EVALUATION OF GROUNDWATER SUSTAINABILITY IN A MULTILAYER AQUIFER

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ABSTRACT

Sustainability of aquifers is a necessary term for the long-term utilization of groundwater resources. Groundwater sustainability indicators maintain the sustainable management of groundwater resources and help to analyze human impacts on groundwater systems. In this paper the sustainability of phreatic and confined aquifers in multilayer groundwater system have been evaluated. Assessing sustainability in such groundwater systems can be complicated due to different effect of recharge and discharge processes on each layer. For this purpose, some indicators selected based on their feasibility in the study area and because they proved to be the most reliable. The indices were applied to a 4700 km² alluvial aquifer located in Golestan province, northern Iran, which has semi-arid climate conditions. Results have proven that the region is facing water scarcity and the aquifer is undergoing intensive use. As a result in spite of detecting no significant trend in the precipitation data, there is a descending trend in the water table and piezometric level of phreatic and confined aquifers, respectively. According to the results aquifer sustainability index of phreatic and confined layers were 0.89 and 1.01, respectively that means both layers are unsustainable. Confined layer's condition is worse although the issue has been covered by non-renewable groundwater resources. Also phreatic aquifer is threatened by salty salt-water intrusion. Of course both layers can be recovered soon. Altogether changing economic axis of the region from agriculture to less water demand sectors such as industry and services or at least cropping patterns is highly advised. Eventually, application of the methodology described here may prove useful for the evaluation of similar systems in semi-arid climates.

Keywords: Confined Aquifer, Falkenmark Indicator, Golestan Province, Phreatic Aquifer, Water Scarcity

1 INTRODUCTION

Water has an important role in urban and rural development especially in arid and semi-arid countries. Population growth along with consumerism, development of agricultural and urban regions and limited surface water resources has led to excessive withdrawal of groundwater aquifers that can cause irreparable damages to these natural resources. Domestic water consumption per capita in the very high human development index[b] (HDI) countries, at 425 litres a day, is more than six times that in the low HDI countries, where it averages 67 litres a day (Klugman, 2011). Nowadays densely populated arid areas, Central and West Asia, and North Africa, with projected availabilities of less than 1000 m^3/capita/year are strongly suffered of water scarcity (Rijsberman, 2006). It cause water withdrawals in developing countries to be 27% higher in 2025 than in 1995 (Watkins, 2006). Continued increase in domestic water withdrawals and demands led to the recognition of the importance of water for ecological sustainability (Sullivan, 2002; Vorosmarty et al., 2005; Chaves & Alipaz, 2007).

Groundwater, with a global withdrawal rate of 600–700 km^3/year (Zektser and Everett, 2004), is the world's most extracted raw material. Use of groundwater has increased significantly in recent decades due to its widespread occurrence, mostly good quality, high reliability during droughts and generally modest development costs. Groundwater is the main water supply source in several mega-cities (e.g. Mexico City, Sao Paulo and Bangkok) and provides nearly 70% of piped water supply in the European Union countries (Vrba et al., 2007). Poor protection and management in groundwater resources development plans has led to uncontrolled aquifer exploitation and contamination. Over-exploitation of groundwater may affect springs and streams base-flow and can lead to downfall in groundwater piezometric levels and land subsidence. Sustainable groundwater resources development and environmentally sound protection is a holistic process. The main objective of this process is to ensure quantity, quality, safety and sustainability of groundwater as an important component of the ecosystem and a strategic source for life (e.g. drinking and other sanitary purposes) and economic development (e.g. agriculture, industry) (Vrba et al., 2007).

Groundwater indicators provide summary information about the present state and trends in groundwater systems, help to analyze the extent of natural and anthropogenic impacts on groundwater system in space and time and support sustainable management of groundwater resources (Vrba et al., 2007). In the past 20 years many indices have been developed to quantitatively evaluate water resources vulnerability such as water

[b] A composite index measuring average achievement in three basic dimensions of human development—a long and healthy life, knowledge and a decent standard of living [Klugman, J. (2011)].

