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Evaluation of WEAP-MODFLOW Model as an Integrated Water Resources Management Model for Sustainable Development (A Case Study: Gharesoo at Doab-Merek, Kermanshah, Iran)

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ABSTRACT: This paper evaluated an integrated water resources management approach through linked WEAP-MODFLOW model. Study area is Ravasnar-Sanjabi plain located in Kermanshah province in the west of Iran. A MODFLOW model was evaluated and then, accepted as a groundwater model for the region in present research. Schematic WEAP model was provided as representing general features of water resources system after designing a conceptual model for the study area. The simplified rainfall-runoff model in WEAP was used to perform hydrological simulations. In the second step of present research, the groundwater model was linked to WEAP dynamically. Simulation years with 12 time steps per year included years of 2007-2015 for creating and verifying WEAP-MODFLOW model and years of 2015-2030 for performing scenarios. Statistical criteria included mean absolute error (MAE), root mean square error (RMSE), and Nash-Sutcliffe (NASH), with Box plot diagram being selected to assess accuracy of calibrated model. Four scenarios were implemented for 2015 until 2030. They included unchanged present situation and situations with 35%, 45% and 57% reduction of groundwater and surface water withdrawal. Results showed that the fourth scenario with a 57% decrease in the extraction of surface water and groundwater resources was the best one. Based on this scenario, exploitation of the system will be sustainable, with the system recovering as 0.023 meter rising per year. Finally, the results of present study indicated that the approach was feasible for planning and managing water resources in spite of the lack of some data.

Keywords: Integrated Water Resources Management (IWRM), MODFLOW, Sustainable Development, WEAP.

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INTRODUCTION

The water resource was investigated separately as groundwater and surface water up to 1960. The first basic research on integrated studies was done in 1961 (Hall and Buras, 1961). Studies performed by Bittinger (1967) and Bredehoeft and Young (1983) escalated from the mid-70s. Bittinger (1967) introduced more aspects through his articles. Based on this approach, there are some dynamic interactions between all components of water resources within a basin due to the fact that changes in stress of each component have some effects on others.

Conjunctive use of surface water and groundwater was improved and developed by others (Illangasekare and Morel-Seytoux, 1982; Moddock, 1974; Morel-Seytoux and Daly, 1975). The research on producing a framework for integrated water resources management issues has expanded since 1980s. These issues were related to legal, social, environmental and political objectives. Simulation, hence optimization, were developed to a large extent in 1990s. Ramireddygray et al. (2000) developed an integrated, watershed-scale model by combining POTYLDAR model for surface water and MODFLOW model for groundwater. They concluded that irrigation was a major budget item for managing water resources on watershed scale.

Marino (2001) selected a basin-wide management strategy to consider conjunctive use of surface water and groundwater to achieve optimum condition of use of water, for which different users were competing. Vedula et al. (2005) used an integrated-optimized model to achieve maximum utilization under constrained conditions by integrating the water releasing from reservoir into the canal and pumping from groundwater in order to allocate water in different seasons. Respective constraints were grouped in three categories: 1) mass balance in the reservoir, 2) soil moisture separated by each crop, and 3) equations governing the groundwater flow. Finally, a linear programming (LP) model led to an integrated – optimized model by defining constraints in objective functions.

Gaiser et al. (2008) developed the integrated regional MOSDEW model in Neckar basin in southwest Germany. Then, the model was tested and validated within some other basins under limiting ecological, hydrological and socio-economic boundary conditions. Results were promising with respect to the use of model with scenario simulations for strategic basin-wide planning of water management, which improved strategic planning of water resources management by taking 9 sub-models into account. WEAP MODFLOW link was used as an effective tool in the assessment of groundwater - surface water hydrological water-use system (Lovell, 2009; Condon and Maxwell, 2013; Li et al., 2018).

Sustainable management of groundwater and surface water is particularly important in the areas affected by water shortage such as Central Asia and Western China (Howard and Howard, 2016; Li, 2016). Simulating complex condition of over-extraction and appropriate management approach of aquifers are required to compensate drawdown. Conjunctive use of surface water and groundwater is a common element for integrated water resources management. Several studies have been performed on conjunctive use of surface water and groundwater on the farm and/or river basin scales (Pulido-Velázquez et al., 2006; Diao et al., 2007; Alam and Olsthoorn, 2011; Mahjoub et al., 2011; Alam and Olsthoorn, 2014; Li et al., 2018; Li et al., 2015; Singh, 2014; Hanson et al., 2014; Xin et al., 2015; El-Rawy et al., 2016).

Hadded et al. (2013) assessed water resources based on various scenarios by using an integrated model within the framework of WEAP-MODFLOW and DSS in the Zeuss

Kuotine aquifer, southeast Tunisia, during a protracted period terminating in 2030.

Dimova et al. (2014) used System of Economic and Environmental Accounts for Water (SEEAW) and Water Evaluation and Planning System (WEAP) to perform a hydrological integration study. Kareem (2015) did some research on conjunctive use of surface water and groundwater within Jolack basin of northern part of Kirkuk, Iraq, using different models (SWAT for surface water and GMS for groundwater modeling). Safavi et al. (2015) studied water demand and supply in Zayanderud river basin, Iran, using Adaptive Network-based Fuzzy Inference System (ANFIS). Results of their research showed that current water management policy was not viable, and additional water management policies were required that could reduce water demands by improving irrigation water efficiency and decreasing groundwater extraction in order to achieve sustainable conditions within Zayanderud basin. Safavi et al. (2016) performed a study to develop and analyze three scenarios based on their own 2015 research as supply management, demand management, and meta management (combined supply and demand management). Five performance criteria were used in the process of scenario analyses as follows: time-based and volumetric reliability, resilience, vulnerability, and maximum deficit. Results of meta scenario indicated that both supply and demand management scenarios needed to be applied if water resources were to be protected against degradation and depletion.

Finally, the authors demonstrated that Meta scenario could improve water resources sustainably. Omar and Moussa (2016) studied different scenarios to eliminate water shortage by 2025 by using WEAP model. Above literature review shows that different combinations of models and scenarios were selected by different researchers to examine integrated water resources management regarding the conjunctive use of surface water and groundwater. Seo et al. (2018) developed a conjunctive management model to obtain optimal allocation of surface water and groundwater under different constraints during drought periods. The model was tested for Haw River basin located in North Carolina. A combined simulation model consisting of a fully distributed hydrological model and a Penn State integrated Hydrological Model (PIHM) was used to compute depletion of stream flow and groundwater level simultaneously under pumping condition. A reservoir simulation model was then incorporated in the optimization framework to determine optimal allocations of surface water and groundwater resources. It can be concluded that management model proposed by present study is a big step toward sustainable groundwater withdrawal during drought periods.

Ravansar-Sanjabi plain is located in Ravansar-Sanjabi basin leading to Doab Merek outlet in Kermanshah, southwest of Iran. This plain has experienced an increasing drawdown equal to 12 meters for the past 10 years (Porhemmat et al., 2016).

Ravansar-Sanjabi aquifer is under critical conditions due to severe drawdowns according to many reports (Kavab Consulting Engineers, 2002; Eghlimtarh Consulting Engineers, 2007; Porhemmat et al., 2016). As a result, it is necessary to perform present study to investigate water resources management in this area.

MATERIALS AND METHODS

Location, Hydrology, River Network

Ravansar-Sanjabi basin is located in northwestern part of Kermanshah province, west of Iran (Figure 1). Average altitude of Ravansar-Sanjabi basin is 1556 m above mean sea level, its lowest elevation is 1307 m in south-southeast and the highest one is 2737 m above mean sea level.

