low energy consumption is one of the main parameters of desalinated water [5]. The distance between the resource of salty water and the desalination plant, and the density of contaminants in the wastewater are other concerns associated with the non-conventional water production [6]. The parameters such as energy demand, air pollution and environmental impact have been addressed in studies on the process of non-conventional water production [7]. Accordingly, limits such as impurity, salinity, brine concentrate, plant site [8], thermal and electrical energy requirements, total dissolved salts and the temperature of effluent exiting desalination plants have been proposed as selection criteria for non-conventional water technologies [9]. Public acceptance based on socio-demographic and psychographic trends has been another criterion related to non-conventional water production [10]. For potable recycling water, the water quality index based on toxicity [11], and the number of re-use are of paramount importance. The long-term and frequent use of recycled water is not recommended, even for agricultural irrigation [12]. Some studies have discussed constraints and criteria such as the cost of modernizing desalination plants or the cost of raw materials [13]. Also, organic micro-pollutants or chemical residues remaining after secondary treatment are constraining factors with respect to the use of recycling water [14]. To identify the optimal point of non-conventional water production, suitable criteria should be taken into account. In China, pumping water from underground requires massive energy sources while consuming this energy produces more than 33 tons of CO_2 equivalent [15]. CO_2 is a major constituent the greenhouse gas, which has aggravated global warming in recent years. Therefore, energy is a vital factor for determining the production of non-conventional-water. However, despite its importance, scant attention has been paid to a general framework to figure out the relationship between water-energy and greenhouse effect generated by gas emissions.

In this study, two criteria for identifying the permitted amount of brackish and recycled water use have been proposed: energy consumption and environmental impact of burning energy. Obviously, energy is essential for the production of water, and failure to consider energy criteria will incur exorbitant costs and damages.

Kashan basin in the central desert of Iran, which deals with severe shortage of conventional water resources, was chosen as the case study. In this basin, we identified the optimum/ permitted limit of water production from non-conventional resources. The optimum limit was determined based on economic and environmental parameters associated with energy burning.

To achieve this goal, first conventional and non-conventional water resources in the arid basin were simulated using Water Evaluation and Planning model (*WEAP*) in accordance with the Integrated Water Resources Management (*IWRM*) perspective and the quantity of required water was predicted for the 2041 planning horizon [16]. Then, the energy was calculated by the Long-range Energy Alternatives Planning model (*LEAP*). Finally, using an optimization method, the optimal water-energy interaction was obtained [17]. The optimal point indicates a scenario under which energy and water shortage parameters are in an admirable balance. According to this study, stakeholders should not produce the desalination and recycled waters incalculably. The *nexus* approach ensures sustainable development in the region.

2. MATERIALS AND METHODS

2.1 Methods

2.1.1 Modeling of water resources

WEAP software is used for Integrated Water Resources Management. It is designed to stabilize scheduling in order to minimize water shortage (*Unmet Demand*). First, using this software, the model of resources (conventional and non-conventional) and demands (drinking, industry and agriculture) was constructed for the base year (i.e. 2014) and then calibrated with actual data in 2015. The scenarios were based on the regional Master Plan Documents. For the purpose of abridgement, considering the wide application of *WEAP* in water resources management, we have not provided in-depth details on this software. For more information, see [18]. To apply the *Nexus* approach to Water-Energy issue, it is necessary to link the *WEAP* water model to an Energy model with a dynamic proceeding.

2.1.2 Modeling of energy resources

The best energy model that can be linked to the *WEAP* water model is the one created by the LEAP software. *LEAP* offers a framework model, which allows the analysis and planning of the energy and environmental scenarios in the long term based on a combined approach to the sustainable development. The *LEAP* is founded upon a hierarchal and systematic mechanism. There are several methods for modeling *LEAP*, but consistent with the types of data available, *Final Energy Analysis* method was adopted. This method evaluates the amount of energy that is consumed in the final phase. For instance, the amount of electricity used in a water pump in the final phase can be measured. In this method, the energy demand can be calculated by multiplying consumption per capita by final energy intensity (Formula 1).

$$e = a \cdot i \qquad (1)$$

In the above formula, *e* and *i* are activity level and final energy intensity, respectively and *a* is the usage per person. In *final energy analysis* (FEA) method, there are two styles of modeling the demand side:

1. Bottom-Up/End-Use style
2. Top-Down/Economic style

In first style, each energy system is considered separately and they are then aggregated in the last phase. In the second style, the general energy consumption is considered. The latter is concerned with econometric and macro-oriented models. According to the results of the field study, the Bottom-Up/End-Use style was adopted in this research.

