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Estimation of Artificial Groundwater Recharge by Flood Water Spreading System in an Arid Region Using Inverse Modeling and SCS Method; A case Study of Mosian Plain

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ABSTRACT

Aims In arid and semi-arid regions, to reduce the impact of infrequent flood, groundwater recharge and decrease flood damages, runoff should be stored through Flood Water Spreading (FWS) systems. The aim of the present study was to estimate of artificial groundwater recharge by flood water spreading system in an arid region using inverse modeling and the Soil-Conservation Service-Curve-Number (SCS-CN) method in Mosian plain.
Instruments & Methods The present study is the original research which was done in a computational manner, groundwater recharge by FWS system under arid conditions of west of Iran was estimated using mathematical and empirical methods. The annual component values of the water balance equation were estimated using the mathematical model (MODFLOW). Groundwater recharge by FWS system was estimated using the inverse modeling approach for the study area. Daily rainfall data (1994-2014) was used to estimate the daily runoff from the upland using SCS-CN method. The estimated runoff was used to estimate the groundwater recharge from FWS system. The R-squared statistic test and PMWIM? Software were used.
Findings Estimated annual average groundwater recharge by the MODFLOW model and SCS method were 6.55 and 8.47MCM respectively (1994-2014). Comparison between mathematical and empirical models showed minor differences. A minimum of 13mm daily rainfall was required to generate 1mm of recharge from the floodwater spreading system.
Conclusion Combination of the mathematical and empirical models can increase the accuracy of the groundwater recharge predictions. Groundwater recharge in FWS system area increase with increasing of rainfall, but after the certain value of precipitation, it is nearly constant due to ponds capacity and infiltration speed limitation.

Keywords Ground-Water; Inverse Modeling; SCS-CN Method; Floodwater Spreading; Mosian Aquifer

CITATION LINKS

[1] Development of a rainfall–recharge relationship for a fractured basaltic aquifer ... [2] Impact of flood spreading on groundwater level ... [3] River water shortage in a highland–lowland system: A case study of the impacts ... [4] Coupled modeling approach to assess climate change impacts on groundwater recharge ... [5] Application of GIS techniques to determine areas most suitable for... [6] The influence of initial soil moisture content on field ... [7] Spatial and temporal trend analysis of temperature and ... [8] Artificial recharge by floodwater spreading estimated ... [9] Artificial groundwater recharge, quantification through inverse ... [10] Artificial ground water recharge with special reference to ... [11] Issues in artificial ... [12] Direct measurement of floodwater infiltration into shallow ... [13] Groundwater recharge from irrigated cropland ... [14] Assessment of natural groundwater recharge ... [15] Changes in components of the water balance in the ... [16] Large-scale groundwater modeling using global datasets ... [17] Ground water modeling with processing modflow ... [18] Assessment of natural groundwater recharge for a river ... [19] Impact of rainfall variability on groundwater levels ... [20] Estimation of surface runoff in nallur amaniker ... [21] A web-based model to estimate the impact of best management ... [22] Identification of rainwater harvesting structure for yerala river ... [23] Rainfall-runoff and soil erosion modeling using ... [24] Estimation of surface runoff in Malattar sub-watershed ... [25] Runoff estimation and morphometric analysis for Hesaraghatta watershed using ... [26] A modular three-dimensional finite difference ground-water ... [27] Modeling the impact of soil and water conservation on surface ... [28] MODFLOW-2000, the U.S. geological survey modular ground-water ... [29] Visual MODFLOW v. 4.1 User's ... [30] Numerical studies on groundwater-grassland ... [31] Studies project of utilization of soil and water ... [32] Investigation of flood spreading effects on ... [33] Estimation of Groundwater Recharge from the ... [34] Past, present and future SCS runoff ... [35] Study the impact of land use and over ... [36] SCS national engineering ...