This area has a mountainous humid climate in northern and southwestern parts and semi-humid in central parts (Kavab Consulting Engineers, 2002). The average annual rainfall is 526 mm, with maximum monthly rainfall occurring in March and April, and the minimum in July.

Ravansar-Sanjabi basin has a drainage network in direction of northwest to southeast, which is equipped with two hydrometric stations on the main river, as shown in Figure 2 (Ravansar shown in the middle part of Figure 2 and beginning of main river; Doab-e Merek shown at the outlet). Mean monthly discharges from above mentioned hydrometric stations are given in Table 1.

Long-term temperature statistics at Ravansar synoptic station is 14.9 ºC as the average, and 22.5 ºC, 41.4 ºC, 8.2 ºC and 21.6 ºC as absolute minimum, absolute maximum, average minimum and average maximum temperatures, respectively. Similarly, evapotranspiration values are 795.45 mm/yr and 713.32 mm/yr within the plain and on the mountains, respectively.

Table 1. Comparison of long-term means monthly Doab and Ravansar hydrometers statistics in m^3/s

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Ravansar	1.34	2.929	3.083	3.73	6.833	10.9	13.15	10.19	7.714	5.251	3.625	2.58
Doab	3.343	5.44	8.6	9.7	15.57	31.58	44.61	30.50	10.15	5.806	3.88	3.06
Difference	1.998	2.511	5.517	5.97	8.737	20.68	31.46	20.31	2.436	0.55	0.25	0.48

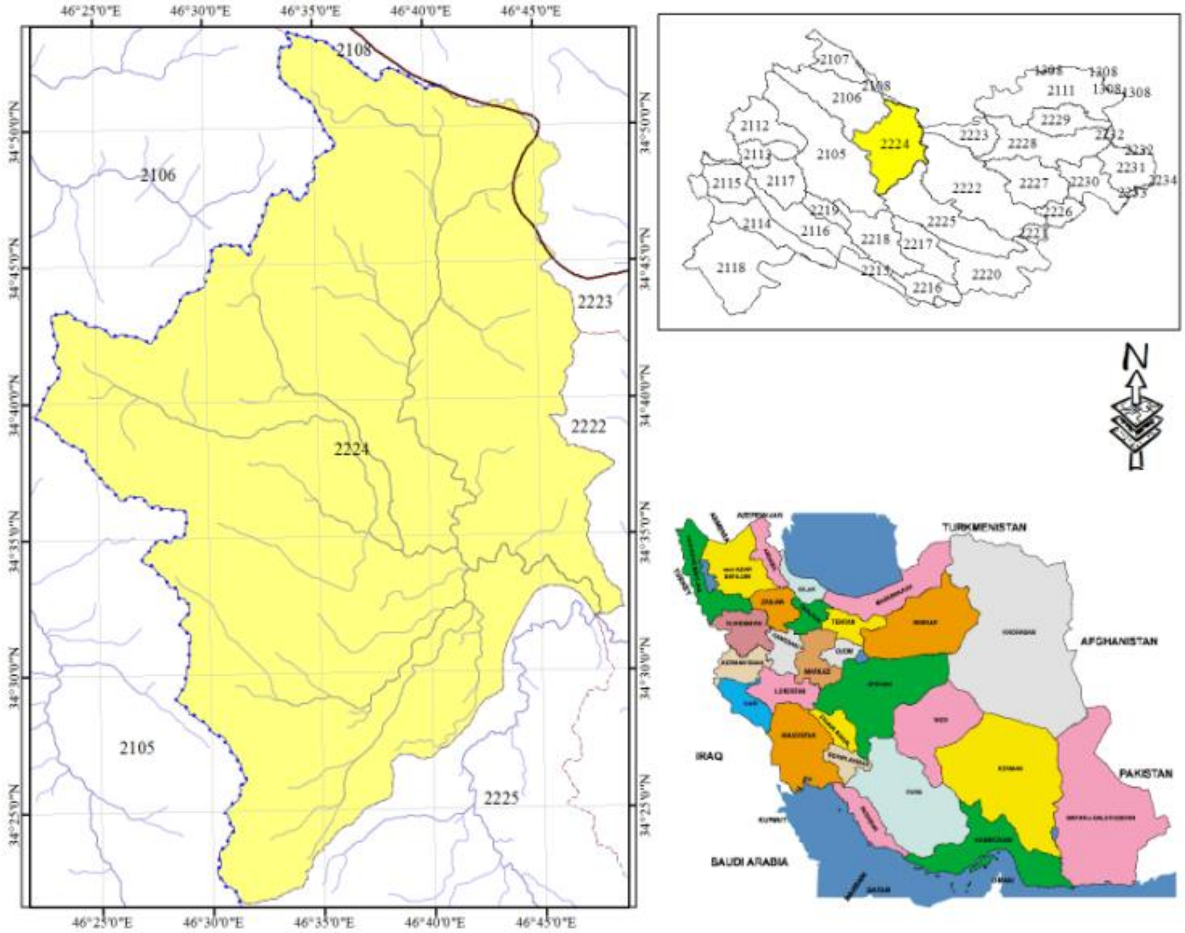

Fig. 1. Location of the study area relative to Kermanshah province, Iran

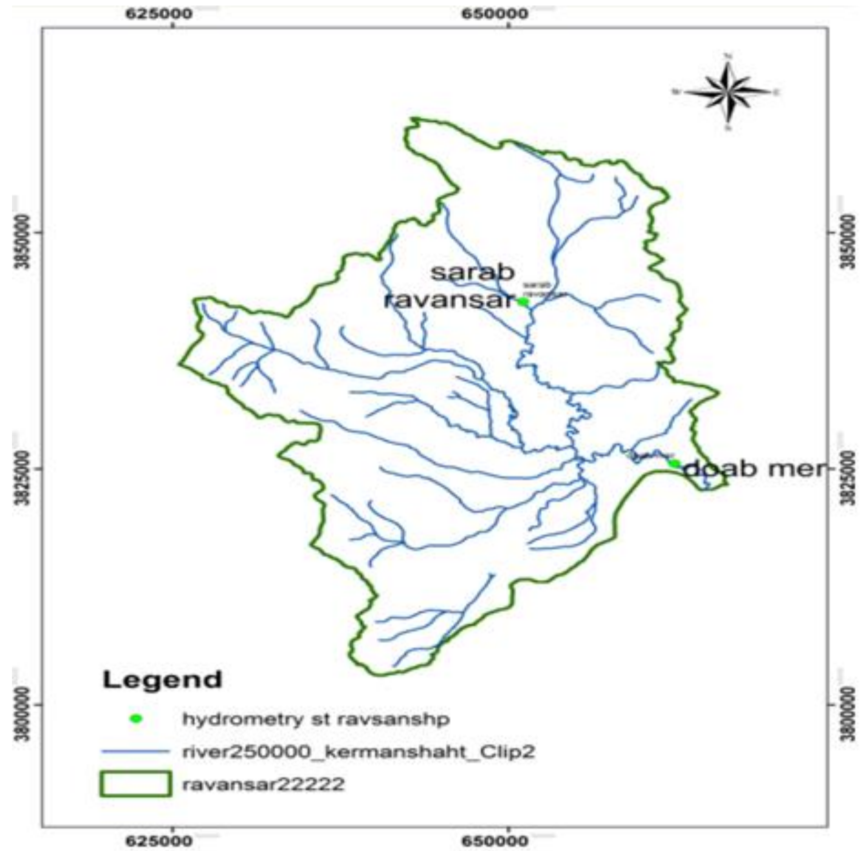

Fig. 2. Drainage network with hydrometric stations

Geology and General Karst Setting

Based on structural geology, the region includes a large number of thrust faults situated between the edges of crushed and folded zones of Zagros belt, creating some imbrications structures. General trend of these structures is northwest-southeast, details of which can be seen in the simplified map shown in Figure 3 (Nazari et al., 2015).