scarcity or water stress indices (Brown and Matlock, 2011). Some indices used frequently to evaluate water availability and sustainability, including Falkenmark indicator (FI), renewable groundwater resources per capita (RGPC), dependence to groundwater (DG), dependence of agriculture to groundwater (DAG), the role of groundwater in the supply of drinking (RGSD), aquifer sustainability (AS), sustainability of groundwater quality (SGQ), groundwater abstraction development (GAD), pressure on non-renewable resources of groundwater (PNRG), aquifer recovery potential (ARP) and groundwater decay rate (GDR). Among above mentioned indices the two first indices (FI and RGPC) relates to water resources availability of the studied region, next three ones look at multilayer aquifer as a unit water body and the other indices deal with each layer of the aquifer separately. Main functions of indicators are simplification, quantification, communication, ordering and allowing for comparison of different resources. They evaluate the effect of performed policy making actions and can help to develop new actions. Indicators also serve to forecast trends in groundwater quality, but only if they are repeatedly generated during a long period of time to be statistically significant (Vrba et al., 2007).

Combinations of several indicators are frequently used, because implementation of one single indicator can rarely satisfy the intended objectives. For example, Lamban et al. (2011) applied sustainability indicators such as AS and GAD to a small carbonate aquifer (26 km^2) situated in the province of Seville, southern Spain, with semi-arid climate. They concluded the aquifer is undergoing intensive use and exploitation of its water resources is surpassing the threshold of sustainability when both the quantity and the quality of the groundwater are taken into consideration. Shrestha and Udmale (2014) studied groundwater resources of Dhubdhubhi watershed in Maharashtra state of India. They calculated FI, RGPC, DAG, AS and GAD equal to 537, 490, 87.5, 71.5 and 64.5, respectively and concluded the whole watershed is at stage of sustainable development; even though over exploitation detected in some parts of the region. Also Anbazhagan and Jothibasu (2016) used AS and GAD to evaluate sustainability of Uppar Odai sub-basin, India. The study demonstrate only in 29 percent of the area groundwater development is possible.

Shiklomanov (2000) assessed world water resources per capita using FI. The results show among the most water scarce regions in the world, FI of Western Asia that IRAN located in it, is equal to 2110 m^3 per capita and placed in third place after Northern Africa and Southern Asia. Golestan province is an agricultural hub with high water consumption in agriculture. Of course this province has a great talent for agricultural development if the water is supplied. On the other hand, groundwater resources are the main domestic water supply of many parts of the region. Almost maximum capacity of the aquifer is using for various tasks, therefor it is necessary to control water table drop based on studies on groundwater variations and performing management measures in order to prevent the major source of water to be faced with serious risks (kuhestani et al., 2013). The groundwater system consists of a multilayer aquifer with both phreatic and confined layers. The confined aquifer is abstracting all over the plain but it is only recharging across its southern and south-eastern boundary, that confining layer does not exist. However, rainfall recharges the phreatic aquifer throughout the plain.

Worldwide researches on water resources sustainability and lack of such studies in the region besides importance of groundwater among water resources system of Golestan province, altogether lead to do evaluative works on current hydrological status and future development capability of this vital resource. After all different porous media characteristics, recharge regime and accessibility create different geo-hydrological processes which should be investigated, separately, in order to efficient integrated water resources management. Looking at this aquifer as a lump system can cause unsustainability of one layer while the total system is in sustainable state. In another research Karimirad et al. (2016) investigated the effect of climatic variability on multilayer aquifer of Golestan province using groundwater resource index (GRI) and correlation analysis. They concluded that confined aquifer is more reliable and react to climate fluctuations (as a main driver) with more delay and recover more quickly. This paper aims to evaluate phreatic and confined aquifers in the multilayer groundwater system in terms of sustainability through index-based approach.

2 MATERIALS AND METHODS

Golestan is one of the 30 provinces of IRAN, located in the northeastern part of the country, south-east of the Caspian Sea. Golestan is situated between 36° 44' and 38° 05' north latitude and 53° 51' and 56° east longitude. The region’s climate classified as semi-arid in the north and semi-humid in the south and southwest according to De-Martonne method (Mostafazadeh and Sheikh, 2012). There is an alluvial multilayer aquifer in this province that has about 4720 square kilometers area. Location of Golestan province and the multilayer aquifer in Iran is illustrated in Figure 1. This groundwater system includes both phreatic and confined aquifers. The confined aquifer beneath the phreatic one (multi-layer aquifer in Figure 1); it spread across the phreatic one except about 400 square kilometers in southern part (single-layer aquifer in Figure 1). The aquifer is extended from the Caspian Sea in the west to the city of Kalale in the East for about 130 kilometers and from the southern mountains to the Great Wall of Gorgan in the north for about 35 kilometers. The multilayer aquifer supply almost all demands for drinking water and about 65 percent of agricultural needs (Kankash-Omran, 2009).