Introduction

In arid and semi-arid regions of the world, fresh water is scarce [1]. In this area, rainfalls have a bimodal distribution and rainfalls with high intensity mainly occur in winter and spring. High evapotranspiration and bimodal rainfall distribution should cause intra seasonal drought. These rainfall characteristics lead to infrequent damaging floods in wet seasons and high water scarcity in dry seasons [2]. Consequently, groundwater is the primary water source for irrigating and drinking in dry seasons. In such area, groundwater abstraction is expected to increase from 20% in the wet season to more than 70% in the dry season [3, 4].

In arid regions, recharge often occurs via irregular flow [5]. Floodwater produced in the superior catchment, flows into the ephemeral rivers, and is transferred in the adjacent lower catchment. Runoff storage and artificial groundwater recharge are techniques that increase surface water infiltration, consequently should reduce evapotranspiration, mitigate flood hazards and increase groundwater recharge [2, 6]. In the arid and semi-arid areas, artificial recharge has been a traditional method in solving water scarcity problems [7]. Flood water spreading is a type of artificial recharge structure in the arid and semi-arid areas that increase groundwater recharge and should also improve physical and chemical soil properties [2, 8, 9].

Artificial recharge should recover groundwater resources through Flood Water Spreading (FWS) systems and injection wells [10]. FWS system is a technique that upstream runoff collects and spread on a downstream smaller area in order to increase groundwater recharge [11]. Artificial recharge by flood water spreading has been accomplished at 36 multipurpose flood water spreading sites in Iran since 1983 [5]. Estimating groundwater recharge via flood spreading is a key component in the assessment of groundwater systems in arid and semi-arid areas [12]. Evaluation of the viability of proposed projects and the study of the efficiency of the present project needs to an understanding and predictive capability of their chemical and hydraulic effects, which are controlled by the hydrological and geological characteristics of the aquifer system [8].

Various methods were proposed for groundwater recharge estimation. The quantity and quality of information for each model depends on the complication of the methods [13, 14]. Many researchers investigated the effect of total recharge on groundwater storage via many different methods, including water table fluctuation methods, Darcy's law, tracer techniques, and mathematical models [15-18], but very few studies have focused on the separation of different sources of recharge for example artificial recharge.

The Soil Conservation Service Curve Number (SCS-CN) method (SCS 1956) is an empirical model that has been widely accepted by scientists [19-21]. A mathematical model was used to estimate rainfall via remote sensing data and GIS using SCS CN method and runoff potential map [22]. Estimation of runoff via the SCS-CN method and GIS can be used in watershed management [23]. IRSID LISS III satellite images and SCS curve number method were applied to estimate the amount of the surface runoff in Hesaraghatta watershed and an acceptable level of accuracy was reported [24].

The effect of total recharge on groundwater storage was evaluated in several studies using different mathematical and empirical models, but there are few studies that combined empirical and mathematical models.

The main aims of the present study were; 1) to estimate groundwater recharge by FWS system, 2) to combine mathematical and empirical models for prediction of groundwater recharge via flood water spreading and 3) to decrease egregious error in estimation of artificial groundwater recharge.

Materials and Methods

The present study is the original research which was done in a computational manner.

The study area: Mosian plain is located in the western part of Iran in Ilam Province (latitude 32° 22' N and 32° 34'N, longitude 47° 20'E and 47° 39'E) at a height of 247m above mean sea level. (Figure 1). The yearly potential evaporation rate is 3,560mm. The average annual rainfall of Mosian plain is 261mm. The total floodplain area in the northeast of Mosian aquifer is about 120km^2 (20km length and 6km wide) and flood spreading area was located in the southwest of floodplain area. The FWS systems were active for 21 years at the time of the study. The main benefits of the construction of FWS system were flood mitigation and enhance groundwater recharge.

The FWS system in the studied area located in the northeast of Mosian plain. The study area consists of 5 earth embankments situated along contour lines with a distance of about 200m between embankments and 10km length for each one, which consists of water gateway and infiltration pools (Figure 2).

