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Mitigation of the groundwater stresses via surface water harvesting in an arid environment

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Abstract

Groundwater resources are the most important water resources in many arid and semi-arid environments. Also groundwater resource is already under pressure in such area, but groundwater over extraction and climate change should still increase this stress. Aquifer recharge management via surface water harvesting should plays an important role in the mitigation of the groundwater stress. The main aim of this study was to investigate the impacts of the artificially recharge of the aquifer via storm-water reclamation techniques. The potentials role of the application of several water harvesting systems on groundwater level changes in Kashan aquifer was examined using MODFLOW. This study was conducted in two stages: 1) Estimation the amount of harvestable surface runoff via differences water harvesting system and 2) Examination the effect of water harvesting on groundwater level. According to results, Kashan aquifer has a negative budget, as groundwater discharge is about 35MCM more than groundwater recharge and this amount will increase with this condition. Water harvesting operation suggested in this study would increase groundwater recharge. Also this operation could not stop groundwater decline, but it can mitigate it.

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Introduction

In arid and semi-arid area, groundwater is the most important resources of fresh water (Leblanc *et al.*, 2007; Sheng, 2013). In this area, rainfall occurs bimodal and with high intensity (Ghazavi *et al.*, 2012). Irregular rainfall and high evapotranspiration cause seasonal drought, while high intensity rainfall lead to infrequent damaging flood (Ghazavi *et al.*, 2010). As surface water resources are unreliable and ephemeral, groundwater abstraction vary from 70% in the wet season to lessees than 20% in the dry season (Edmunds *et al.*, 2002; Aeschbacher *et al.*, 2005). Also groundwater resource is already under pressure in arid and semi- arid area, but groundwater over extraction and climate change should still increase this stress.

Low precipitation and high amount of evapotrans piration in dry seasons lead to increase groundwater abstraction (Stephens and Ellis 2008), as groundwater extraction should increase from 20% in the wet periods to over 70% in the dry periods (Aeschbacher *et al.*, 2005).

In arid area, Ephemeral River should be the most important resources of groundwater recharge. In Iran, for example, the total surface runoff is about 127 billion cubic meters, by that, 65 billion cubic meters resulting from the ephemeral streams. Most of which runoff ends up in deserts, sea and swamps (Ghayoumian *et al.*, 2007), but these runoffs should use for groundwater recharge via artificial water harvesting systems.

Pressure on the water resources should restrain economic and social development in many countries, and menacing ecological values in others countries (Hedelin, 2007; Xia *et al.*, 2007). According to the United Nations world water development report, with the current water management strategy and population growth, the world will experience a global freshwater deficit of 40% in 2015 (WWAP 2015).

Artificial groundwater recharge via ephemeral surface water resources is critical techniques that could decreases the impacts of the seasonal drought, decreases flood damaging, reduces evapotranspiration and increases groundwater recharge (Konikow and Kendy 2005; Ghazavi *et al.*, 2010; Drumheller *et al.*, 2017).

Artificial recharge should use to improve groundwater resources. Estimating of the effects of the artificial groundwater recharge on groundwater quality and quantity is a key factor in groundwater management systems especially in arid and semi-arid area (Kendy *et al.*, 2004; Regnery, 2013).

Different methods were proposed for groundwater recharge estimation, but the essential information for each model varies due to complication of the methods (Lin *et al.*, 2008, Szilagyi *et al.*, 2003).

The effect of water harvesting on groundwater storage was investigated via many different methods such as Darcy's law, water level variation methods, tracers, and mathematical models (Massuel *et al.*, 2014, Sutanudjaja *et al.*, 2011, Bhoopesh and Joisy 2012, Nyakundi *et al.*, 2015), but a few studies have focused on artificial groundwater recharge.

A coupled of empirical and mathematical models was proposed to estimate the effects of total recharge on groundwater storage in several studies. SCS-CN method as an empirical model and MODFLOW as a mathematical model were widely used by researchers for estimation groundwater recharge (Lee al. 2012, Karthiyayini *et al.*, 2016, Mane *et al.*, 2015).

The main aims of this study were:

1. To estimate the volume of the harvestable water through artificial water harvesting systems

2. To apply a couple of the mathematical and empirical models to estimate groundwater recharge rate via artificial water harvesting system, and

3. To investigate. The effects of the applying of the surface water harvesting systems on mitigation of the groundwater stresses in an arid environment.

