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Performance Evaluation of Hydraulic Structures for Artificial Recharge in the Bushkan Plain, Dashtestan County, Bushehr Province

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Abstract

This study was conducted to evaluate the performance of hydraulic structures used for artificial recharge in the Bushkan Plain, located in Dashtestan County, Bushehr Province, Iran. Artificial recharge projects have been implemented across the country for more than four decades using various methods. In previous years, artificial recharge basin systems accounted for the largest share of these projects; however, over the past two decades, implementation has increasingly shifted toward basin flooding and floodwater spreading techniques. In general, development projects designed for specific purposes generate both positive and negative impacts, and water-related projects, including artificial recharge schemes, are no exception, as they may also lead to undesirable environmental and operational consequences. This research aims to identify the factors that contribute to either the positive or negative outcomes of artificial recharge projects, ultimately determining their success or failure. Furthermore, the study investigates the role and influence of the key parameters affecting the performance of artificial recharge systems. The present paper can be regarded as a retrospective study in which critical factors were identified based on accumulated practical experiences and expert assessments. More than 50 researchers participated in the survey process by contributing their professional experiences. The findings revealed that, considering the prevailing environmental and hydrological conditions of the country, 16 factors play a significant role in the success of artificial recharge projects in Iran. Among these, seven factors were identified as the principal determinants of project performance: 1) the number of annual recharge cycles, 2) infiltration capacity of the recharge area, 3) groundwater depth, 4) hydraulic conductivity of the aquifer, 5) structural stability of recharge facilities, 6) water quality, and 7) the regional importance of water resources. The results further demonstrated that the artificial recharge project in the Bushkan Plain was able to raise the groundwater level by up to 600 meters within a 500-meter radius from the center of the recharge basin during the first three months of operation.

Keywords: Artificial recharge, Performance evaluation, Bushkan Plain.

1 | Introduction

Groundwater resources are among the most important freshwater supplies for agricultural, industrial, and domestic uses, particularly in arid and semi-arid regions. However, rapid population growth, urbanization,

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climate change, and excessive groundwater abstraction have led to severe groundwater depletion worldwide [1], [2]. Continuous decline in groundwater levels has caused land subsidence, deterioration of water quality, and reduction in aquifer sustainability in many regions [2], [3]. Consequently, sustainable groundwater management has become a major global challenge in recent decades.

Managed Aquifer Recharge (MAR), also known as artificial groundwater recharge, has been recognized as an effective strategy for restoring depleted aquifers and improving long-term water security [4]. MAR refers to the intentional recharge of water into aquifers for storage and subsequent recovery or environmental benefits through techniques such as recharge basins, infiltration ponds, flood spreading systems, and aquifer storage and recovery wells [5], [6]. Compared with surface water reservoirs, aquifer storage systems offer lower evaporation losses, better protection against contamination, and improved sustainability [7].

Several studies have demonstrated the significant role of MAR systems in mitigating water scarcity and enhancing groundwater resilience. Dillon et al. [4] reported that MAR technologies have experienced remarkable global expansion over the last six decades due to increasing pressure on water resources. Similarly, Page et al. [8] emphasized the importance of MAR systems in sustainable urban water management and climate adaptation strategies. Furthermore, recent research has shown that MAR systems can contribute to flood mitigation, salinity control, and groundwater quality improvement [9], [10].

Despite these advantages, the efficiency and long-term performance of MAR systems are highly dependent on hydrogeological, hydraulic, and operational conditions. Clogging processes caused by suspended solids, microbial growth, and geochemical reactions are among the major factors reducing infiltration capacity and recharge efficiency [11–13]. In addition, inappropriate site selection and insufficient operational management may considerably reduce the effectiveness of recharge projects [14], [15].

