International Journal of Agricultural Management and Development
Available online on: www.ijamad.iaurasht.ac.ir
ISSN: 2159-5852 (Print)
ISSN:2159-5860 (Online)
Research Paper

Sustainable Management of Groundwater Resources Using Multi-Criteria Programming (A Case Study of Kashmar Plain)

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Received: 25 May 2017,
Accepted: 05 September 2018

Abstract

Frequent droughts and their consequences result in the loss of groundwater, the deficiency of nutrients, the drying of surface water resources, and substantially more exploitation of the groundwater resources, which, altogether, cause the mobilization of saline waters to groundwater tables. This will impair the capacity of the aquifers and the quality of the water. The VIKOR method was applied to determine the best feasible solution according to the selected criteria including the local rainfall status in different years, soil permeability, land slope, and water quality indicators, including SAR, RSC, salinity for determination of groundwater resources quality and land-use restrictions in the Kashmar Plain in the northeast of Iran. The results of sampling performed on the Kashmar Plain showed that water quality was lost as one moved from the northern groundwater tables to the southern ones. The excessive use of groundwater resources, the downfall of the groundwater level, and subsequently, the increased salinity account for the loss of the agricultural water quality and the land-use restrictions. Furthermore, the results of the model within years 2010 and 2014 showed that if the current form of indiscriminate exploitation of groundwater resources is kept, it will lead to the mobilization of the salinity to the lowly-saline upstream regions. Therefore, it is necessary to focus on sustainable management of groundwater resources, control their indiscriminate exploitation, and minimize the damage to the groundwater tables in the study site. In addition, agronomists should work on limiting the use of agricultural land by modifying the cropping pattern and on using deficit-irrigation methods.

Keywords:
Sustainable management; Kashmar Plain; VIKOR Method; water pollution

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INTRODUCTION

Ninety percent of the world water has been used in agricultural section (Rahman et al., 2004). This is equal to 90 percent in Iran (Regional Water Company of Khorasan Razavi, 2014). Due to climatic conditions, rainfall distribution, the slope of the land, and the fact that Iran is an arid country, water shortage is enumerated as a factor limiting the development of Iran. Severe restrictions and the decline of water quality on the one hand and population growth, urban, agricultural, and industrial development, and the growing demand for water on the other hand are challenges that, if neglected, will hinder the development of the country in the near future. Accordingly, to prevent the critical situation of water and the consequences of curbing the excessive use of groundwater resources in these areas, it is necessary to consider these issues.

Kashmar County is severely suffering from the shortage of water resources in Iran and is faced with a gradually increasing number of problems. This county is located in the southwest of Khorasan Razavi Province and the eastern periphery of the Kavir Plain. It receives, on average, 680 Mm^3 rainfall every year of which about 483 Mm^3 (71%) is evaporated directly, about 156 Mm^3 (23%) is lost as surface runoff, and 41 Mm^3 (6%) is infiltrated into the groundwater aquifers. The variety of agricultural products is high in this county, and various crops of subtropical and moderate regions are cultivated (Agricultural Jihad Office of Khorasan Razavi, 2013).

Ground tables are a dominant source of water for agriculture; however, their discharging rate exceeds their charging rate so that the average decline of groundwater levels in Kashmar is reportedly more than one meter a year (Agricultural Jihad Office of Khorasan Razavi, 2013). The factors underpinning replenishing the ground tables include the infiltration of rainfall into the basin, the surface flows of input from adjacent basins, the charging rate of groundwater, transfer of water from other basins, permeation of flood, the returning water from farms, and urban and industrial wastewater whose value depends on the conditions of the different regions of the Kashmar plain (Regional Water Company of Khorasan Razavi, 2014).

The present study focused on agricultural land in Kashmar Plain that was divided into eight subsections of eight deep wells. To this end, eight wells were sampled that irrigated the lands located in the northwest, west, southwest, and south of Kashmar.

According to the area under irrigation in the north-south part of plains, these wells include Kalate Khan, Haji Abad, Argha, Shoorab Noghab, Ali Abad Barkal, Gharbe Shoorab, Shargh Sad Al-din, and Jafar Abad, respectively. According to the source of the groundwater table that is originated from the mountains of northwest of Kashmar County, the well located in the Kalate Khan District is the closest to the watershed that was selected as the sample source. Water quality standards and salinity have measured based on other wells that are far away from the watershed. The water of the wells in this path (north to south) was sampled to determine its quality, its quantity, discharge rate, its physical and chemical changes, and its quality impacts on surrounding agricultural land (irrigated with water). The climate of Kashmar Plain, rainfall, permeability, soil characteristics, slope, and excessive exploitation of the groundwater resources, due to the population increase, has affected environmental quality of the natural resource and consequently, the local people's lives, as well as the efficiency and sustainability of water resources and agriculture. Therefore, the protection of groundwater resources with the application of agricultural land use restrictions is an appropriate strategy that should be considered further.