Material and methods

The study area located in Kashan plain (longitude: 51°32' to 51°03'E, latitude: 33°27' to 34°13'N), Esfahan province, Iran (Fig. 1). The studied plain has an area of 1570.23km².

Annual precipitation of the study area is about 140 mm, but it is varied temporally (minimum precipitation was reported in the Jun with about 0 mm and maximum precipitation was recorded in the January with about 31 mm) and spatially (from 75 mm at the plane area to 300 mm in the mountains area). The annual potential evapotranspiration of the study area is about 3000 mm. The Kashan aquifer experiences an annual groundwater negative budget (about -32 million m³).

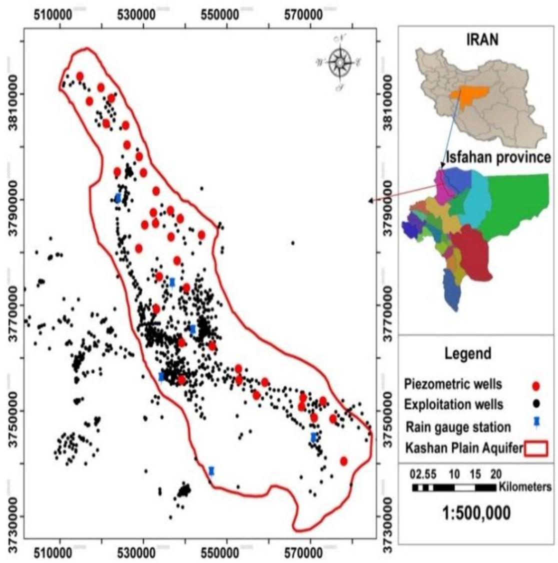

Fig. 1. Location of the study area in Iran.

Methodology

In this study, based information includes topographical and geological maps, rainfall data, aquifer information, number of extraction wells and volume of annual groundwater discharge were obtained from Kashan regional water authority.

The result of geophysical studies was used to determine the thickness of the alluvium area in the various parts of the aquifer. The pumping test Results was used to determine the hydrodynamic coefficients (effective porosity and hydraulic conductivity).

Monthly water table level during 20 years (1999-2014) and polygon area affected by 22 observation wells were evaluated. Thiessen method was used to determine the area affected via each study wells. In order to evaluate the overall condition of the aquifer and spatial change of groundwater level, the unite hydrograph of the aquifer was drawn.

For investigate the suitable area for groundwater recharge via water harvesting systems, the study area divided in to 23 sub-basin using topographical map. For each sub-basin, land-use, soil, geological, drainage, and physiographical maps were obtained from topographical maps, GIS and direct land survey. Stream order of the studied watershed was obtained using Horton (1945) method. Climatologically data recorded at a meteorological station in the study site (Kashan Station) was used. Rainfall data of the watershed was analyzed for recurrence of storm/flood event at different returns periods (2,5,10,20,50 and 100 years). For each sub-basin, the precipitation was estimated separately using a linear regression between rainfall and elevation.

The soil conservation service curve number (SCS-CN) method was used for runoff estimations in each sub-basin. Suitable sites for each rainwater harvesting/ recharge method are determined using Iranian reports standard for rainwater harvesting structure and international researches. An overlay information layer was prepared using runoff coefficient, slope, drainage network, land use permeability, litho logy and soil maps of each sub basin. Suitable sites for each rainwater harvesting/recharge method are determined using Iranian reports standard for rainwater harvesting structure and international researches (Fig. 2). In each sub basin, the amount of the harvestable runoff was estimated for selected water harvesting systems. We supposed that each water harvesting method should absorb and penetrates a percent of the runoff to the groundwater.

The effects of water harvesting system on groundwater level was exanimated under several scenarios using MODFLOW models.