Figure 3 shows Bistoon Karstic limestone thrusted over a radiolarite formation in a zone of thrust faults and ZF formation (from a floded zone of Zagros) being separated by the above thrust faults. Lithology and stratigraphy of Bistoon include bioclastic and oolitic limestones dating back to the upper Triassic_ upper Cretaceous. This formation is severely crushed, generating mature karst in the region. Radiolarite formation contains two upper and lower parts, with alternating chert, conglomerate, marl, and shale and then microbreciated limestone in lower part. ZF formation is lime clay with microgranular texture known as Ilam formation, granular limestone and dark gray Gourpi formation. The top formation is quaternary deposits about 150-200 m thick (Zamin Kave Gostar Consulting Engineers, 2013).

Water Supply and Demand

Water demands in the study area include: drinking water required by the city and villages equal to about 3.095 MCM/yr; industrial water requirements equal to 0.593 MCM/yr; traditional water rights equal to 7.741 MCM/yr; and the amount of water required for hydraulic interactions between surface water and bedrocks (Fotovat et al., 2018), equal to about 6.279 MCM/yr, as shown in Figure 4. These numbers are given as input data separated by their time periods for the model and also for the future time based on calculated population growth.

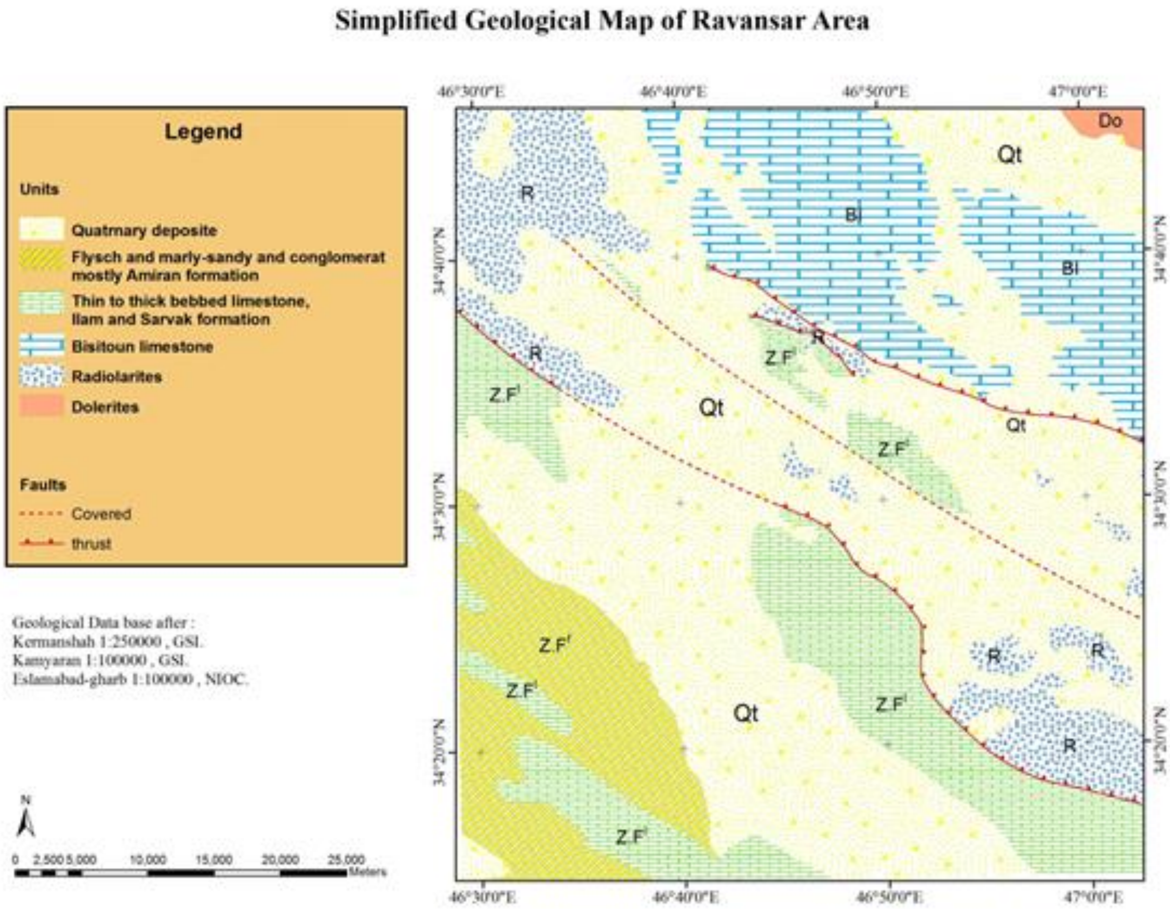

Fig. 3. Simplified geological map of the study Ravansar-Sanjabi area (Nazari et al., 2015)

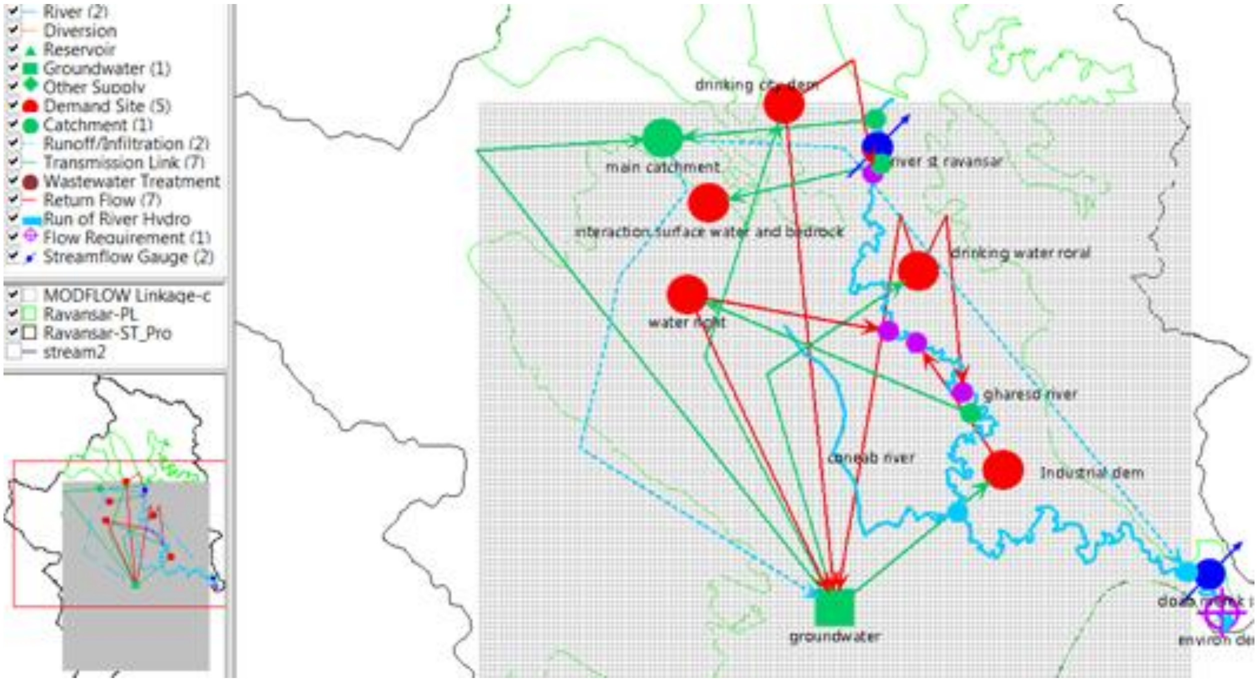

Fig. 4. Schematic of WEAP with demand and supply nodes

General Framework of WEAP Model

This section includes three sub-sections: schematic of water demands and supply resources, groundwater model, and surface water resources model, which are explained below.