Accordingly, it is necessary to rank the strategies of land use restrictions for various districts of Kashmar watershed that emanates from the northern mountains with varying degrees of potential effects on environmental quality of groundwater sources (wells) and agricultural land. Since the investigation of destruction and potential harm to groundwater resources rising from the excessive exploitation of arable lands are measured and expressed in terms of several criteria, the multi-criteria analysis method was used as a technique for quality loss problem and damage to groundwater resources. The VIKOR method was used in this study. This method expands multi-criteria optimization of complex systems to find alternative compromised ranking according to criteria selection (Opricov & Tzeng, 2004).

In recent years, multi-criteria optimization has been widely used in environmental resource management (Bryan & Crossman, 2008; Chung & Lee, 2009). To the best knowledge of the authors, no study on agriculture has used Multi-Criteria Decision Methods (MCDM) via the VIKOR method. However, some studies that have employed the VIKOR method in other research areas are reviewed below.

Hafezalkotob and Hafezalkotob (2017) proposed an interval target-based VIKOR model supported by interval distance and preference degree to solve machine selection problems. Canto-Perello et al. (2017) proposed a hybrid model combining Delphi, Analytical Hierarchy Process (AHP), and the VIKOR technique for the selection of a rehabilitation project considering social, economic, and landscape indicators. Buyukozkan and Karabulut (2017) presented a combination approach integrating AHP and VIKOR for energy project performance evaluation with a sustainability perspective. Xu et al. (2017) used a VIKOR-based method to evaluate the service performance of electric vehicle sharing programs in Beijing, China. Soner et al. (2017) applied AHP and VIKOR methods within an interval type-2 fuzzy context for selecting a hatch cover type for bulk carriers. Sharma et al. (2017) employed a novel Entropy-VIKOR approach for optimizing the performance of discrete V obstacles in a solar airflow channel. Ghorabaee et al. (2017) presented an extended VIKOR method with interval type-2 fuzzy sets for solving the multi-criteria project selection problem. San Cristobal (2011) studied the selection of renewable energy projects in Spain using the VIKOR method. In this study, AHP was used to determine the weights and degree of criteria importance. The results showed that according to the options considered in the model, plant biomass was the best choice.

Liou et al. (2010) used the VIKOR modified multi-criteria decision method to improve the quality of airline passenger services to families in Taiwan, and ultimately, it was found that it had improved different programs for increasing of customer satisfaction. Kuo and Liang (2011) studied the combined VIKOR method and analyzed the Gray relationship to assess the quality of service in seven northeastern Asia international airports. The results showed that the method is effective and applicable to multi-criteria decision-making problems and includes the unique quality traits in the fuzzy environment. Kaya and Ghahraman (2010) proposed the planning for multi-criteria renewable energy via the hierarchical combined method and fuzzy VIKOR in Istanbul for the best selection and location of energy policy. The results showed that, among the options that were available for the creation of wind turbines, the wind energy is a renewable and important energy in Katalka in Istanbul. Sanayei et al. (2010) studied the group decision method to choose their supplier by the fuzzy VIKOR method.

The present study ranks problematic regions in an attempt to achieve sustainable agriculture. The area of the agriculture regions irrigated by the wells have been considered between 50 to 100 acres and the crops included wheat, barley, melons, grapes, pomegranates, and saffron. Groundwater samples obtained from the wells are the only source of water supply for these crops. Data for the study were collected from the Agricultural Jihad and Regional Water Company of Khorasan Razavi during the years 2010 to 2014.

METHODOLOGY

There are several conflicting criteria to prioritize the agriculture problematic areas; therefore, a compromised solution is preferred over an optimal solution. The VIKOR method is a tool applicable to multi-criteria analysis that can be used for the recognition of solution adaptive weights and criteria by selecting and ranking from a set of conflicting criteria (Opricovic, 1998; Opricovic & Tzeng, 2004; Tzeng et al., 2005; Tong et al., 2007).