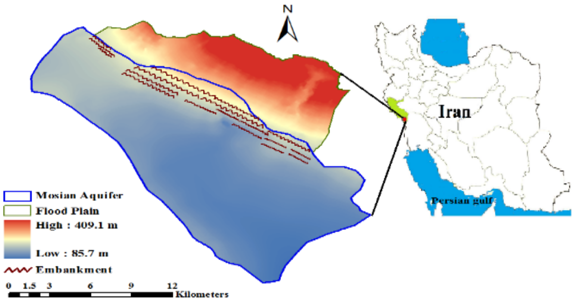

Figure 1) Mosian aquifer, Flood plain area and location of the study area in Iran

Figure 2) Embankments and infiltration pools in the Mosian FWS system

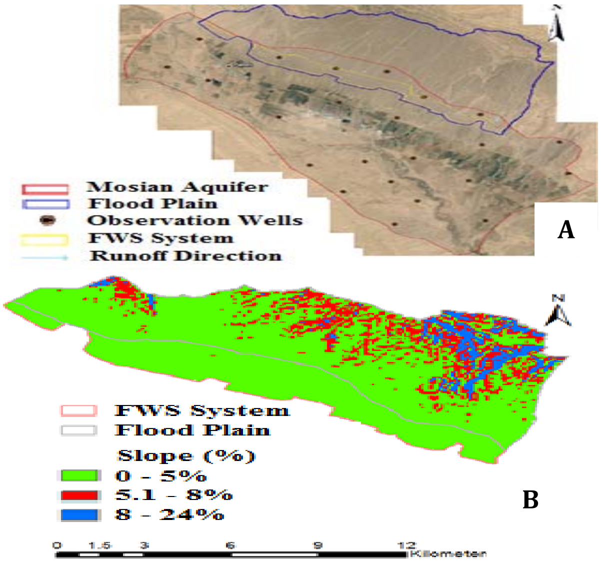

Figure 3) a: Floodwater spreading system, runoff direction; recharge zone and observation well distribution in the Mosian plain; b: Slope map of the upland of the FWSP system

FWS system obtains floodwater directly from the upland area and hillside by ephemeral channels. The upland area (collector area) is a poor rangeland with an area of about 100 km^2 (Figure 3a) General slope in the flood spreading area is between 0.01 to 0.05 and increase until 0.24 upslope of the FWS system (Figure 3b). When floodwater spreads homogeneously behind of each earth embankments and reaches to a certain high, the water should flow to the next infiltration pools via gateways.

Mathematical model: The mathematical model is based on many different equations for calculating hydraulic heads accompanied by specifications of system geometry, boundary, and initial conditions. Dimensions of the numerical model and the design of grids are based on available data regarding the study area, mainly inflows, outflows and system Hydrogeology. The conceptual model must be as much as the representative of the real system as possible, in which constructing the numerical model depends on the conceptual model [25].

Modular Three-dimensional Finite-difference Groundwater Flow Model (MODFLOW) is a mathematical model distributed by the U.S. Geological Survey [26]. This model can simulate groundwater flow in a three dimensional heterogeneous and anisotropic medium. Using the finite-difference method, the domain is divided into a rectilinear mesh of rows, columns, and layers [26, 27]. Aquifer storage; wellhead capture zone delineation, and pumping well optimization were applied [28]. The partial differential equation was used to describe the three-dimensional movement of the groundwater in the constant density through porous earth material [26, 27]:

$$\frac{\partial}{\partial x}\left(Kxx-\frac{h}{x}\right)+\frac{\partial}{\partial y}\left(Kyy-\frac{h}{y}\right)+\frac{\partial}{\partial z}\left(Kzz-\frac{h}{z}\right)+W= Ss\frac{\partial h}{\partial t} \qquad (1)$$

Where Kxx, Kyy, and Kzz in Eq (Equation 1) are hydraulic conductivity values along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (ms^{1}); W is a volumetric flux per unit volume representing sources and/or sinks of water (W.0 for flow into the system and W,0 for flow out of the groundwater system), and; h is the potentiometric head (m); t is time (min) and Ss is the specific storage of the porous material ($1m^{-1}$) [29].