Schematic Views of Hydraulic System, Water Demand and Supply

A conceptual model of water demand and supply was designed based on the present conditions of the basin. Figure 4 shows water demand and supply as a schematic in the conceptual model. These nodes represent abstract entities and do not have a direct match in real world. Groundwater node, for example, represents the entire groundwater reservoir in the area and environmental demand based on Tennant method (Azari, 2011; Sedighkia et al., 2017) indicates the entire system environmental demand. Nodes in the schematic model of WEAP are dynamically related to each other and to other components of the combined model with connected lines such as transmission links, return flow, runoff/ infiltration, etc. It is also possible to establish a link between groundwater model and WEAP by creating a linkage file and connecting the MODFLOW cells to the nodes (Azari, 2011).

Groundwater Model

To design grids in the study area is an early step in developing a groundwater model consisting of active (cells with inflow or outflow) and inactive (cells without inflow or outflow) cells relative to spatial distribution of recharge or discharge in aquifer (Figure 5).

MODFLOW 2000 was used to develop the hydrodynamic model of Ravansar-Sanjabi aquifer based on MODFLOW calibration model developed by Porhemmat et al. (2016) for this plain. Results of above research showed that hydraulic conductivity varied between 0.1 to 120 meters per day and average storage coefficient was 7.1×10^{-2}.

Hydrological Simulations

There are five methods available in WEAP to simulate evapotranspiration, runoff, infiltration, and irrigation demands. These methods are rainfall-runoff, simplified coefficient approach for irrigation demands, Soil Moisture Method (SMA), MABIA method (Allen and et al., 2005), and Plant Growth Model approach (PGM) (Sieber and Purkey, 2016).

In this research, the first method (rainfall-runoff) was applied given the possibilities and available data. The basis of this method is to calculate effective rainfall based on differences in rainfall and evapotranspiration, separation infiltration, and runoff portion. ET_0 was used to calculate crop water requirements, having higher accuracy for ET_{crop} with respect to the type of regional cultivation (Allen, 1998).

In the WEAP, required data was entered into the model through DATA tab.

RESULTS AND DISCUSSION

Results of WEAP-MODFLOW model was presented generally for two time periods: first, current state (status quo) or reference scenario period from October 2007 to September 2015, during which the model was developed and verified. Second, the time period from October 2015 to September 2030, during which future scenario was implemented and forecasts were made. Results were acceptable in spite of the existence of some uncertainty parameters and models such as the absence of hydrometric stations for sub-basins, K_c in rainfall-runoff model, quantity of hydraulic interactions between porous media and bedrock of aquifer in vicinity of main river, and amounts illegal withdrawal of groundwater and surface water based on statistical indexes and comparison curves for calculated and observed data shown in Figures 6-11. Results for these two scenarios are shown in Figures 8, 12, 14, 16 and 18 as volumetric changes in groundwater reservoir and comparisons of observed and calculated discharges of surface water at Doab-e Merek station are shown in Table 3 and Figures 6, 7, 13, 15, 17 and 19.

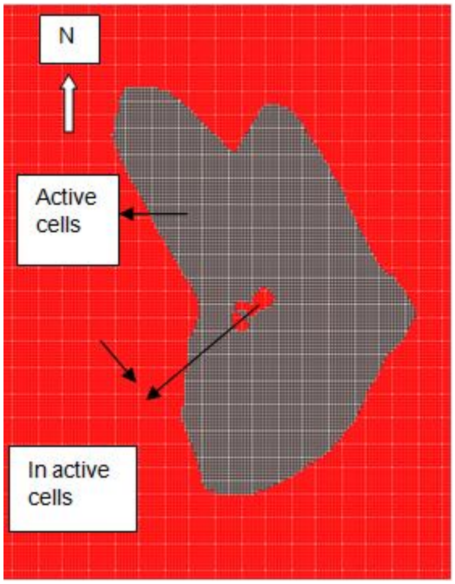

Fig. 5. The area of aquifer active and inactive cells in the study region (Porhemmat et al., 2016)

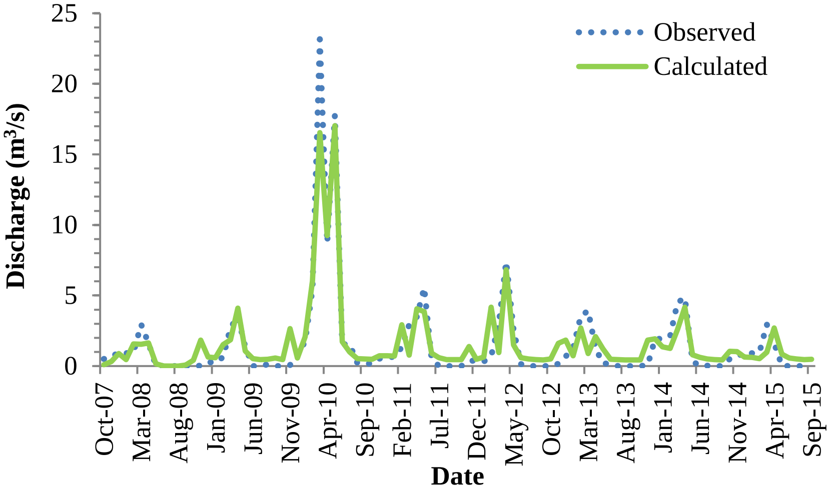

Fig. 6. Comparison of observed and calculated monthly discharge curves at Doab station in current years

Table 2. Water balance components (2007-2015)

Year Parameter	2008	2009	2010	2011	2012	2013	2014	2015	Sum
Consumption	-132.0	-143.7	-199.2	-150.3	-147.0	-160.2	-160.9	-157.5	-1250.8
Inflow from Ghareso river	17.50	24.1	59.6	44.5	46.3	51.1	50.4	50.8	344.3
Inflow from groundwater	88.14	83.9	72.9	80.6	97.5	89.2	86.3	89.5	688.1
Outflow to Ghareso river	-9.4	-27.9	-38.3	-31.9	-33.7	-33.1	-30.1	-25.3	-229.6
Outflow to groundwater	-15.6	-50	-69.8	-57.5	-61.3	-59.8	-53.9	-45.5	-413.4
Precipitation	51.42	113.52	174.79	114.49	98.3	112.8	108.2	88.0	-861.5
Sum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