Here, the main issue is modeling the energy of water resources rather than all energy components. Hence, with this innovation, the virtual simulation or conceptualization technique was used. In fact, LEAP only models energy containers while water is not an energy container. Therefore, LEAP cannot be used to model water. However, since water is a fluid flow and energy carriers (e.g. gas or electricity) are fluid flow as well, water can be defined as a virtual energy carrier in the LEAP system. For this purpose, a few subcategories including treated water, transportation tunnel water, brackish well and etc were created in the *Transformation* section as virtual energy containers.

In this model, 1 m^3 of water is considered virtually as 1 Gigajoules energy. Using this technique, water can be added to the LEAP as a container of energy. To ensure the precision of the technique, results were compared with the actual energy in the base year. Afterwards, the energy model of LEAP was linked to the water model of WEAP.

In terms of internal structure, Application Programming Interface (API) is the factor that links LEAP to WEAP and is coded in these models. In operational step, nonetheless, the parameters that LEAP is expected to receive from WEAP is seen as the WEAP Value function (Fig. 1). A schematic of the model created in LEAP is shown in Fig. 2.

To illustrate carbon dioxide emission generated by energy consumption, Equivalent Carbon (EC) expression was used. The results derived from LEAP covered energy costs and EC weight generated by the energy consumption. Each group of conventional and non-conventional waters was divided into related water volume to compute their quantity per volume unit.

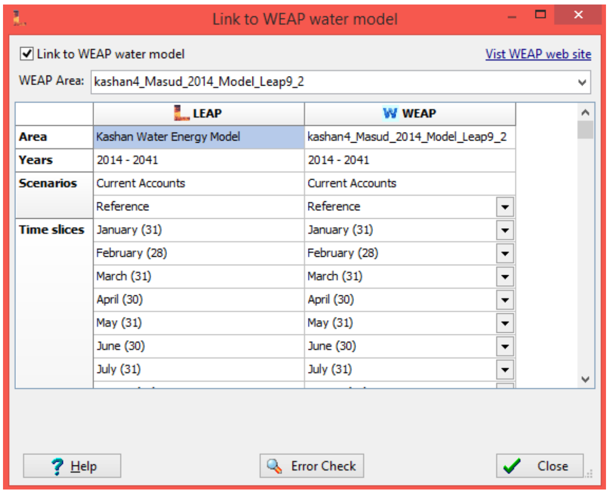

Figure 1. Advanced module for linking of two models

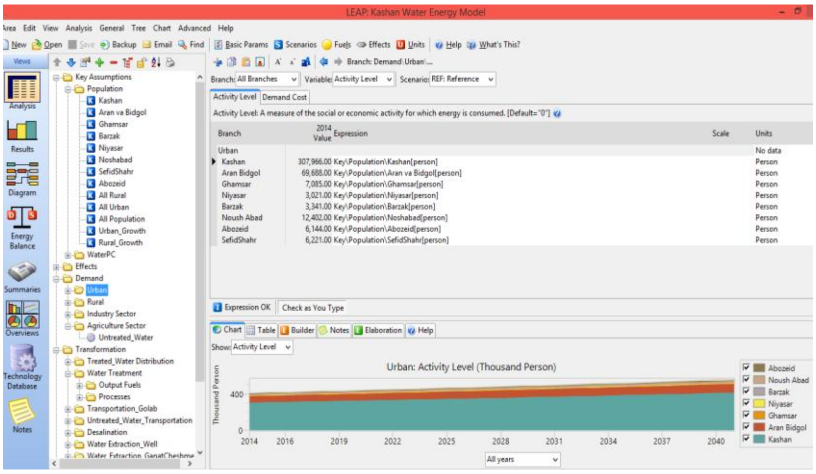

Figure 2. Schematic Model of Kashan Created in LEAP

2.1.3 Optimization of water and energy interaction point

The Genetic Algorithm is an optimization method that is widely used in water researches. The Genetic Algorithm is a highly efficient method that is employed to find proper solutions for water management problems around the world.