Alternatives in this study included eight agricultural areas with known wells, such as Kalate Khan, Haji Abad, Argha, Shoorab Noghab, Ali Abad Barkal, Gharbe Shoorab, Shargh Saad Eddin, and Jafar Abad. The selected criteria for each subsection included low quality of water for assessment of environmental potential effects of the Kashmar Plain, rainfall, permeability, land slope, and distance of any alternatives to the original watershed. Since factors such as slope, rainfall, and the distance of each subdivision to original watershed can play an important role in the transmission of quality, these factors were selected as measures of quality for each subsection. The water quality criteria were based on six factors: Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), acidity (PH), chlorine (CL), Total Demand Solids (TDS) and excess carbonate (RSC). Two of these factors that represent the electrical conductivity and total soluble salts in water (SAR) as the ratio of sodium ions to calcium and magnesium ions are more effective than other qualitative factors for agriculture(Chang & Chung, 2009). In addition to salinity problem, the extra carbon in water is another limiting factor that is represented as RSC, and it encompasses the excessive carbonate and bicarbonate per liter to milligrams of calcium and magnesium on the Meq. If the RSC in this ranking is more than 2.5 Meq, water usage in agriculture is limited (Alizadeh, 2000). Since the factors that are mentioned to determine the importance of quality criteria and standards for multi-criteria analysis have different scales, they are normalized by using 1 to 3 relationships (Chang & Chung, 2009). Equation 1 is a normalized indicator of Rainfall (R), Slope (S), permeability (F), Total Demand Solid (TDS), Electrical Conductivity (EC), the chlorine (CL), Sodium Adsorption Ratio (SAR), acidity (PH) and excess carbonate (R.S.C) criteria. It set the values of these indicators between 0 and 1.

$$\mathrm{XI_i} = 10 - 9\left(\frac{\mathrm{X_{max}} - \mathrm{X_i}}{\mathrm{X_{max}} - \mathrm{X_{min}}}\right) \tag{1}$$

$$(\mathrm{X{:}\ R, S, F, TDS, EC, CL, SAR, PHand\ R.S.C})$$

The distance criteria (DI) and water loss quality (PI) are normalized by using Equations 2 and 3. PI is the mean of TDS index in water, EC, the amount of CL, SAR, PH, and excess carbonate (Chang & Chung, 2009).

$$DI_i = \left[10 - 9\left(\frac{D_{max} - D_i}{D_{max} - D_{min}}\right)\right]^{-1} * 10 \tag{2}$$

$$PI_i = \frac{1}{6(TDS_i + EC_i + CL_i + SAR_i + PH_i + R.S.C_i)} \tag{3}$$

The VIKOR prioritization algorithm approach can be described in the following steps (Chang & Chung, 2009):

1- Determine the best f_i^* and the worst f_i^- values for the five criteria considered in whole subsection: m represents subdivision or any area of agriculture and n represents the criteria in each subsection. In this study, it is considered that m = 8 and n = 5.

$$f_i^* = \max[(\mathrm{f_{ij}}) \mid \mathrm{j} = 1{,}2, \mathrm{onsid}] \tag{4}$$

$$f_i^- = \min[(f_{ij}) \mid j = 1{,}2, \ldots \ldots m] \tag{5}$$

2- Compute the criteria optimal values and the unfavorable values (R_j) for each subdivision.

$$S_j = \sum_{i=1}^{n} w_i \, (f_i^* - f_{ij}) \Big/ (f_i^* - f_i^-) \qquad (6)$$

$$R_j = \max\left[w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} | i = 1,2,3, \dots \dots \dots n \right] \qquad (7)$$

in which f_{ij} is the i_{th} criteria amount in the subsection j and w_i is the weight of each criterion. In this study, it was assumed that all criteria would have a similar effect on ranking importance of each subsection. Thus, the weight of each criterion was 0.2, i.e.

w1= w2=........wn =1/n=0.2

3 - Compute the values Qj= 1, 2, ... , m by the following relation:

$$Q_j = \gamma \frac{(S_j - S^*)}{(S^- - S^*)} + (1 - \gamma) \frac{(R_j - R^*)}{(R^- - R^*)} \qquad (8)$$

in which γ is the weighting strategy for the maximum desirable and (1(n) is the unique weight for the undesirable values that are considered to be 0.5, generally.

$$S^* = min[(S_j) | j = 1,2,3, \dots \dots \dots . m] \qquad (9)$$

$$S^- = max[(S_j) | j = 1,2,3, \dots \dots \dots , m] \qquad (10)$$

$$R^* = min[(R_j) | j = 1,2,3, \dots \dots . . , m] \qquad (11)$$

$$R^- = max[(R_j) | j = 1,2, \dots \dots \dots . , m] \qquad (12)$$

4- Computing amount Q_j for each subsection that is normalized by Equation 13. The largest amount for this indicator is representative of farms use restriction ranking strategy performance for each subsection.