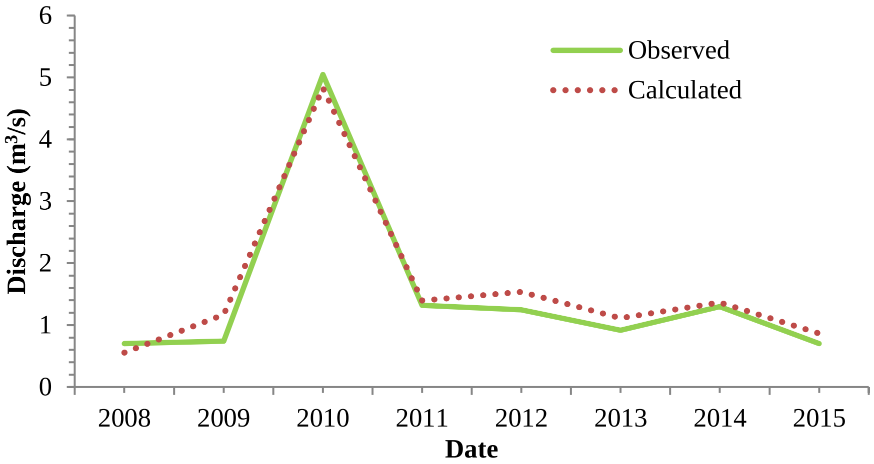

Fig. 7. Comparison of observed and calculated annual discharges of Gharesoo river at Doab-Merek station (2007-2015)

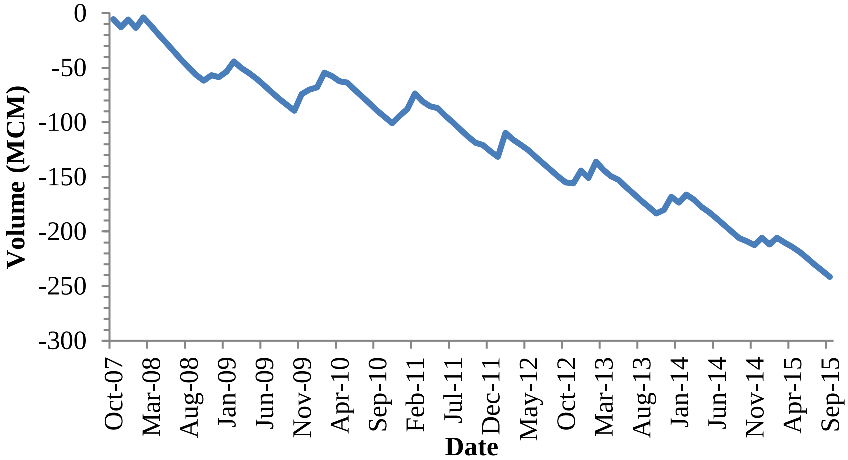

Fig. 8. Volumetric changes of groundwater storage under current conditions and reference scenario during the period of 2007-2015

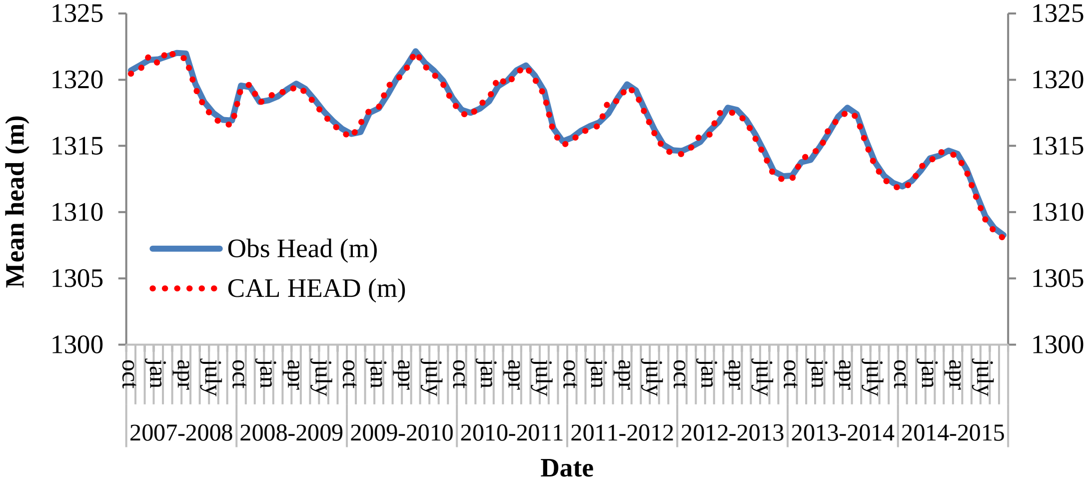

Fig. 9. Comparison of observed unit hydrograph and calculated mean monthly decrease in groundwater levels in current condition and reference scenario years (2007-2015)

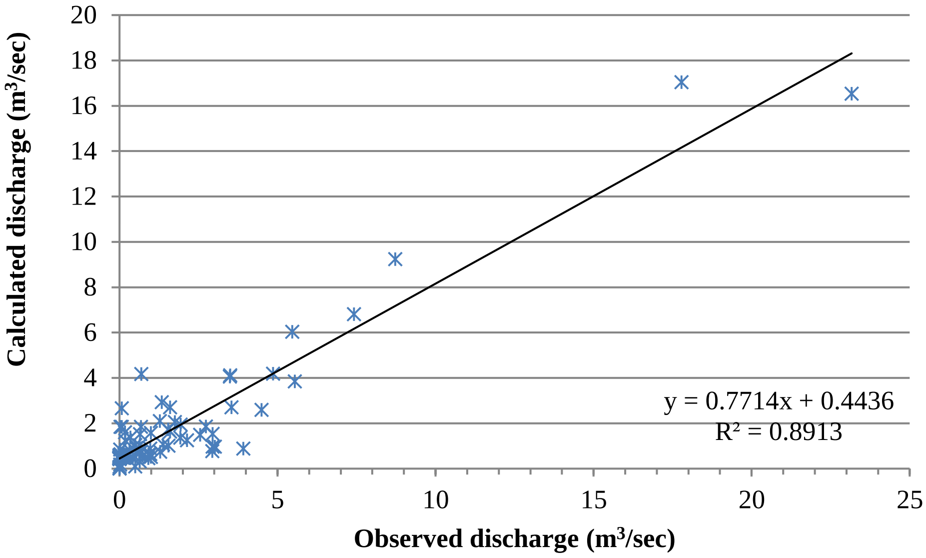

Fig. 10. WEAP model evaluation based on mean absolute errors (MAE) at Doab Merek station (gauge)