The solutions provided by the Genetic Algorithm are more effective than that of the classic algorithm with linear programming. Also, similar to the non-linear programming, it is not dependent on decision variables [19].

In this study, to optimize three equations (functions) of “unmet demand, energy cost and environmental impact”, the non-dominated sorting Genetic Algorithm (NS-GA) was utilized. NS-GA is suited for solving these problems since its results are more desirable than other methods [20]. Others has provided in-depth information about the NS-GA [20]. In the genetic algorithm [21], the above equations are considered as f (x), g (x) and h (x) in 2 to 4 equations.

$$f(x) = ADW - [(x_1 + \cdots + x_9) + (y_1 + \cdots + y_9) + (z_1 + \cdots + z_9)] \quad (2)$$
$$g(x) = Ax_1 + \cdots + Ax_9 + By_1 + \cdots + By_9 + Cz_1 + \cdots + Cz_9 \quad (3)$$
$$h(x) = Dx_1 + \cdots + Dx_9 + Ey_1 + \cdots + Ey_9 + Fz_1 + \cdots + Fz_9 \quad (4)$$

The parameters used in the above equations are as follows:

ADW: Anticipated Demand Water, i.e. water estimated by WEAP model;

x_i: Discharge of recycled water required in specified nodes of the model;

y_i: Discharge of desalinated water required in specified nodes of the model;

z_i: Discharge of conventional water required in specified nodes of the model;

A: Cost of energy used for producing 1 m^3 of conventional water;

B: Cost of energy used for generating 1 m^3 of non-conventional water;

C: Cost of energy used for producing 1 m^3 of recycled water;

D: Weight of equivalent carbon emission caused by generating 1 m^3 of conventional water;

E: Weight of equivalent carbon emission caused by generating 1 m^3 of desalinated water;

F: Weight of equivalent carbon emission caused by producing 1 m^3 of recycled water.

To apply the genetic algorithm, the above three equations were coded in the MATLAB program. Thus, in this study, based on the *Nexus* approach, the energy norm was also incorporated in the equations of water management. According to *Nexus* approach, water scarcity alleviation should not be implemented irrespective of energy consumption and its side effects.

2.2 Case study

The basin of Kashan is located between the Karkas Mountains in the west and the Great Salt Desert in the east of Iran. Located in the Isfahan city (Fig. 3), it is an arid and semi-arid area with an average rainfall of 100 mm [22]. The main problems of this basin are seasonal rivers, desertification, population growth, unsustainable agricultural development, and growth of crops with high water consumption [23]. Its UTM system in Zone 39 is 490855 to 602177 east longitude and 3719029 to 3819043 north latitude.

Kashan Basin stretches in an area of 1044300 ha, covering eight towns and twelve villages. For water modeling of these towns and its villages, nine nodes were defined in the WEAP software (i.e. eight nodes for cities, and one node for villages). In 2014, a total population of 460027 people lived in this basin and the average population growth rate was about 0.9. Conventional and non-conventional resources as well as basin demands in 2014 are depicted in Table 1.