In this study, Mosiain aquifer was modeled via MODFLOW using a network of 261 columns and 236 rows. 61596 square grid cells with 100m dimension within the boundary of Mosian district were created. Cells located inside of the aquifer boundary were indicated by type 1 in which rise or drawdown may occur, whereas, no flow cells indicated by 0 type Utilization of Mosian aquifer was suspended from 1981 to 1989 due to warm between Iran and Iraq, consequently a steady-state for this aquifer was created in these years. The year of 1991 was determined for modeling of Mosian aquifer in the steady state condition. Period 1994-2014 selected as the unsteady state condition. This period was divided into 42 time steps with 6 month length.

Data collection: All available data include geological maps, topographic maps, water level measurements for the selected years, historical rainfall data from all rainfall gauges, different types of wells and wells properties were collected for the Mosian aquifer.

Depth to groundwater was measured in the twenty-three observation wells. The collected data were obtained from many local sources in different formats. The main source of this data was the various regional and local government offices such as Ilam Regional Water Company, Agricultural and Natural Resources Research Center of Ilam Province, Ilam Province Meteorological Office [30-32].

Empirical model: The SCS runoff equation is an empirical model for estimating the amounts of runoff in different soil types and land use [33, 34].

The SCS curve number equation [35] is according to the below equation:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad (2)$$

Where Q_{surf} is the accumulated runoff (mm), R_{day} is the daily rainfall depth (mm), I_a is the initial abstractions (mm), and S is the retention parameter (mm) that varies temporally related to changes in soil water content and spatially due to change in land use, soils, and management system. The retention parameter (S) should estimate by the below equation:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (3)$$

Where CN is the curve number ($0 \le CN \le 100$). The CN is a function of soil permeability (Hydrologic soil group), land use, and antecedent soil water conditions. The initial abstractions, I_a, is commonly approximated as 0.2S and below equation becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \qquad (4)$$

Runoff will only occur when $R_{day} > I_a$.

The land use, cover description, hydrologic soil group, and rainfall frequency of the study area were determined. The field observation was used to determine the land area and cover description. The published soil survey of the study site was used to determine soil type and hydrologic soil groups [36]. Using land cover description and hydrologic group, a curve number was determined for the area of the FWS system. Consequently, the CN value is revised using the empirical equations. SCS Curve Number was used to estimate the amounts of runoff and flood in the flood water spreading project.

The daily precipitation values were used to determine the runoff amount of the study area. The overland runoff in the study region was calculated using the SCS curve number method.

To estimate the amount of floods entering the FWS system, the daily rainfall was taken from the local meteorology organization. In the next step, numbers and amounts of daily rainfalls more than initial abstractions (the times of utilization of FWS system) were extracted and the depth of runoff for each rainfall event was calculated using SCS equations. Finally, the annual runoff was estimated via accumulation of all runoffs multiplied to surface area of upland.

The annual runoff of the study region was estimated using the annual runoff depth and area of the region. It was presumed that annual groundwater recharge by FWS system is equal or lower than calculated runoff.

The R-squared statistic test and PMWIM 5.3.2 Software were used for statistical analysis and groundwater modeling.

Findings

In the calibration step, the optimum Hydraulic conductivity (K) in the Mosian plain had estimated to be 3.7 m per day. A scatter graph of the observed and calculated values represented a comparison between the values simulated by the model and the values observed in the field.

For 23 observation boreholes during the calibration period, determination coefficient (R^2) for groundwater levels was 0.98.

The observed and simulated hydraulic heads of the observation wells were shown in the steady state conditions (Diagram 1 and 2).