$$\acute{Q}_j = \left[10 - 9\left(\frac{Q_{max} - Q_j}{Q_{max} - Q_{min}}\right)\right]^{-1} * 10 \qquad j = 1,2, \; m$$

(13)

RESULTS

The rainfall average of Kashmar plain and its situation in comparison with other cities of Khorasan Razavi province during the years 1989-2014 is shown in Fig. 1. As can be seen in Figure 1, Kashmar plain is located in the city's ranks of low rainfall in province.

Figure 1. The rainfall average of Khorasan Razavi province during 1989-2014
Source: Regional Water Company of Khorasan Razavi , 2014

Table 1

Irrigation Water Quality Guide

Water quality criteria		Unit	Amount of water exploitation: No problem	Problem	Dangerous
Salinity	EC	ds/m	<0.7	0.7-3	>3
	TDS	mg/L	<450	450-2000	>2000
Ion toxicity	SAR		<3	3-9	>9
	CL	Meq/L	<4	4-10	>10
PH			Normal range 6/5 – 8/4		
R.S.C		Meq/L	Restriction of water consumption for agricultural when R.S.C> 2.5		

Source: Alizadeh, 2000

Different factors of groundwater qualitative criteria survey for different subdivisions in 2010 and 2014 are presented in tables 2 and 3. According to Table 2 and based on the irrigation water quality guide in Table 1, all subsections have an EC > 0.7 (ds/m), except for Haji Abad and Argha and three subdivision (Gharbe Shoorab, Shargh Saad Eddin, and Jafar Abad), are the problematic region because of groundwater loss quality. In addition, the evaluation of SAR in various subsections showed that, due to high SAR of greater than 3, all subsections are in the range of salinity problem except Kalate Khan. The water extra carbon in the total of regions was less than 2.5 except for Argha subdivision. Based on the water quality standards outlined in Table 1, the evaluation amount of chlorine (water toxicity) and TDS showed that Gharbe Shoorab, Shargh Saad Eddin, and Jafar Abad are the regions with the most problems and highest water quality loss. Also, pH for all subsections is at the threshold levels of problem.

In addition, by comparing Tables 2 and 3, it was shown that the factors of water quality loss criteria are increased in 2014 as compared to 2010, and this is representative of an additive trend to groundwater quality loss and salinity increase due to excessive use of agricultural lands and this makes agricultural land use restrictions more apparent.

Table 2

Different Factors of Agricultural Water Quality Loss Standards in the Different Subdivisions of the Kashmar Plain in the Cropping Year 2010

Subsection \ Factor	EC	SAR	PH	CL	TDS	R.S.C
Kalate khan	0.838	2.86	8.2	4	527.94	0.51
Haji Abad	0.591	4.2	8.3	0.8	372.33	1.65
Argha	0.539	6.08	8.2	1	339.57	2.8
Shorab Noghab	0.783	5.53	8.4	1.8	493.29	1.64
Aliabad Barkal	26	12.54	8.1	17	16.38	0.31
Garb Shoorab	9.85	24.71	8.4	68	6205.5	0.18
Shargh Saad Eddin	13	21.11	8	80	8190	0.1
Jafar Abad	14.060	25.85	7.9	94	8857.8	0.1

Source: Regional Water company of Khorasan Razavi (2014).

Table 3
Different Factors of Agricultural Water Quality Loss Criteria in the Different Subdivisions of Kashmar Plain in the Cropping Year 2014

Subsection \ Factor	EC	SAR	PH	CL	TDS	R.S.C
Kalate khan	1.08	2.6	8.2	5.7	634.95	0.42
Haji Abad	0.711	3.82	8.3	0.11	391.7	0.87
Argha	0.599	5.02	8.3	0.9	315.25	2.92
Shorab Noghab	0.656	3.71	8.6	0.82	323.10	2.03
Aliabad Barkal	2.8	13.45	8.1	18.2	15.2	0.45
Garb Shoorab	0.87	25.98	8.5	52.3	5899.5	0.26
Shargh Saad Eddin	14.2	19.91	7.9	79.12	8431	0.21
Jafar Abad	15	27.14	8	95.5	9120	0.19

Source: Regional Water company of Khorasan Razavi (2014).