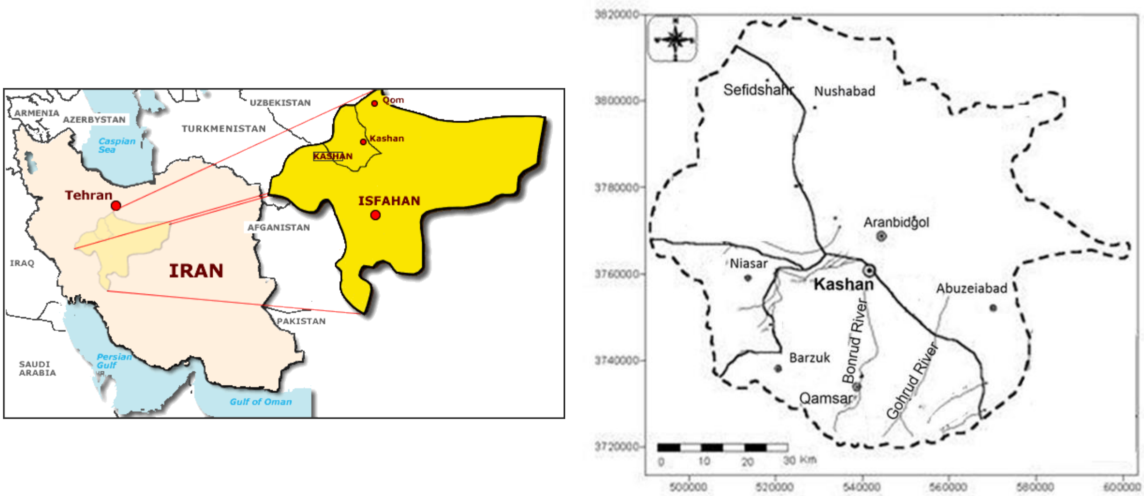

Figure 3. The Location of Kashan Basin

To compensate for the scarcity of water, the use of non-conventional waters such as recycled water obtained from wastewater and desalinated water obtained from brackish water is rapidly on rise and it is estimated to grow exponentially by year 2041. According to the Regional Master Plan, by the year 2041, the industry will be tripled, but the agriculture will remain constant. The recycled water is only used in the industrial sector [9]. In this research, the water demand of the final year has been taken into account, provided that it meets the minimum water shortage and energy cost criteria.

Table 1: Resources of Kashan Basin, 2014, MCM

Resource	**River**	**Aquifer**	**Transfer of neighborbasin by tunnel**	**Recycling water**	**Desalinated water**
Discharge	15.2	218	11	27.2	**4**

2. RESULTS

The predicted total water shortage (Unmet Demand) in the year 2041, as calculated by the WEAP modeling, will be 339.35 MCM. Of this figure, 322 MCM will be allocated to agriculture, 17 MCM to drinking and 0.3 MCM to industry (Fig. 4).

The non-conventional water used in this system does not represent the maximum of capacity of this basin. Thus, it may be argued that the total water shortage can be compensated by increasing the production of non-conventional waters. However, according to the *Nexus* approach, an important norm called Energy is presented to limit the production of non-conventional water.

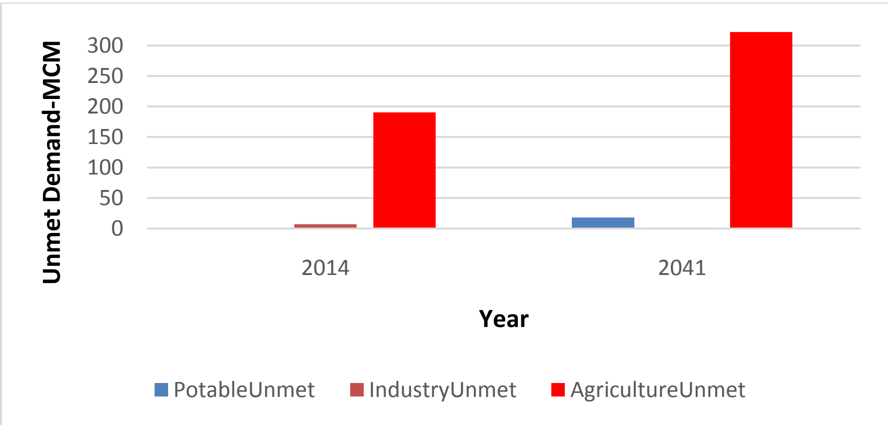

Figure 4. Water shortage in basic year and final year

The energy cost and EC generated by energy production are two subsets of the energy. In Table 2, the energy cost and EC generation obtained from the LEAP calculations for producing 1 m^3 of water is shown.