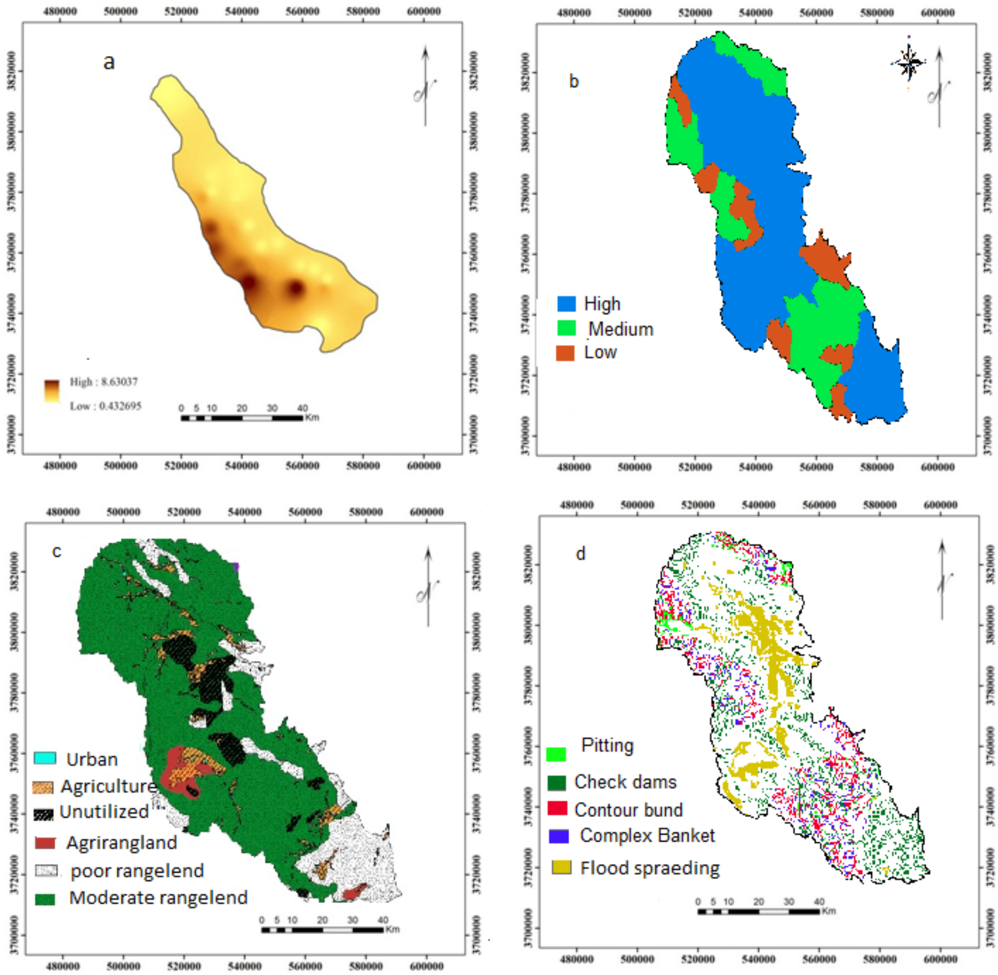

Fig. 2. Hydraulic conductivity of the aquifer (a); Runoff potential (b); Landuse (c) and suitable area for differences water harvesting systems (d).

Results and discussion

Based on the overly maps created via land-use, soil, geological, drainage, physiographical maps, potential runoff and standards characteristics for each water harvesting method (Iranian reports standard for rainwater harvesting structure and international researches shows in Table 1), five water harvesting methods was selected as the suitable methods for rainwater harvesting/recharge in the study area (For more information please see ghazavi, 2014). Suitable area (hectare) and volume of the harvestable water (thousand cubic meter) with different return periods for selected water harvesting systems was shown in Table (2). For each sub basin, the volume of the harvestable water via each method was estimated using CN method, area selected as a suitable method for each water harvesting methods and rainfall with different return period.

The sum of the harvestable water of the studied watershed for differences return period was shown in Table (2) and estimated volume of the harvestable runoff of 5 sub-basins was shown in Table 3 (As example). According to results, maximum harvestable runoff was related to check dams and flood spreading methods (about 74% of the total harvestable runoff). The suitable area for complex banket, check dams, contour bunds, flood spreading and pitting were 43.03, 477.24, 180.93, 489.3 and 81.72 hectares respectively.

Assuming that the proposed procedures can only penetrate the storage runoff created in the areas occupied by each method, the volume of the harvestable runoff will be about 6.89, 7.96 and 8.86 million cubic meters for the return period of 10,25 and 50 years.