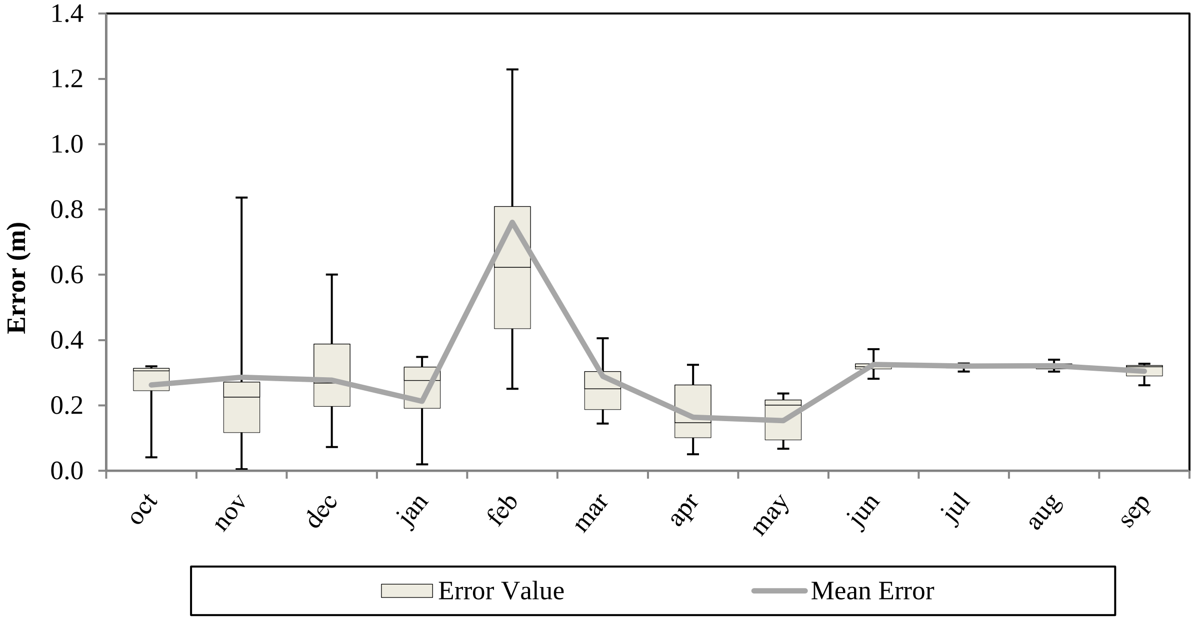

Fig. 11. Box plot of observed and calculated mean monthly groundwater heads simulations in current condition and reference scenario periods (2007-2015)

Results for Current Conditions and Reference Scenario

These results are presented in Table 2 as water balance, evaluated surface water simulations, and groundwater modeling all within framework of WEAP model.

Based on Table 3 and Figures 6 and 7, except for some peaks of curves in some months, a good match is seen between observed and calculated graphs. The mismatch in peaks of curves can be explained by complexities in structural geology and in interaction of karst and fractured media with porous media along main river in the region.

Figure 8 shows groundwater volumetric changes calculated at 236 MCM during current condition and reference scenario years.

Figure 9 illustrates comparison of unit hydrograph based on observed data and calculated mean monthly decrease in groundwater levels. On this basis, the model performs well in simulating the study area groundwater.

Figure 10 shows the results for calculated discharge versus observed discharge at Doab-e Merek station. As shown in Figure 10, R^2 is 89%, RMSE is 1.1, and NASH is 86%. Accordingly, calculated model curves do match with observed items. This overall synchronization can be explained by statistical indices such as MAE, RMSE and NASH.

Box plot of differences between heads calculated by the model and observed heads of groundwater unit hydrograph is shown in Figure 11. Based on the plot, mean errors are close to median ones, and, in addition, good matches are seen in June, July, August and September.

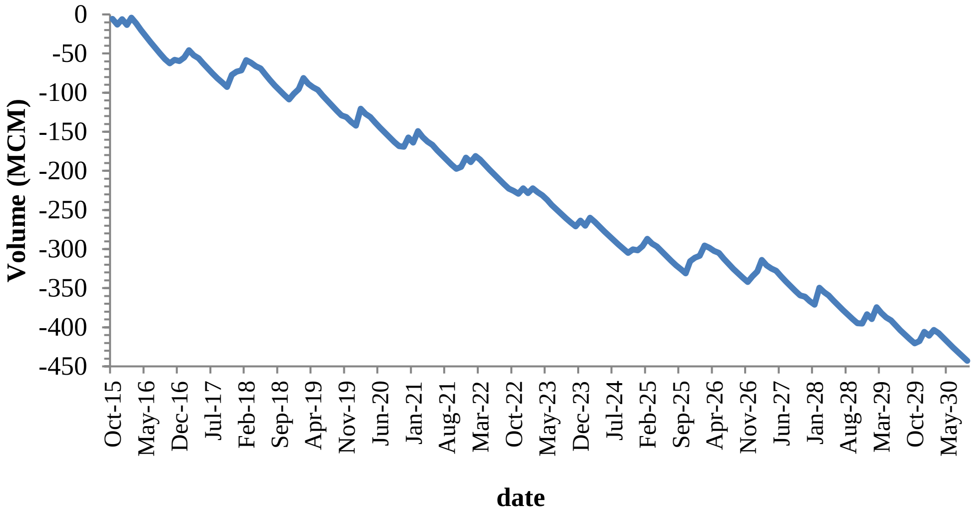

Fig. 12. Volumetric changes in groundwater storage based on Scenario 1

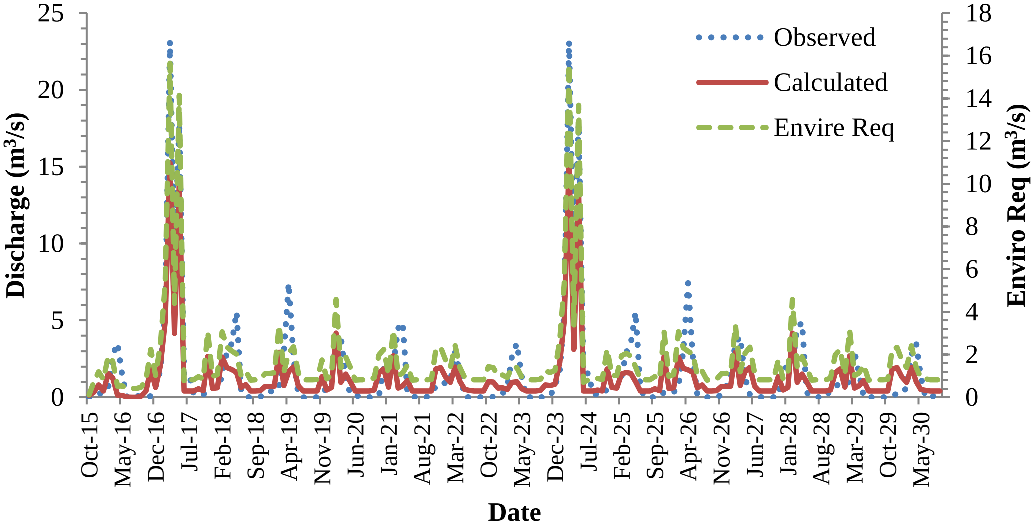

Fig. 13. Comparison of observed and calculated discharges of Gharesoo river at Doab Merek station based on Scenario 1