Table 2: Energy Cost and Environmental Effect in Kashan

Parameters	Unit	Conventional Water	Desalinated Water	Recycling Water
Cost of Energy	$/m^3$	A=0.4	B=0.6	C=0.1
Carbon Produced	Ton/m^3	D=128.2	E=861.1	F=28.6

By replacing values of A, B, C, D, E, and F coefficients from Table 2 in the Eqs. 2, 3 and 4, and simplifying them, the optimization objective functions (equations) are achieved, as demonstrated in relations 5, 6, and 7.

$$f(x) = 500\_\{\sum_{i=1}^{9} x_i + \sum_{i=1}^{9} y_i + \sum_{i=1}^{9} z_i\} \quad (5)$$

$$g(x) = 0.1\sum_{i=1}^{9} x_i + 0.6\sum_{i=1}^{9} y_i + 0.4\sum_{i=1}^{9} z_i \quad (6)$$

$$h(x) = 28.6\sum_{i=1}^{9} x_i + 861.1\sum_{i=1}^{9} y_i + 128.2\sum_{i=1}^{9} z_i \quad (7)$$

Typically, in water resource management, the goal is to reduce Eqs. 5 by increasing water production (conventional and non-conventional). In other words, the only criterion is the reduction of water shortage. Considering the uncertainties and changes surrounding the amount of conventional water resources of the basin in the future, the water shortage calculated by WEAP is not definitive. Hence, Eqs.5 in the range of the response proposed by WEAP model (water shortage: from 150 MCM to 500 MCM) was evaluated with respect to the effect of energy factor. The results for the prediction of water shortage under thirteen situations in the horizon year are shown in Fig. 5. These thirteen situations represent some possible states for gradual change of water scarcity in this basin.

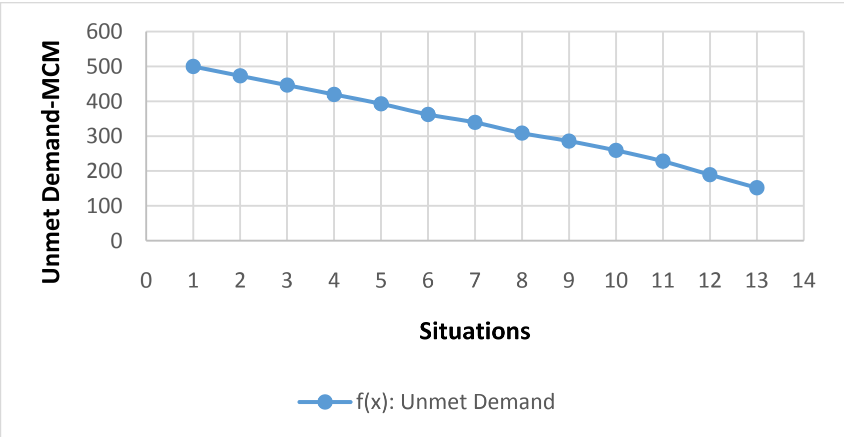

Figure 5. Reduction Trend of Water Shortage

To obtain the optimal point in the blue curve of Fig. 5, an *optimization* method was used. In this regard, to plot the general representation of three equations of possible water and energy situations in the future, the values of these three equations for all 13 states are shown non-dimensionally in Fig. 6. To obtain non-dimensional values for these three equations, the value of each equation under each scenario was divided by the largest value of that equation. In Fig. 6, the trends of mitigating water shortage, increasing energy consumption and producing EC are shown for all of thirteen situations.

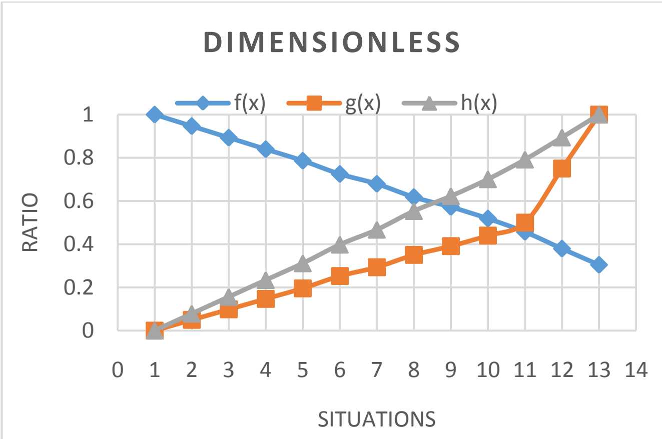

Figure 6. Changes Trend of Three Functions – dimensionless

Obviously, if the problem is considered without the nexus approach, as shown in Fig. 6, the best point in the f (x) curve will be observed in the thirteenth situation, which has the lowest water shortage. In this state, however, the energy consumption and environmental impacts are at their peak, which undermines its desirability and suitability.