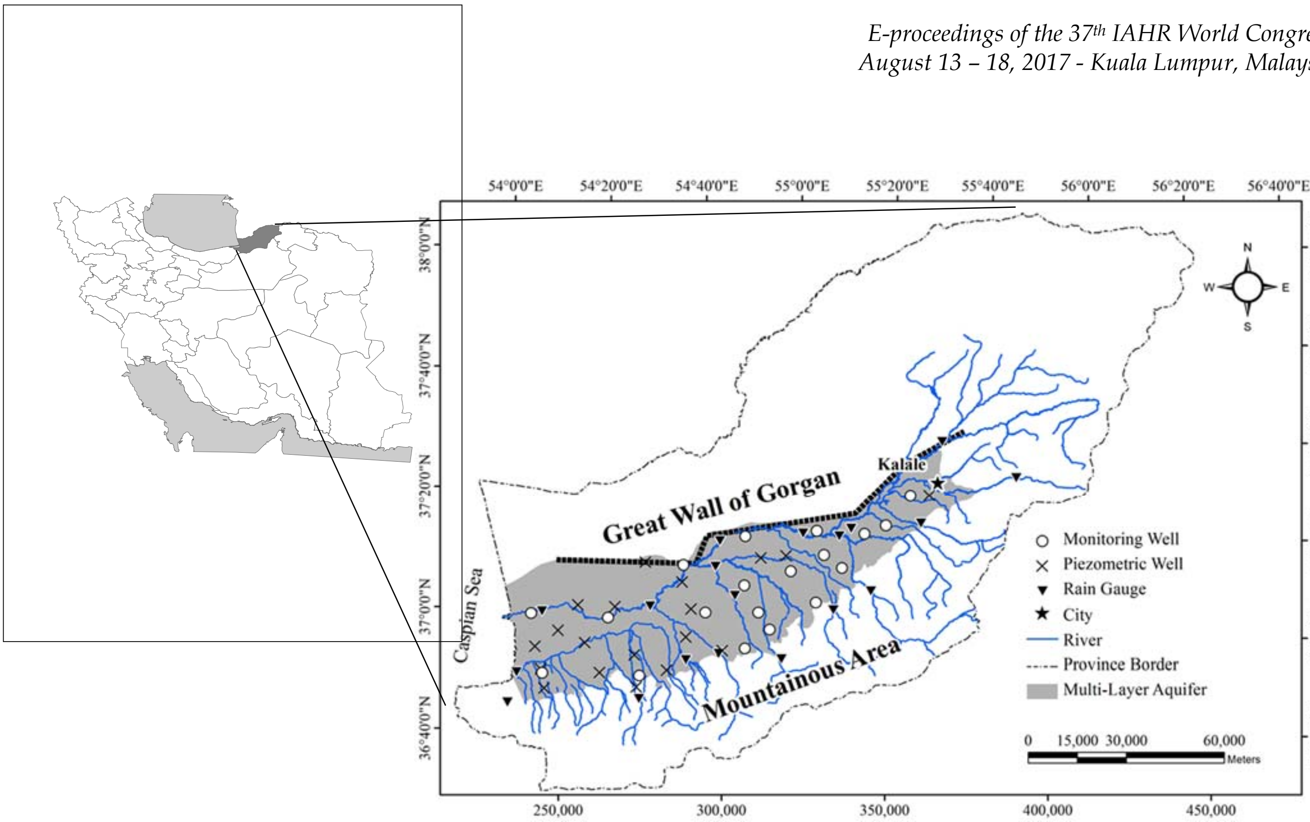
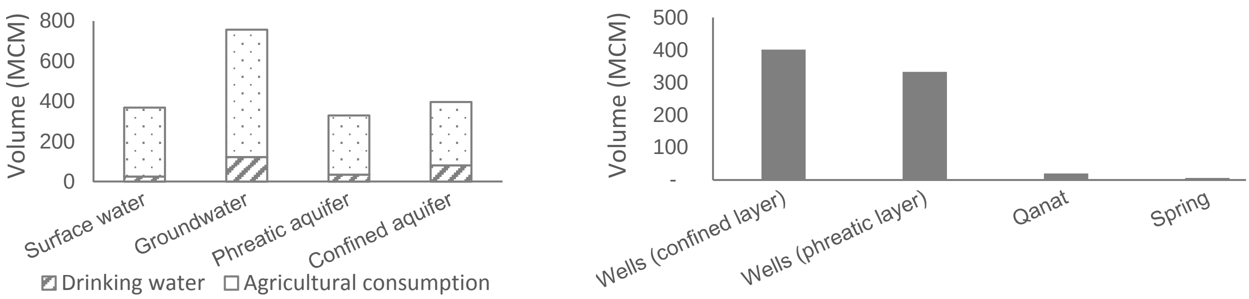