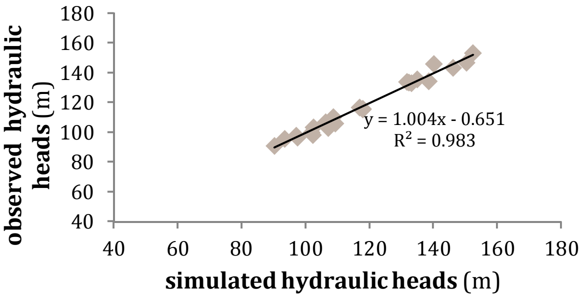

Diagram 1) Observed and simulated hydraulic heads in steady state

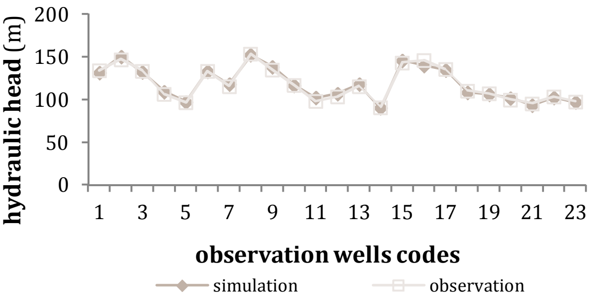

Diagram 2) Observation and simulation hydraulic head for 23 study wells at Mosian plain for steady state condition (Year 1991)

Two different recharge zones were investigated for estimating the recharge rate through the FWS system. The first recharge zone corresponded to the FWS system; the second zone represents the natural recharge. Estimations and simulations recharges were accompanied for the entire model period (1994–2014) as the unsteady conditions. Determination coefficient (R^2) for groundwater levels at the location of 23 observation boreholes well was 0.97 during the calibration period (Table 1).

The accuracy of the model was shown as a management tool for the scrutiny of different suggestions, policies, and scenarios. Maximum and minimum estimated annual groundwater recharge from the floodwater spreading system during 1994-2014 was 18 MCM and 0.58 MCM respectively (Table 2).

The mean annual rainfall of the study area was 261.00±110.00m for the period between 1994 and 2014 with a maximum rainfall of 625mm in 1996 and a minimum of 103mm in 2012 (Diagram 3). The curve number (CN) for the study area was obtained about 79. Based on the rainfall distribution pattern, groundwater discharge via surface runoff occurred for about 6 months of the years. The initial abstractions (0.2S) or threshold of rainfall for producing runoff was obtained about 13mm. This amount was approximately according to the viewpoint of experts of the FWS system project.

According to SCS Curve number method, maximum and minimum runoff in the study area was estimated to be 434.5mm 1.1mm in the years 1996 and 2012 respectively (Table 3).

Table 1) Observed and simulated hydraulic head of observation wells in Mosian aquifer, during 1994-2014 (in Novembers)

Year	OW01		OW02		OW03		OW03		OW04		OW05	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1994	42.94	42.08	22.34	21.89	6.95	6.81	26.55	26.02	19.8	19.40	42.94	42.08
1995	42.26	41.41	21.75	21.32	6.32	6.19	26.34	25.81	18.9	18.52	42.26	41.41
1996	43.59	42.72	22.36	21.91	6.72	6.59	28	27.44	19.3	18.91	43.59	42.72
1997	44.1	43.22	23.15	22.69	9.63	9.44	28.89	28.31	19.36	18.97	44.1	43.22
1998	43.49	42.62	22.26	21.81	7.93	7.77	28.93	28.35	19.7	19.31	43.49	42.62
1999	42.44	41.59	23.65	23.18	8.37	8.20	30.68	30.07	19.87	19.47	42.44	41.59
2000	45.03	44.13	25.15	24.65	10.17	9.97	33.1	32.44	20.04	19.64	45.03	44.13
2001	45.54	44.63	25.97	25.45	11.39	11.16	34.55	33.86	20.44	20.03	45.54	44.63
2002	47.52	46.57	26.16	25.64	12.17	11.93	34.92	34.22	21.16	20.74	47.52	46.57
2003	47.72	46.77	27.29	26.74	13.48	13.21	39.36	38.57	21.92	21.48	47.72	46.77
2004	48.37	47.40	27.5	26.95	13.45	13.18	41	40.18	22.02	21.58	48.37	47.40
2005	48.77	47.79	27.53	26.98	14.94	14.64	42.67	41.82	21.67	21.24	48.77	47.79
2006	48.77	47.79	26.23	25.71	15.48	15.17	43.29	42.42	21.88	21.44	48.77	47.79
2007	48.81	47.83	26.99	26.45	15.96	15.64	44.91	44.01	22.04	21.60	48.81	47.83
2008	49.4	48.41	29.35	28.76	17.33	16.98	46.73	45.80	22.57	22.12	49.4	48.41
2009	50.22	49.22	31.62	30.99	18.41	18.04	47.85	46.89	22.69	22.24	50.22	49.22
2010	51.25	50.23	33.05	32.39	18.33	17.96	50.08	49.08	22.72	22.27	51.25	50.23
2011	52.85	51.79	34.75	34.06	20.06	19.66	51.58	50.55	22.5	22.05	52.85	51.79
2012	54.33	53.24	36.25	35.53	21.48	21.05	53.15	52.09	22.7	22.25	54.33	53.24
2013	55.06	53.96	36.32	35.59	20.11	19.71	53.64	52.57	22.42	21.97	55.06	53.96
2014	55.27	54.16	32.2	31.56	20.28	19.87	54.3	53.21	22.72	22.27	55.27	54.16