The genetic algorithm, based on a trial and error process, gradually approaches the optimal answer. In the optimal answer, water shortage, energy costs and carbon equivalent weight are 325.62 MCM, $69.32 million, and 22800.83 tons, respectively. The optimal point for calculating the genetic algorithm is shown by a blue star in Fig. 7. The x-axis represents the equation of G (x), the y-axis represents the equation of H (x) and the z-axis denotes the equation F (x).

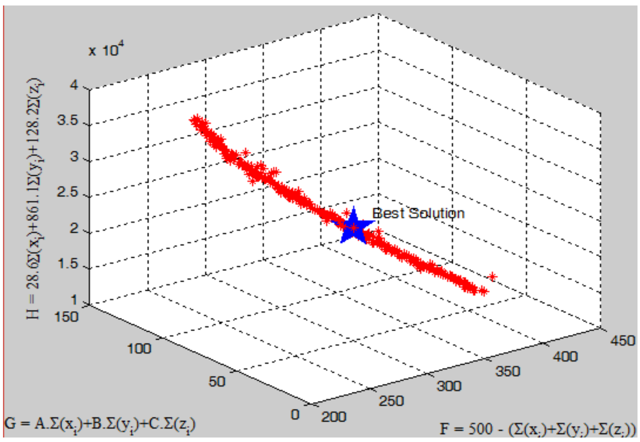

Figure 7. The Results of the Genetic Algorithm in MATLAB

Tables 3 and 4 show the optimized values of conventional and non-conventional waters in each town in comparison with the actual production. These values indicate that the maximum capacity of non-conventional water production exceeds the optimal water production. In all cases, the non-conventional water production should be reduced to optimize environmental and energy costs.

Table 3: Optimized Recycling Water for Each City- MCM

Unknow Parameter	Town or Village	Actual recycled Production	Calculating Optimized Wastewater
X_1	Abuzeiabad	1.2	**0.48**
X_2	Aranbidgol	7.44	**6.02**
X_3	Barzuk	0.48	**0.31**
X_4	Kashan	34.64	**33.12**
X_5	Niasar	0.48	**0.25**
X_6	Nushabad	1.12	**0.72**
X_7	Qamsar	1.44	**0.81**
X_8	Sefidshahr	0.32	**0.18**
X_9	Villages	5.68	**4.51**

Table 4: Optimized Desalinated Water for Each City- MCM

Unknown Parameter	Town or Village	Actual Desalinated Water Production	Calculating Optimized Desalinated Water
Y_1	Abuzeiabad	1.3	**0.82**
Y_2	Aranbidgol	8	**1.5**
Y_3	Barzuk	1	**0.56**
Y_4	Kashan	9	**2**
Y_5	Niasar	1.5	**0.78**
Y_6	Nushabad	2.3	**0.68**
Y_7	Qamsar	0.5	**0.22**
Y_8	Sefidshahr	0.1	**0.06**
Y_9	Villages	2	**0.56**

Fig. 8 illustrates the results of total actual non-conventional water at its maximum capacity compared to the optimized non-conventional water for different towns in the basin.