Recent advances in hydrogeological modeling and spatial analysis have improved the assessment and optimization of recharge systems. Rahman et al. [14] proposed a multi-criteria decision support framework for MAR site selection and highlighted the importance of integrating hydrogeological, environmental, and land-use parameters. Likewise, Fiori et al. [16] developed analytical solutions for evaluating infiltration efficiency in recharge basins and demonstrated the significance of hydraulic conductivity and soil properties in recharge estimation. More recently, machine learning approaches have been successfully applied to predict recharge efficiency and optimize MAR operations [17], [18]. In addition, numerical models such as MODFLOW have been widely used for groundwater flow simulation, and analytical solutions such as the Hantush model have been applied to evaluate recharge mound formation in artificial recharge systems.

Iran is among the countries facing severe groundwater stress due to prolonged droughts, decreasing precipitation, and overexploitation of groundwater resources. According to the Iranian Ministry of Energy [19], out of approximately 550 aquifers in the country, more than 300 are currently experiencing negative water balance, and around 220 aquifers have been declared restricted or prohibited for new drilling. Therefore, numerous artificial recharge projects, particularly flood spreading systems and recharge basins, have been implemented in different regions of the country to improve groundwater conditions and enhance aquifer sustainability. Nevertheless, many of these projects have been developed without comprehensive hydrogeological evaluation and long-term performance assessment, which has limited their operational efficiency and sustainability [20].

The Bushkan Plain, located in Dashtestan County, Bushehr Province, Iran, is one of the regions experiencing groundwater decline and water scarcity. Artificial recharge structures have been implemented in this area to improve groundwater recharge and stabilize groundwater levels. However, the hydraulic performance and operational efficiency of these recharge systems have not been comprehensively evaluated under field conditions.

Based on practical experience and expert assessments from more than 50 researchers, 16 factors have been identified as influential in the success of artificial recharge projects in Iran. Among these, seven factors are considered the principal determinants of project performance: 1) number of annual recharge cycles, 2) infiltration capacity of the recharge area, 3) groundwater depth, 4) hydraulic conductivity of the aquifer, 5) structural stability of recharge facilities, 6) water quality, and 7) regional importance of water resources. Preliminary field observations in the Bushkan Plain indicate that the recharge system initially raised groundwater levels by up to 600 meters within a 500-meter radius from the center of the recharge basin during the first three months of operation. However, long-term performance has been constrained by progressive reduction in infiltration capacity over time.

Therefore, the present study aims to assess the performance of artificial recharge hydraulic structures in the Bushkan Plain. The novelty of this research lies in the integrated evaluation of hydraulic, hydrogeological, and operational factors affecting recharge efficiency under real field conditions. Using field observations, numerical modeling (MODFLOW), and analytical solutions (Hantush), this study investigates the effects of infiltration conditions, hydraulic conductivity, recharge operation, and site characteristics on the overall performance of the recharge system. The findings of this research can provide a practical framework for improving the design, operation, and sustainability of MAR systems in arid and semi-arid regions.

2 | Research Background

Artificial recharge and Managed Aquifer Recharge (MAR) systems have been widely studied as sustainable solutions for groundwater management. Bouwer [7] presented one of the earliest comprehensive studies on artificial groundwater recharge and discussed the hydrogeological and engineering principles governing recharge systems. The study emphasized the importance of infiltration capacity, aquifer characteristics, and operational management in recharge performance.

Scanlon et al. [21] reviewed different methods for quantifying groundwater recharge and highlighted the uncertainties associated with recharge estimation in arid and semi-arid regions. Their findings demonstrated that accurate recharge assessment requires integrated field observations and hydrogeological analysis. More recently, Scanlon et al. [22] emphasized the role of groundwater in global water resilience and called for integrated surface water–groundwater management under climate change.

Dillon et al. [4] conducted a global review of MAR applications and reported significant worldwide expansion of recharge technologies. They concluded that MAR systems play an important role in addressing groundwater depletion, climate variability, and urban water scarcity. However, the authors also noted that many recharge projects suffer from insufficient monitoring and lack of long-term hydraulic performance evaluation.

Page et al. [8] investigated the role of MAR in sustainable urban water management and highlighted the importance of water quality control and operational optimization in recharge systems. Similarly, Sharma and Kennedy [23] examined soil aquifer treatment systems and demonstrated that biological and chemical clogging processes can substantially reduce infiltration rates and recharge efficiency.