For 50 years return period, total harvestable runoff via complex banket, check dams, contour bunds, flood spreading and pitting were 370.16, 3641.18,1409.27, 2885,85 and 549.71 thousand cubic meter respectively. GIS and MODFLOW model were used to predict the impact of the applying of the water harvesting on groundwater recharge and groundwater level under several scenarios. All necessary information including hydrology, meteorology, geology, and satellite images were collected and processed in GIS. Model was calibrated and validated using simulated and measured values of hydraulic conductivity and discharge in the study area.

Table 1. Adopted specifications for potential rainwater harvesting structures based on standard for rainwater harvesting structure and international researches shows.

Structure	Land cover	Slope %	Soil structure	Stream order	Specific runoff volume
Pitting	Low	3-8	clay loam	1-2	Low
contour bunds	Moderate	0-20	clay loam	1-2	Low/moderate
Complex Banket	Moderate/low	20-30	Sandy clay	1-2	Moderate/low
Flood spreading	High	1-5	Sandy clay	3-4	High
Check dam	Moderate/High	>15	Sandy clay loam	1-4	Moderate

Table 2. Suitable area (hectare)and volume of the harvestable water (thousand cubic meter) with different return periods for selected water harvesting systems.

	Complex Banket	Check dam	Contour bunds	Flood spreading	Pitting
	79.47	649.04	2556.44	23405.3	2933.95
	331.15	5576.48	4251.9	807.99	715.27
	1039.8	7291.82	1423.92	165.57	231.8
	490.09	5185.73	417.24	66.23	99.34
	211.93	5159.24	397.37	19.87	105.97
	2152.44	23862.32	9046.88	24465	4086.33
Sum	4304.88	47724.6	18093.8	48930	8172.66
V10	287.22	2840.67	1094.87	2247.38	427.41
V25	335.08	3287.89	1275.23	2592.81	494.96
V50	370.16	3641.18	1409.27	2885.85	549.71

V10, V25 and V50, volume of the harvestable water for 10, 25 and 50 years return period respectively.

Table 3. Estimated volume of the harvestable runoff (thousand cubic meter) of 5 sub-basins (As example).

Sub basin	Method	Area (ha)	V10	V25	V50
1	Farow	1185.5	12.18	14.41	16.11
1	Chekdam	1092.7	11.23	13.28	14.85
1	Pitting	993.44	10.21	12.08	13.5
1	Farow	13.25	0.14	0.17	0.18
2	Chekdam	1125.89	11.91	14.08	15.71
2	Flooding	980.19	10.37	12.26	13.68
2	Pitting	26.49	0.28	0.33	0.37
3	Chekdam	748.39	7.09	8.4	9.48
3	Flooding	5622.84	53.28	63.08	71.2
3	Banket	46.36	5.41	6.17	6.9
3	Farow	99.34	11.6	13.23	14.78
4	Chekdam	4291.64	501.23	571.54	638.58
4	Flooding	9980.71	1165.68	1329.17	1485.08
4	Pitting	46.36	5.41	6.17	6.9
4	Banket	158.95	18.12	22.25	24.69
5	Farow	258.29	28.33	36.16	40.11
5	Banket	112.59	12.35	15.21	16.89
5	Farow	264.92	29.05	35.78	39.75

According to results, a significant relationship (R^2 = 0.87) was observed between simulated and observed hydraulic head for (Fig. 3). These results indicate the accuracy of the model for studied plain. (Fig. 4). indicate water budget of the study. Aquifer using MODFLOW. According to results, Kashan aquifer has a negative budget, as groundwater discharge is about 35 MCM more than groundwater recharge and this amount should increase with this condition.

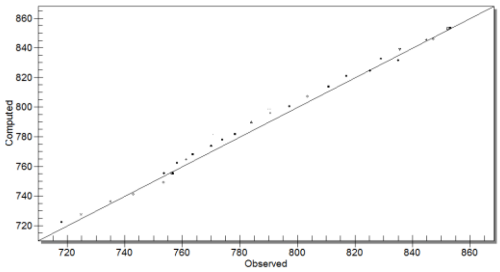

Fig. 3. Relationship between observation and simulation hydraulic head in Kashan aquifer.