Figure 1. Location of alluvial multilayer aquifer in Golestan province of IRAN

In the present paper, the long-term monthly precipitation data of 19 gauges in time period of 1976 to 2013 which have a good distribution over the studied area has been used. Also recorded data of 19 observational wells drilled in the phreatic aquifer with the time period of 38 years (the same as the precipitation data) and 19 piezometric wells in the confined aquifer with 14-year time period (2000-2013) are used. This data has been measured and recorded by the Golestan regional water authority. Consumption of each water resource in drinking and agricultural sectors and share of each exploitation method in total abstraction of Golestan aquifer has been shown in Figure 2. Also geo-hydrological characteristics of Golestan aquifer are presented in Table 1 (Kankash-Omran, 2013).



a b

Figure 2. a. Consumption of each water resource in drinking and agricultural sectors, b. Share of each exploitation method in total abstraction of the aquifer (Kankash-Omran, 2013)

Table 1. Geo-hydrological characteristics of each layer in Golestan aquifer (Kankash-Omran, 2013)

Characteristic	Phreatic layer	Confined layer
Static volume (non-renewable water) (MCM/year)	1533	1121
Dynamic volume (renewable water) (MCM/year)*	513	397
Recharge (MCM/year)	852	398
Underground discharge (MCM/year)	399	2
Discharge into the sea (MCM/year)	2	2
Total abstraction (MCM/year)	358	401
Abstraction from non-renewable water (MCM/year)	0	3
Average thickness (m)	15	150
Average drop in last 10 years (m)	0.047	0.726
Aquifer area (Km^2)	4393	4050
Saline water area (Km^2)	1402	0

* Calculated according to instruction of FAO[1] (2003)

[1] Food and Agriculture Organization (United Nations)

Eleven proposed groundwater indicators selected based on available data in the region. They provide information about groundwater quantity and quality and are focused on social (groundwater accessibility, exploitability and use), economic (groundwater abstraction and protection) and environmental (groundwater depletion and pollution) aspects of groundwater resource. These indices are described below.

2.1 Falkenmark indicator (FI)

The Falkenmark indicator is perhaps the most widely used measure of water stress (Eq. [1]). Based on the per capita usage, the water conditions in an area can be categorized as Table 2. The index thresholds 1,700 m^3 and 1000 m^3 per capita per year are used as the thresholds between water stressed and scarce areas, respectively (Falkenmark, 1989). In the context of this indicator, particular drivers are population growth and climate change, which can dramatically affect groundwater resource availability. However FI do not consider important variations in demand among countries due to culture, lifestyle and so on. Moreover, the water availability per person is calculated as an average without considering both the temporal and the spatial scale and thereby neglects water shortages in dry seasons or in certain regions within the region.

$$\text{FI (m}^3\text{ per capita per year)} = \frac{\text{Renewable freshwater resources (MCM)}}{\text{Population}} \quad [1]$$

Table 2. Water resources conditions according to FI (Falkenmark, 1989)

FI (m³ per capita per year)	Condition
>1,700	No stress
1,000-1,700	Under stress
500-1,000	Scarcity
<500	Absolute Scarcity

2.2 Renewable groundwater resources per capita (RGPC)

The state of this index annually in the study area gives an indication of the availability of groundwater (Shrestha and Udmale, 2014).

$$\text{RGPC (\%)} = \frac{\text{Renewable groundwater resources (MCM)}}{\text{Population}} \quad [2]$$

Where, the numerator is total renewable groundwater resources, without considering groundwater quality but excluding brackish and saline waters. Renewable groundwater resources calculation is explained by FAO (2003).