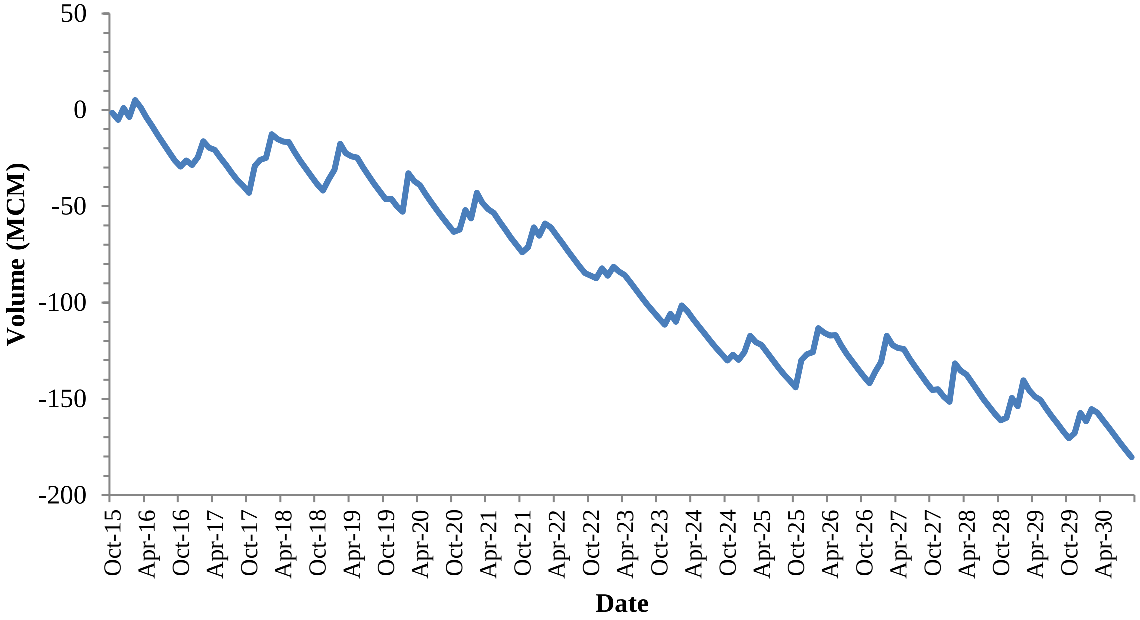

Fig. 14. Volumetric changes in groundwater storage based on Scenario 2

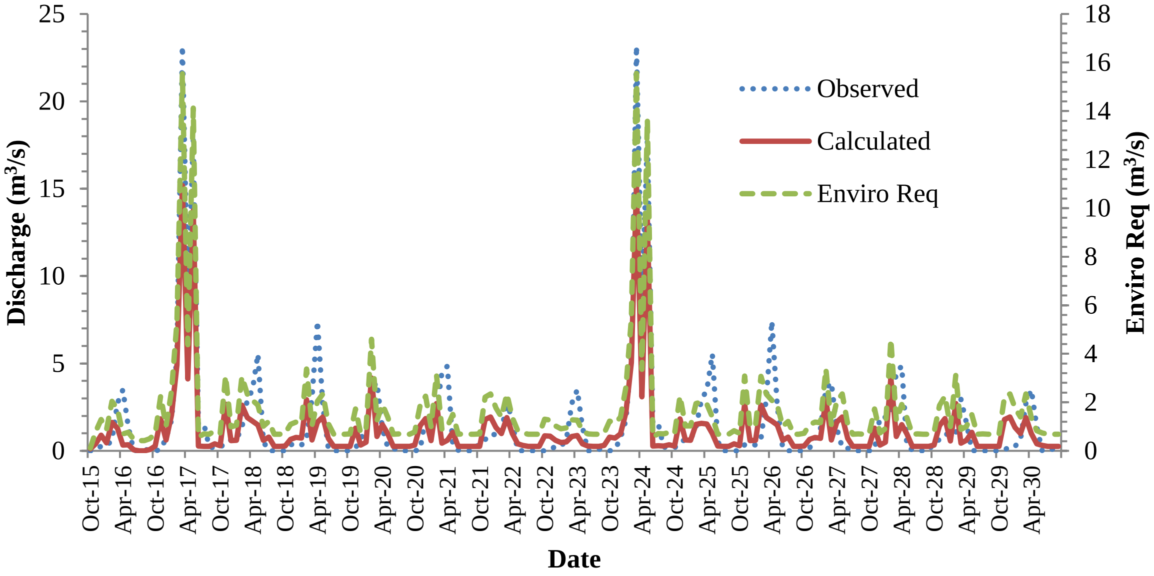

Fig. 15. Comparison of observed and calculated discharges of Gharesoo river at Doab Merek station based on Scenario 2

Table 3. Comparison of observed and computed annual discharges of Gharesoo river at Dab station

Year	Observed discharge (m^3)	Computed discharge (m^3)
2008	22119264	17501295.3
2009	23286614.4	3697112.96
2010	159182150	152344316.3
2011	41560646.4	44086357.76
2012	39318048	48430348.73
2013	28885046.4	35146604.23
2014	40978742.4	43019858.48
2015	22119264	27290117.5

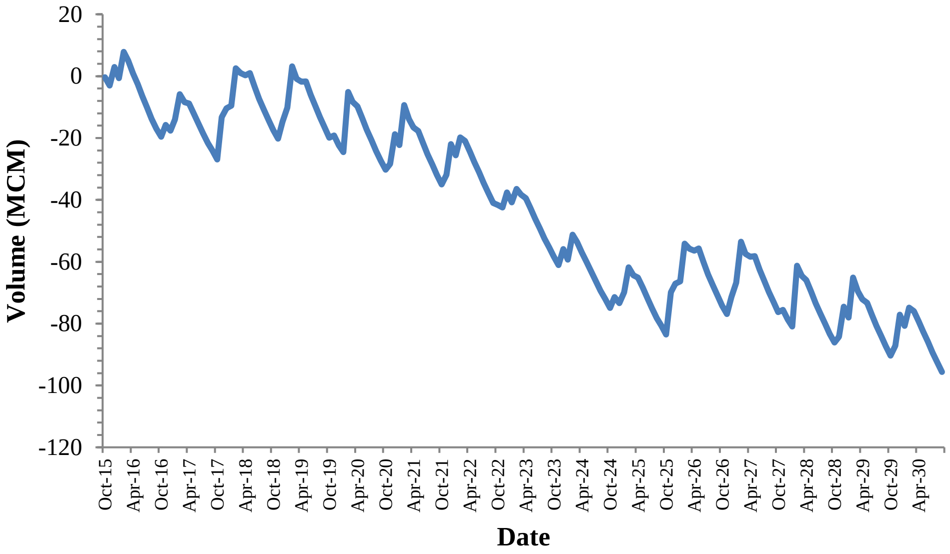

Fig. 16. Increasing rate of monthly groundwater storage based on Scenario 3

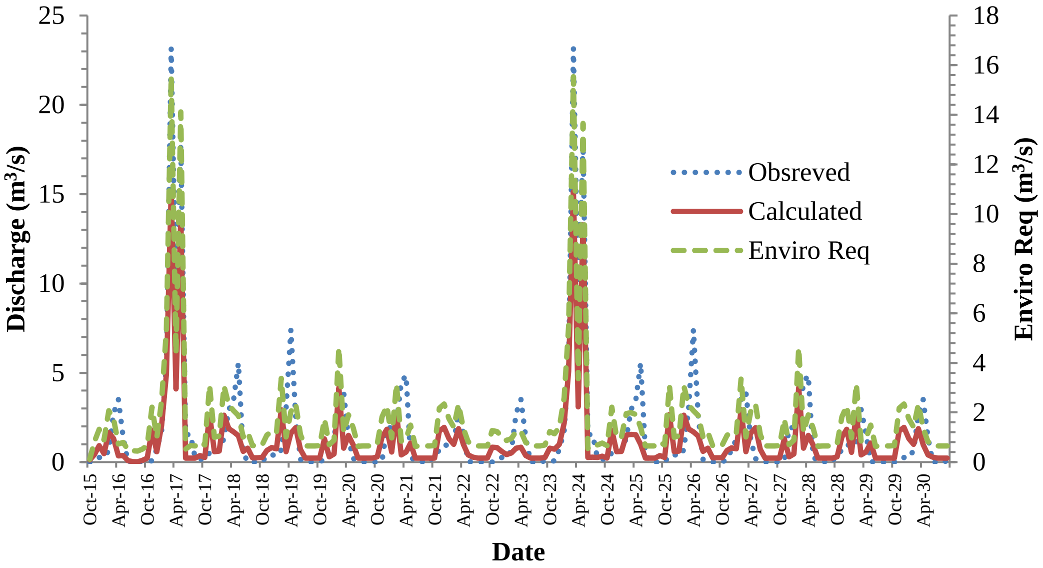

Fig. 17. Comparison of observed and calculated discharges of Gharesoo river at Doab Merek station based on Scenario 3