Lippera et al. [12] used reactive transport modeling to analyze clogging mechanisms in MAR systems and identified suspended particles, microbial activity, and geochemical reactions as major causes of permeability reduction. In a complementary study, Shanafield et al. [13] conducted field-scale experiments showing that intermittent recharge operations can partially recover infiltration capacity by allowing drying and cracking of the basin surface. Likewise, Zaidi et al. [24] emphasized the importance of continuous monitoring and maintenance for preserving long-term recharge efficiency.

Rahman et al. [14] developed a spatial multi-criteria decision support tool for MAR site selection and demonstrated that hydrogeological suitability, land use, and environmental conditions are critical parameters influencing recharge performance. Stefan and Ansems [15] also presented a global inventory of MAR applications and reported increasing implementation of MAR systems in water-stressed regions worldwide. More recently, Hatefi Ardakani et al. [20] applied a fuzzy-AHP approach for MAR site selection in semi-arid regions of Iran and showed that infiltration rate and groundwater depth are the most influential criteria.

Recent studies have focused on improving recharge evaluation through analytical, numerical, and AI-based approaches. Fiori et al. [16] proposed analytical solutions for infiltration from recharge basins and highlighted the significance of hydraulic conductivity and soil characteristics in recharge estimation. Pavelic et al. [11] investigated soil clogging processes under laboratory conditions and concluded that sediment accumulation and suspended solids are major factors reducing infiltration capacity. Abdalrahman et al. [18] used artificial neural networks to predict infiltration rates in recharge basins with high accuracy, while machine learning techniques have been successfully applied for real-time optimization of water resources systems [17], [18]. Numerical modeling using MODFLOW has also been extensively employed to simulate groundwater flow and evaluate the hydraulic response of aquifers to artificial recharge, while the Hantush analytical solution has been applied to estimate recharge mound development under different infiltration scenarios.

In addition to technical challenges, several studies have emphasized the broader sustainability aspects of groundwater management. Famiglietti [2] described groundwater depletion as a global environmental crisis threatening future water security, while Foster and Chilton [3] discussed the environmental impacts of aquifer degradation caused by excessive groundwater abstraction. The UNESCO World Water Development Report [25] also highlighted the critical role of groundwater in achieving the Sustainable Development Goals.

Although previous studies have provided valuable insights into MAR technologies and groundwater recharge processes, several research gaps still remain. Most existing studies have primarily focused on numerical simulations, site selection, or water quality assessment, whereas integrated field-based evaluation of recharge hydraulic structures under actual operational conditions remains limited. Furthermore, the combined effects of hydraulic conductivity, infiltration characteristics, operational management, and hydrogeological conditions on recharge system performance have not been comprehensively investigated in many arid and semi-arid regions, particularly in Iran.

Accordingly, the present study addresses these gaps through an integrated field-based assessment of artificial recharge hydraulic structures in the Bushkan Plain. The innovation of this research lies in evaluating the combined impacts of hydraulic, hydrogeological, and operational parameters on recharge efficiency and groundwater response under real environmental conditions. The results are expected to contribute to the optimization and sustainable management of MAR systems in arid and semi-arid environments.

3 | Number of Recharge Cycles

In general, the timing and duration of recharge cycles in artificial recharge projects are determined based on predictive models during design and implementation stages. However, actual field conditions often differ significantly from expected outcomes. Generally, the higher the number of recharge cycles per year, the greater the volume of water stored in the aquifer, which leads to greater satisfaction among water managers.

An analysis of artificial recharge projects implemented using flood spreading methods in Iran shows significant variation in annual recharge frequency across different provinces. For example, the Tsooj flood spreading project recorded the highest recharge frequency with 17 events per year. In contrast, the Qom Qamrud flood spreading project experienced only five recharge events over a 12-year period. The Jarmeh flood spreading project in Khuzestan averaged two recharge events per year and had no recharge activity between 2007 and 2009.

Table 1. Total number and average annual recharge events in flood spreading systems.