2.3 Dependence to groundwater (DG)

This index demonstrate groundwater share in total water consumption in different sectors of the region (Eq. [3]). Different grades of groundwater dependency given in Table 3 (Beiki-khoshk, 2011).

$$\text{DG (\%)} = \frac{\text{Total groundwater abstraction (MCM)}}{\text{Total water consumption (MCM)}} \quad [3]$$

Where, total groundwater abstraction is the total withdrawal of water from a given aquifer by means of wells, qanats, springs and other ways for the purpose of public water supply or agricultural, industrial and other usage.

Table 3. Grades of Groundwater dependency using DG index (Beiki-khoshk, 2011)

Range	Groundwater dependency
G < 25 %	High
25 % < G < 50 %	Moderate
G > 50 %	Low

2.4 Dependence of agriculture to groundwater (DAG)

Regarding the importance of groundwater to supply agricultural needs, this index is defined as follows (Beiki-khoshk, 2011):

$$\text{DAG (\%)} = \frac{\text{Groundwater used in agriculture (MCM)}}{\text{Total water used in agriculture (MCM)}} \quad [4]$$

2.5 The role of groundwater in the supply of drinking (RGSD)

RGSD can be used to represent the amount of dependence on groundwater to supply drinking water compared with surface water. This indicator is of particular social importance since it highlights the importance of groundwater for drinking purposes on a national basis, i.e. the population dependency on groundwater and therefore, its key role in public and domestic water supply. Ideally, at a later stage, the indicator could be applied separately for urban and rural areas (Vrba and Lipponen, 2007).

$$\mathrm{RGSD}\ (\%) = \frac{\text{Groundwater used for drinking (MCM)}}{\text{Total drinking water (MCM)}} \qquad [5]$$

2.6 Aquifer sustainability (AS)

AS index present groundwater abstraction as a portion of aquifer recharge (Vrba and Lipponen, 2007):

$$\mathrm{AS} = \frac{\text{Total groundwater abstraction (MCM)}}{\text{Aquifer recharge (MCM)}} \qquad [6]$$

The main sources of recharge are rainfall, surface water bodies, irrigation losses and seepage from urban water supply distribution and waste water collection systems. For the indicator two possible scenarios are conceivable: (1) sustainable use of the groundwater with respect to quantity (total output < recharge) and (2) non-sustainable use of the groundwater (groundwater mining) with respect to the amount (total output > recharge). This indicates, in a preliminary manner, the degree of sustainability with regard to the use of groundwater, although aspects related to quality and/or affections to groundwater-fed ecosystems are not considered. The meaning of different values of AS has been given in Table 4.

Table 4. Aquifer sustainability on basis of AS index (Vrba and Lipponen, 2007)

Range	Aquifer sustainability
AS > 1	Critical
1 > AS > 0.8	Highly unsustainable
0.8 > AS > 0.6	Unsustainable
0.6 > AS > 0.4	Little sustainable
0.4 > AS	Sustainable

2.7 Sustainability of groundwater quality (SGQ)

Groundwater quality indicators can inform about the present status and trends in groundwater quality and help to deal with groundwater quality problems in space and time. One of the parameters that determine the quality of groundwater is groundwater salinity that SGQ index accordingly defined and is expressed as follows (Beiki-khoshk, 2011):

$$\mathrm{SGQ}\ (\%) = \frac{\text{Saline zone of aquifer (KM}^3\text{)}}{\text{Total area of aquifer (KM}^3\text{)}} \qquad [7]$$

2.8 Groundwater abstraction development (GAD)

In many countries there is an intention to quantify GAD as an index to specify usable groundwater reserves. Accordingly, aquifer’s ability to develop conclude according to table 5. (Vrba and Lipponen, 2007).

$$\mathrm{GAD}\ (\%) = \frac{\text{Total groundwater abstraction (MCM)}}{\text{Exploitable groundwater resources (MCM)}} \qquad [8]$$

Where, total exploitable non-renewable groundwater resource means the total amount of water that can be abstracted from a given aquifer under prevailing economic, technological and institutional constraints as well as ecological conditions (GIWG, 2004).