Results of the Future Scenarios Modeling

Four scenarios were evaluated for the future. Scenario 1 was designed as continuation of current condition and reference scenario until 2030. Based on results of this scenario, groundwater storage will decrease by nearly 437.3 MCM (equal to 19.6 m height). Main river at Doab station will be dried throughout all months of years (Figures 12 and 13). With Scenario 2, we evaluated effects of a 35% decrease in the extraction from both groundwater and surface water defined in Scenario 1. Implementation of Scenario 2 led to a drop equal to 178.8 MCM in groundwater reservoir, meaning an 8m drawdown in water level until 2030. Also, surface water will be mostly dried, especially in summer (Figures 14 and 15). In the third scenario, a 45% reduction of extraction from both groundwater and surface water was applied, as shown in Figure 16. As a result, a 95.2 MCM decrease occurred in groundwater storage, therefore, environmental requirements in main river were not met and it was dried in summer (Figure 17). Although conditions of this scenario were better compared to previous ones. In the fourth scenario, a 57% decrease in extraction from both groundwater and surface water resulted in some 7.6 MCM rise of groundwater reservoir (approximately 0.34 m height) until 2030. Compared to previous scenarios, however, surface water levels will lower although environmental requirements will be met. In addition, no river dryness will happen (Figures 18 and 19).

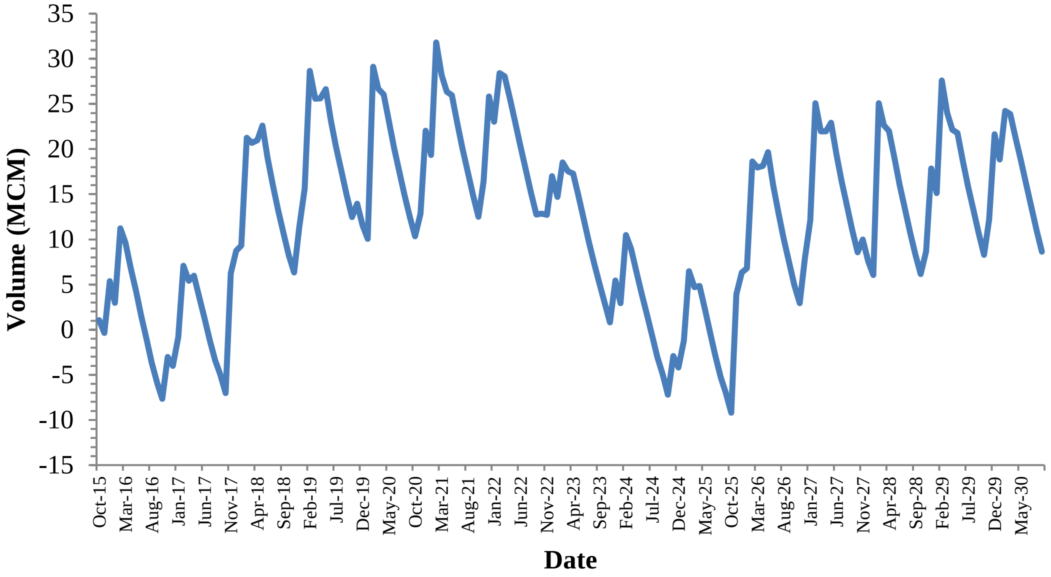

Fig. 18. Volumetric changes in groundwater storage based on Scenario 4

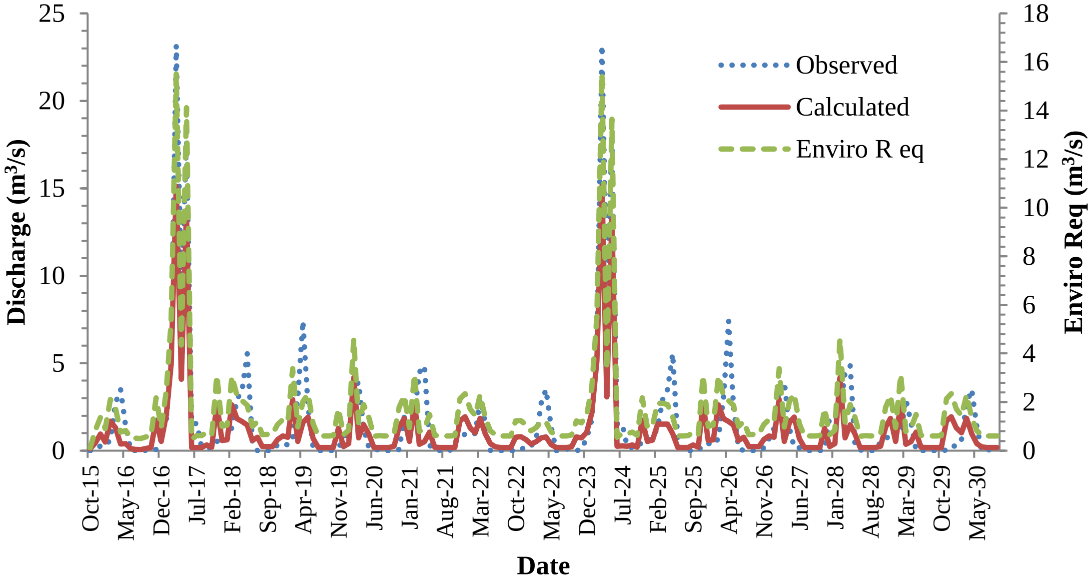

Fig. 19. Comparison of observed and calculated discharges of Gharesoo river at Doab Merek station based on Scenario 4

CONCLUSIONS

Severe depletion of aquifer water yield in Ravansar-Sanjabi catchment is a critical problem caused by over extraction. WEAP-MODFLOW link was used to analyze different scenarios to implement a comprehensive management program based on conjunctive use of surface water and groundwater resources to cease drawdown of water table. Initially, the models were calibrated and verified next, they were checked by different statistical criteria. Then, current condition was chosen as reference scenario being implemented along with 4 other scenarios within the framework of water resources management in the study area.

Scenario 1 is the continuation of present condition through 2030, based on which severe drawdown in water level of aquifer and dryness of the river are imminent. Scenarios 2 and 3 involve 35% and 45%, respectively, reduction of water withdrawal, which can only postpone above calamitous effects.

Scenarios 2 and 3 improve water resources conditions, but they cannot make them stable and sustainable. Eventually, the fourth scenario was performed with a 57% reduction of withdrawal of groundwater and surface water resources. Based on this scenario, groundwater storage will rise about 7.6 MCM (equal to 0.34 m height) until 2030. Due to this situation, Gharesoo as the main river in the region will not be dry in any months of year.

The scenario with a 57% decrease in surface water and groundwater discharge is eligible for being considered as the best scenario for sustainable development. This is because this scenario (4th) can balance the system and establish steady state of it. In this scenario, surface water will not suffer monthly dryness, there will be no water interruption in river flow, and although environmental demands will not be met completely, such a condition will be more satisfying than those in other scenarios.

Admittedly, economic constraints of the regional residents and farmers have are the major obstacles to implementation of mentioned scenarios, especially that one (4th) with a 57% reduction of present extraction from water resources. Such obstacles can be overcome by modifying and shifting the cultivation patterns through replacement of existing crops by those being more valuable and needing less irrigation, and by constructing agro-industrial centers, etc.

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