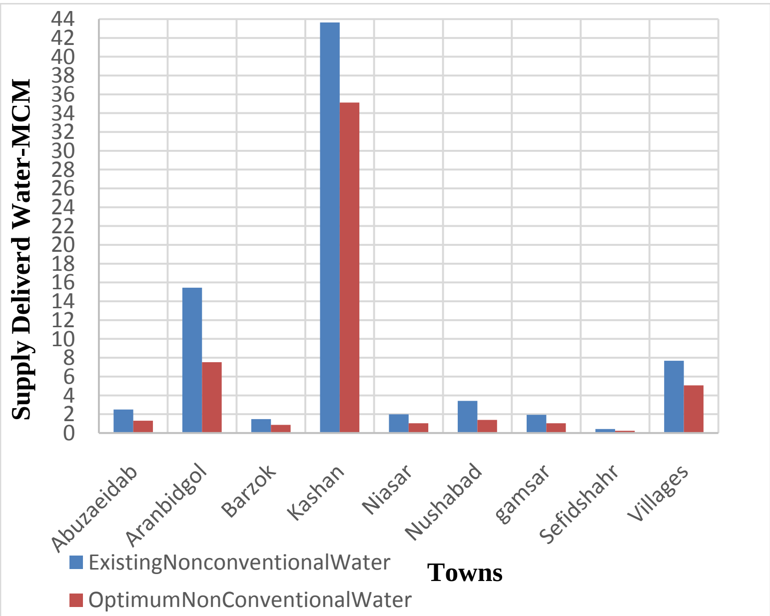

Figure 8. Comparison between Optimum and Produced Non-Con. Water in Towns

As depicted in Fig. 9, the production of non-conventional water is higher than the optimum limit. A more detailed analysis of this figure, based on the type of non-conventional water, reveals that upon the production of 46.4 MCM of recycled water and 7.2 MCM of desalinated water, the minimum costs of energy and environmental damages will be achieved. Nonetheless, if the total volume of non-conventional water (desalinated and recycled) exceeds this limit (53.6 MCM), although the water shortage could be alleviated, the energy consumption and environmental damage would be enormous. A comparison of the maximum production capacity with the optimal production capacity of conventional and non-conventional waters in the plan horizon is shown in Fig. 9. As for the non-conventional water, according to the figure, the permissible share is 69% of the actual produced share. Also, with regard to the conventional water, the actual production is 247 MCM and the optimum water is 121 MCM. In this way, the total actual water production (conventional and non-conventional) will be 150.5 MCM greater than the total optimal water.

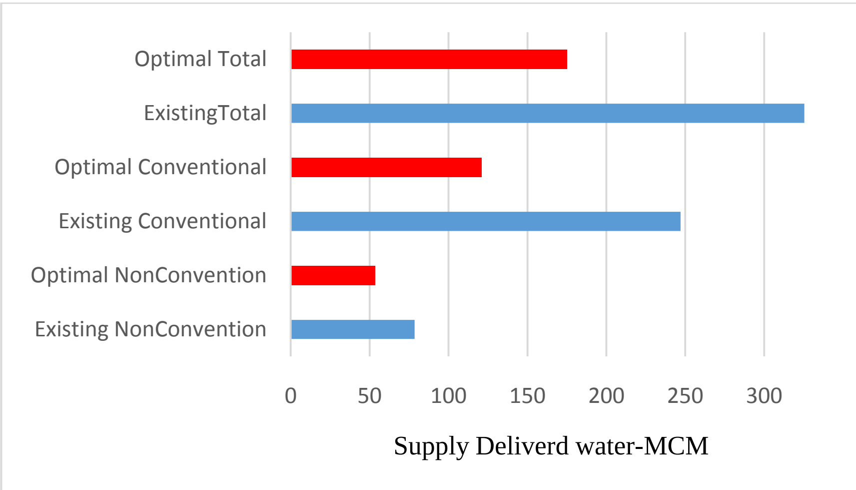

Figure 9. Comparison between total optimum and produced waters

4. DISCUSSION AND CONCLUSION

In this research, water scarcity in an arid area was examined. The goal was to apply the *nexus* approach to water resources management. In this context, the energy price and greenhouse gas production were considered as limiting factors in the production of water from non-conventional resources. This is the first study in which WEAP and LEAP models were utilized to predict the resources and consumptions of water and energy to simulate the situation of Kashan arid basin. A genetic algorithm was used to create a logical balance and depict the interaction between water resources and energy sources. The results suggested that the production capacity of non-conventional waters should be reduced by about 31% to mitigate damages caused by energy consumption and its environmental impacts. Thus, applying the *nexus* perspective onto the management of water resources in arid areas indicates that although the allowable percentage of water supplied by non-conventional resources may be reduced, a great deal of energy is saved and also a significant reduction in environmental impact is achieved. Therefore, in arid and semi-arid areas exposed to the risk of water scarcity in the future, importing bottled water could be considered as an alternative solution. It is recommended to explore the role of renewable energies rather than fossil fuels in future research.

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