Table 5. GAD index values and development capability of aquifer (Vrba and Lipponen, 2007)

Range	Development capability
GD < 25 %	Capable
25 % < GD < 40 %	Limited
40 % < GD	No development

2.9 Pressure on non-renewable resources of groundwater (PNRG)

Non-renewable groundwater is a finite water resource to which no or very little recharge takes place and has accumulated over geologic time, and therefore is not replenished over human timescales. Its depletion can cause irreparable damage to the aquifer (e.g. land subsidence) and should be maintained. Through PNRG index (Eq. 9) the situation of non-renewable part of aquifer can be disclosed somewhat (Vrba and Lipponen, 2007).

$$\text{PNRG (year)} = \frac{\text{Total exploitable non-renewable groundwater resources (MCM)}}{\text{Annual abstraction of non-renewable groundwater resources (MCM/year)}} \qquad [9]$$

2.10 Aquifer recovery potential (ARP)

This index (Eq. 10) show the ability of aquifer to recover or return to normal state (Vrba and Lipponen, 2007):

$$\text{ARP} = \frac{\text{Static volume of aquifer (MCM)}}{\text{Recharge of aquifer (MCM)}} \qquad [10]$$

Where, static volume is part of aquifer contains non-renewable groundwater. The potential of aquifer to be recovered can be determined according to table 6.

Table 6. Aquifer recovery potential classification (Vrba and Lipponen, 2007)

Range	Aquifer recovery potential
ARP < 10	High
10 < ARP < 30	Fair
30 < ARP < 50	Low
50 < ARP	No recovery

2.11 Groundwater decay rate (GDR)

Beiki-khoshk (2011) developed groundwater decay rate index to estimate the number of years that an aquifer is reliable as follows:

$$\text{GDR (year)} = \frac{\text{Average thickness of aquifer (m)}}{\text{Average decline in groundwater table or piezometric level in last 10 years (m)}} \times \frac{2}{3} \qquad [11]$$

3 RESULTS AND DISCUSSION

Monthly time series of precipitation, water table of the phreatic aquifer and piezometric level of confined aquifer, are shown in Figure 3. Each chart illustrates average of 19 rain gauges and respective wells. Stationarity checked at 95 percent confidence level using Hurst exponent method and accordingly all three used time series are stationary. Mann- Kendall test results at 95 percent confidence level show no significant trend in precipitation data but water level of phreatic aquifer and Piezometric level of confined aquifer declining at the rate of 1 and 12 mm per month, respectively. It is worth mentioning during the same period with the confined aquifer data (last 14 years), the water level of the phreatic aquifer has no trend.

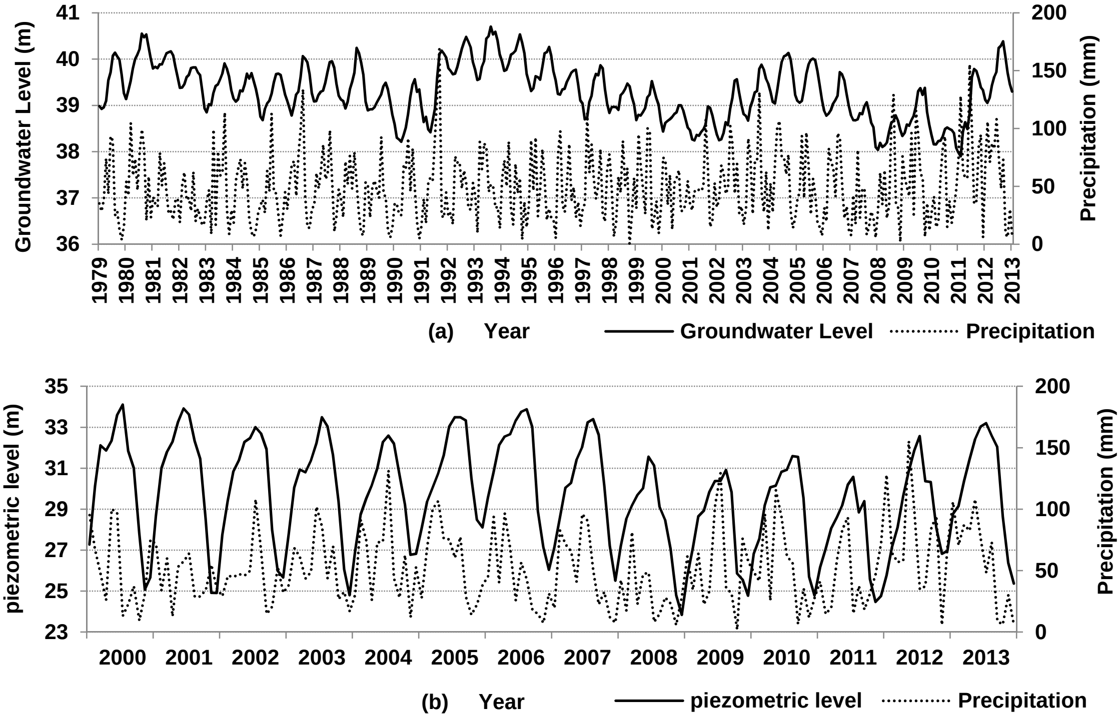


Figure 3 Water table and precipitation monthly fluctuations of (a) phreatic and (b) confined layers (Karimirad et al., 2016)

FI and RGPC for Golestan province is equal to 855 and 512 M^3 per capita per year, respectively that means the region is facing water scarcity. Other indices calculated and demonstrated in Table 7.