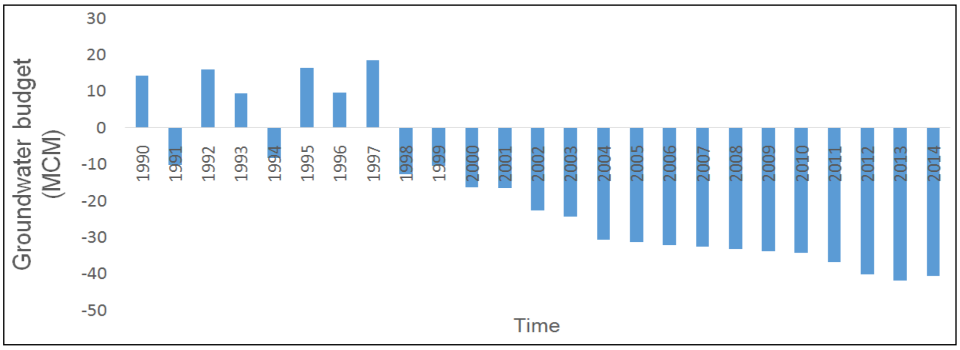

Fig. 4. Water budget of the study aquifer in the normal condition using MODFLOW.

Calibrated model was used to predict the impacts of water storage procedures on groundwater level. To predict the impact of the water harvesting systems, water level data at September 1991 (When minimum negative water budget was reported) was selected as the initial conditions of models and the models was runes for three scenarios (groundwater discharge by rainfall associated with return three return periods of 10, 25 and 50 years).

For estimate the effects of the water storage on the aquifer, exact position of each method was determined within the network aquifer. The initial amounts of the harvestable runoff within the project (the volume of runoff that can accumulate in any method) were determined using SCS. The estimated volume was introduced to the model as the recharge package.

Table 4. indicates the estimated volume of the artificial recharge estimated by MODFLOW in differences scenarios.

Runoff harvesting method	Estimated Volume of the annual recharge via harvestable runoff (Thousand cubic meters)			Average
	V10	V25	V50	
Complex Banket	128.67	137.38	159.17	141.74
Check dam	1107.86	1183.64	1288.98	1193.49
contour bunds	405.10	446.33	450.97	434.13
Flood spreading	1236.06	1400.12	1471.78	1369.32
Pitting	123.95	138.59	144.02	135.52
Sum	3001.65	3306.06	3514.92	3274.21

The results show that the most effective artificial recharge method was flood spreading operation. For 10 years return period, full implementation of flood spreading operation method should recharge 1.2 MCM of water to the aquifer.

Recharge 1.2 MCM of water to the aquifer. Minimum estimated water recharge was related to pitting and Complex Banket with 0.12 and 0.13 MCM respectively.

Conclusion

Rainfall is the main sources of groundwater recharge in the study area. In this area, rainfalls are irregular and unpredictable. The high intensity and short duration of rainfall cause damage floods and less groundwater recharge (Ghazavi *et al*., 2010). In this area, artificial recharge should be main resources of groundwater recharge. These results indicate that artificial recharge should be considering as a main source of groundwater recharge. Some other researchers also show that with artificial recharge, runoff can be contributed in groundwater recharge (Kowsar 1992; Hashemi *et al*., 2013). The results of this study show that the most effective artificial recharge method in this area was flood spreading operation. Hashemi *et al*. (2013) also showed that in a regular year without extreme events, the floodwater spreading system was the main source of groundwater recharge in an arid area in Iran.

According to results, the study aquifer is characterized by a negative water budget (more than -35 MCM per year). Recharge involvement to groundwater from the rainfall should be influence by many factor such as rainfall characteristics (rainfall amount and intensity, rainfall distribution), soil condition (soil texture, pervious moisture of the soil, land cover), and aquifer condition (depth of hydraulic head). In arid area, rainfalls are bimodal, with high intensity and short duration. Moreover, lots of surface runoff lose via evapotranspiration (more than 75% of rainfall in the study area). Hot temperature and low rainfall cause high evapotranspiration and low recharge in via runoff. Water harvesting operation suggested in this study would increase groundwater recharge. Also this operation could not stop groundwater decline, but it can mitigate.

We can conclude that water harvesting operation is an important resource of groundwater recharge in this area. According to results, rangeland was the most suitable area for applying water harvesting systems, as 92, 72,89,54, and 55 presents of the suitable area for complex banket, check dam, contour bunds, flood spreading, and pitting was located in the range land area respectively.

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