Table 2) Annual simulated groundwater recharge volume in floodwater spreading system using MODFLOW model

Year	Groundwater recharge (m^3)
1994	4002632
1995	10409623
1996	18398245
1997	1729649
1998	10116505
1999	4666168
2000	3611537
2001	4475237
2002	5298043
2003	2992036
2004	6042009
2005	3050426
2006	4054265
2007	6452377
2008	921768
2009	3077439
2010	3005494
2011	650238
2012	58933
2013	3722679
2014	5065418

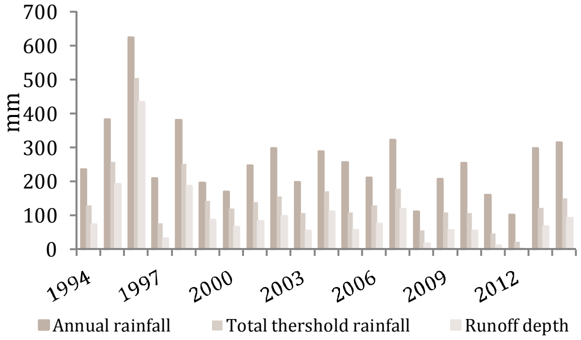

Diagram 3) Total rainfall, effective rainfall, and runoff depth in Mosian plain during 1994-2014

Table 3) Annual runoff volume in the flood spreading estimated via SCS method

Year	Runoff volume (m^3)
1994	6671054
1995	17349372
1996	38997075
1997	2882748
1998	16860841
1999	7776947
2000	6019228
2001	7458728
2002	8830071
2003	4986727
2004	10070015
2005	5084044
2006	6757108
2007	10753961
2008	1536279
2009	5129065
2010	5009157
2011	1083729
2012	98222
2013	6204465
2014	8442363

There were correlated between rainfall and runoff of the study area. The rainfall and runoff were correlated with a coefficient of determination (R^2) value of 0.89 (Diagram 4). A maximum recharge of 150mm showed in 1996 and a minimum of 1mm in 2012 (Table 3). The annual runoff volume estimated via the SCS method in the flood spreading district during 1994-2014 was indicated in Table 3. Maximum and minimum groundwater recharge occurred in 1996 and 2012 respectively (Table 2).

Groundwater recharge in the FWS system area increased with the increasing of rainfall, but it was nearly constant after the certain value of precipitation due to ponds capacity and infiltration speed limitation.

In 1996, when maximum rainfall occurred, the estimated runoff volume via SCS model was about 38 MCM, whereas estimated artificial groundwater recharge via MODFLOW model was about 18 MCM (Diagram 5).