Table 7. Calculated indices of status and sustainability for whole aquifer and its layers separately

No	Index (Unit)	Multilayer aquifer		Interpretation
		Phreatic layer	Confined layer	
1	DG (%)	63.37		Dependency to groundwater is higher than surface water
2	DAG (%)	64.88		Agriculture is more dependent to groundwater
3	RGSD (%)	77.94		Drinking water is more dependent to groundwater
4	AS	0.89	1.01	Phreatic layer is highly unsustainable and Confined one is worse and critical
5	SGQ (%)	0.32	0	Nearly one third of phreatic aquifer area become saline
6	GAD (%)	0.32	0.26	Limitations must be considered to develop both phreatic and confined layers
7	PNRG (year)	0	332	Confined aquifer will be entirely depleted and irreversibly exterminated after 3 centuries
8	ARP	1.8	2.82	Both layers will be recovered soon
9	GDR (year)	213	138	If current trends continue, phreatic aquifer will be depleted 75 years after confined one

Accordingly, calculated FI is far less than which has been estimated by Shiklomanov (2000) as an average amount for Western Asia. Sustainability of the studied aquifer looks alike which evaluated by Lamban et al. (2011). Index-based evaluation show better water availability (pay attention to FI and RGPC) compared to the case of Shrestha and Udmale (2014) but more dependency of agriculture to groundwater (pay attention to DAG) that caused over-exploitation of both layers specially confined one (pay attention to AS). It suggests change in cropping patterns or shifting economic axis of the region from agriculture to sectors with lower water demand such as industry and services. Of course non-renewable groundwater covered mentioned problem, currently (pay attention to GAD) and maybe it is the reason that Karimirad et al. (2016) evaluated the confined aquifer more reliable.

4 CONCLUSIONS

It can be concluded the index-based investigation of groundwater resources in multilayer aquifer of Golestan province, IRAN revealed some valuable information about its current status, sustainability and future perspective. First of all the region is facing water scarcity that is a limitation to economic development and human health and well-being. Studied society is depending on groundwater more than surface water resources and the situation prevailing in both main sectors of drinking and agriculture. First five indices clarified the current status of the region in terms of water resources in general and importance of implementing water management measures. Six other indices have gone more to the details and investigate quantitative and qualitative aspects of sustainability in each layer of aquifer, separately. Accordingly, both phreatic and confined layers are unsustainable and confined layer's condition is worse although it has been covered by non-renewable groundwater till now. But in terms of quality situation is vice versa and phreatic aquifer is threatened by salt-water intrusion.

According to GAD implementation of water resources development plans is allowed with considering some limitations in terms of water quantity and quality. Some restorative measures are advisable to improve sustainability including: expanding watershed management actions especially in the confined aquifer recharge area, more control on abstraction of the aquifer using smart water meters, enforcement the law through Incentives and penalties such as agricultural subsidies, reduce on-farm water loss by changing traditional irrigation, covering canals and repairing distribution networks. However changing economic axis of the region from agriculture to sectors with lower water demand such as industry and services or at least shifting cropping patterns is highly advised.

Despite all, fortunately both layers can be recovered soon if driver factors change toward providing sustainable conditions. As an estimation GDR and PNRG predict one and three centuries, respectively, for confined aquifer depletion which anyway is negligible compared with the time it formed during geological periods. It is necessary to note that aquifer depletion and subsequent land subsidence can cause severe impact on human settlements in the region such as lack of water in dry season, sinkholes and so on. Altogether confined aquifer is more endangered quantitatively while quality degradation threatens phreatic aquifer. Overall, the proposed groundwater indicators are scientifically robust and policy relevant, based on available data, provide information about the present status, trends and impacts on groundwater system and support socially and economically sustainable management and environmentally sound protection of groundwater resources.

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