After normalizing the factors f the groundwater quality loss criteria by Equation 3, they are considered as criteria of quality loss along with other effective normalized criteria on land use restrictions ranking for determining the priority of the agricultural subdivision. The results of this study are shown in Table 4.

As can be seen in Table 4, according to the normalized criteria of rainfall, infiltration, the agricultural lands slope, and distance of each subdivision from the watershed, the subsection Argha has a higher degree of importance for the performance of land use restrictions as per the highest value of Q'. Thus, according to the results, a ranking of subdivision for the performance of land use restriction included Argha, Gharbe Shoorab, Haji Abad, Kalate Khan, Ali Abad, Shargh Saad Eddin, Jafar Abad, and Shoorab Noghab, respectively. For the observation of salt front advancing and quality loss of groundwater resources, the VIKOR method was performed according to the dataset of 2010 in different subdivisions of the Kashmar plain, and the normalized amount of land use restriction ranking (Q') were obtained on the basis of 2010 dataset, which is expressed in comparison with 2014 cropping year whose results are summarized in Table 5.

Table 4
Restriction of Use of Agricultural Land (Q ') Method for Each Subsection VIKOR

	Distance	Rainfall	Permeability	Slope	PI	Q	Q'
Kalate khan	0	10	10	10	2.80	0.5	2.6
Haji Abad	1	7.24	6.79	10	3.52	0.51	2.5
Argha	1.21	6.53	5.53	7	3.2	0.53	1.8
Shorab Noghab	2.31	5.32	5.05	7	3.76	0.32	10
Aliabad Barkal	2.93	4.21	3.44	1	3.71	0.83	1.1
Garb Shoorab	5.84	2.17	2.40	4	7.34	0.42	3.9
Shargh Saad Eddin	6.67	1.90	1.41	1	7.15	0.89	1
Jafar Abad	10	1	1	1	6.87	0.73	1.3

Table 5
Comparison of Agricultural Land Constraints Q'

	Cropping year 2010	Cropping year 2014
Kalate khan	2.1	2.6
Haji Abad	2.8	2.5
Argha	10	10
Shorab Noghab	1	1.1
Aliabad Barkal	2	1.8
Garb Shoorab	3.8	3.9
Shargh Saad Eddin	1.1	1.3
Jafar Abad	1	1

As can be seen in Table 5, the comparison of the results of restriction situation of agriculture land use of Kashmar Plain in different subdivisions from the north to the south in 2010 and 2014 reveal that Aliabad Barkal is ranked the fourth and fifth in 2010 and 2014, respectively. Likewsie, Kalate Khan subdivision was ranked the fourth in land use restrictions in 2010, while it is ranked the third in 2014 that represents a salinity front progressive and an increase of water quality loss from the south to the north of Kashmar plain. Therefore, it is necessary to prevent the destruction of agricultural areas and reduction of groundwater quality, to use groundwater resources of Kashmar plain appropriately and optimally, and to meet the requirements for accomplishing sustainable agriculture.

CONCLUSION

Multi-criteria analysis via the VIKOR method was performed for agricultural land of Kashmar plain. The results showed that in order to achieve sustainable agriculture in the plains of Kashmar, salinity reduction, water quality loss, reduction of groundwater decline, and damage to groundwater table, it is necessary to rank agricultural land use restrictions and change crops. According to the results, Argha subdivision is also faced with the risk of salinity and groundwater quality loss due to excessive exploitation. It is necessary to revise crop programs for achieving sustainable agriculture and water resources of this subsection. Furthermore, the comparison of water quality criteria and factors in 2010 and 2014 showed that salinity front and quality loss are advancing because of neglecting agriculture sustainability and groundwater resources. Therefore, if this procedure continues, we will face water resources crisis and its consequences in the near future in addition to the effects of drought. The continuous exploitation of these groundwater resources will gradually increase water salinity and will reduce their quality resulting in soil salinity. Thus, to tackle this problem, the amount of exploitation should be curbed and groundwater tables should be recharged. Also, it should be tried to take advantage of deficit-irrigation method and improve irrigation efficiency to compensate it.

ACKNOWLEDGMENTS

We would like to thank Dr. Sabouhi for his valuable assistance.

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How to cite this article:

Shirzadi Laskookalayeh, S. & Esfanjari Kenari, R. (2018). Sustainable Management of Groundwater Resources Using Multi-Criteria Programming (A Case Study of Kashmar Plain). *International Journal of Agricultural Management and Development, 8*(4), 465-474.

URL: http://ijamad.iaurasht.ac.ir/article_543720_df6b8f09bdac417472122afbb43c5a16.pdf