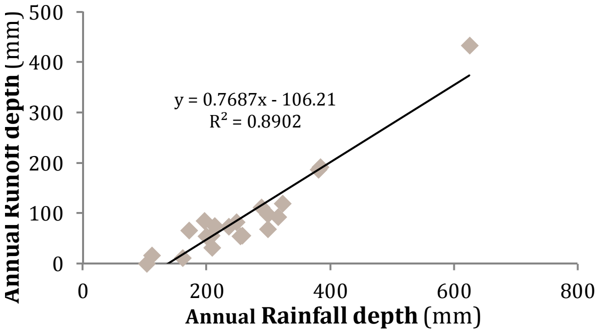

Diagram 4) Rainfall runoff relationships in FWS system during 1994-2014

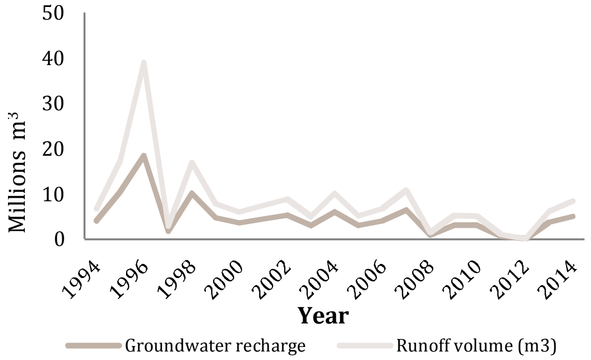

Diagram 5) Groundwater recharge (MODFLOW) and flood volume (SCS)

Discussion

The aim of the present study was to estimate of artificial groundwater recharge by the flood water spreading system in an arid region using inverse modeling and SCS method in Mosian plain.

In this study, the mathematical and empirical models were combined for a better performance of groundwater recharge prediction via FWS in an arid area. According to results; the combination of these models could increase accuracy of the groundwater recharge predictions.

This present showed the annual groundwater discharge via pumping was about 24 MCM in 1994 and increased to 59 MCM in 2014. Groundwater discharge over the past 22 years has been about 1 Billion cubic meters, while, groundwater recharge via artificial recharge was about 80 MCM or about 8 percent of groundwater discharge. FWS in the study area decreased groundwater level dropping (about 1.2 m in the past 22 years. Also, the floodwater spreading system could improve groundwater resources in arid and semi-arid areas [2], but it is not efficient to repair the water utilization completely.

Combination of mathematical and empirical models could decrease estimation errors of the artificial groundwater recharge. This method could also help prevent over-estimation of the artificial recharge via water harvesting systems when the volume of runoff is higher than flood water spreading capacity. The results of empirical model can be used as an indicator to evaluate of the mathematical model and avoid errors in its results.

These results indicate important rainfall data, pond watering rates, and evaporation rates for the evaluation of flood water spreading performance. Combination of empirical relations and mathematical models for FWS systems evaluation causes that this data used in the evaluation processes and consequently, a more accurate result in the evaluation will be derived.

Totally, in this present study the mathematical and empirical models were combined for a better performance of prediction of groundwater recharge via flood water spreading. Combination of mathematical and empirical models could decrease large error in estimation of artificial groundwater recharge. This method could also help prevent over-estimation of the artificial recharge via water harvesting systems when the volume of runoff is higher than flood water spreading capacity. The results of the empirical model can be used as an indicator to evaluate of the mathematical model and avoid errors in its results.

The limitations of this research include the lack of the accurate data and uncertainty of the hydrodynamic parameters of the aquifer. For the next studies, increasing of exploratory wells in the Mossian aquifer and optimizing of the hydrodynamic parameters of the aquifer via new pumping tests was suggested.

Conclusions

The combination of the mathematical and empirical models can increase the accuracy of the groundwater recharge predictions. Also, groundwater recharge in FWS system area increase with the increasing of rainfall, but after the certain value of precipitation, it is nearly constant due to ponds capacity and infiltration speed limitation.

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Ethical permissions: The authors certify that the information contained in this application is accurate. They confirm that the research will be conducted in line with all University, legal and local ethic al standards.

Conflicts of interests: The Authors stat that there is no conflict of interest.

Authors' Contribution: Ghazavi R. (First author), Introduction author/ Methodologist/ Original researcher/Statistical analyst/ Discussion author (50%); Ebrahimi H. (Second author), Introduction author/Methodologist/Original researcher/Statistical analyst/ Discussion author (50%).

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