No.	Station Name	Province	Total Recharge Events	Average Annual Recharge
1	Tasuj	East Azerbaijan	206	17
2	Poldasht	West Azerbaijan	79	17
3	Meymeh	Isfahan	2	<1
4	Hosseinabad	—	8	<1
5	Kashan	—	4	<1
6	Dehloran	Ilam	49	4

Table 1. Continued.

No.	Station Name	Province	Total Recharge Events	Average Annual Recharge
7	Ahram	Bushehr	105	9
8	Chandab	Tehran	38	3
9	Jajarm	North Khorasan	37	3
10	Nehbandan	South Khorasan	21	1
11	Gonabad	Razavi Khorasan	8	<1
12	Sabzevar	—	4	4
13	Kashmar	—	49	<1
14	Sarbisheh	Khuzestan	105	2
15	Jarmeh	—	38	2
16	Suran	Sistan and Baluchestan	21	3
17	Biarjomand	Semnan	8	3
18	Ghousheh	—	46	3
19	Gharbeygan	Fars	6	5
20	Darz and Saiban	—	22	3
21	Cheskhin	Qazvin	22	2
22	Taghroud	Qom	30	<1
23	Emamzadeh Jafar	Kohgiluyeh and Boyer-Ahmad	34	2
24	Kuhdasht	Lorestan	36	5
26	Saveh	Markazi	54	1
27	Sarchahan	Hormozgan	30	1
28	Miyankouh	Yazd	74	3

3.1 | A Brief Overview of Artificial Recharge in Iran

In Iran, artificial recharge is generally implemented to strengthen groundwater resources, compensate for aquifer depletion, and store and regulate surface runoff when needed. Excessive exploitation of groundwater in many plains has caused various problems, such as groundwater level decline, depletion of aquifer storage, and deterioration of groundwater quality. As a result, out of approximately 550 aquifers in the country, more than 300 are currently experiencing negative water balance, and around 220 aquifers have been declared restricted or prohibited for new drilling and exploitation.

To preserve these resources, either groundwater abstraction must be reduced or, where conditions permit, aquifers should be artificially recharged. To date, numerous artificial recharge projects have been implemented and operated in different regions of Iran. In many cases, these projects have been integrated with flood control schemes and are therefore considered multi-purpose water management systems.

More than 350 artificial recharge projects have been implemented across the country, most of which are based on surface water spreading methods. Large-scale basin-type systems have been constructed in plains such as Varamin, Garmsar, Qazvin, Khoy, Sahrin, Zanjan, Lar, Ardo, Borazjan, Lamerd, Aduri, Gowhar Kuh, and Emamzadeh Jafar in Gachsaran. The dimensions of these basins vary considerably, with widths ranging from 45 to 200 meters and lengths from 200 to 2,500 meters.

The infrastructure of these systems typically includes diversion dams, water conveyance canals, and infiltration facilities. Recharge basins generally exhibit different infiltration capacities depending on local hydrogeological conditions and design specifications.

3.2 | Study Area

The study area is located in the southern part of Dashtestan County, Bushehr Province, Iran (*Fig. 1*). The Bushkan Plain is part of the Bushkan watershed within the Mand sub-basin. It lies between 51°51'45" and 51°36'54" east longitude and 28°43'05" to 28°56'05" north latitude.

Geologically, the Bushkan Plain is part of the folded Zagros zone in southwestern Iran. The surrounding topography follows a northwest–southeast structural trend, forming a folded belt. The plain itself is a synclinal structure situated between the Ashkaflo highlands to the east and northeast, and the Maval Koshteh highlands to the west and southwest. The Dasht Palang River flows through the southern part of the area.

According to geological maps of the region, most of the plain is covered by Quaternary deposits formed through erosion and weathering of upstream conglomerate formations, as well as the Mishan and Aghajari formations located in higher elevations.

The study area covers approximately 154.93 km². Apart from Bushkan city and several surrounding villages, most of the plain is used for agricultural activities. The climate is arid, with an average annual rainfall of about 258.5 mm.

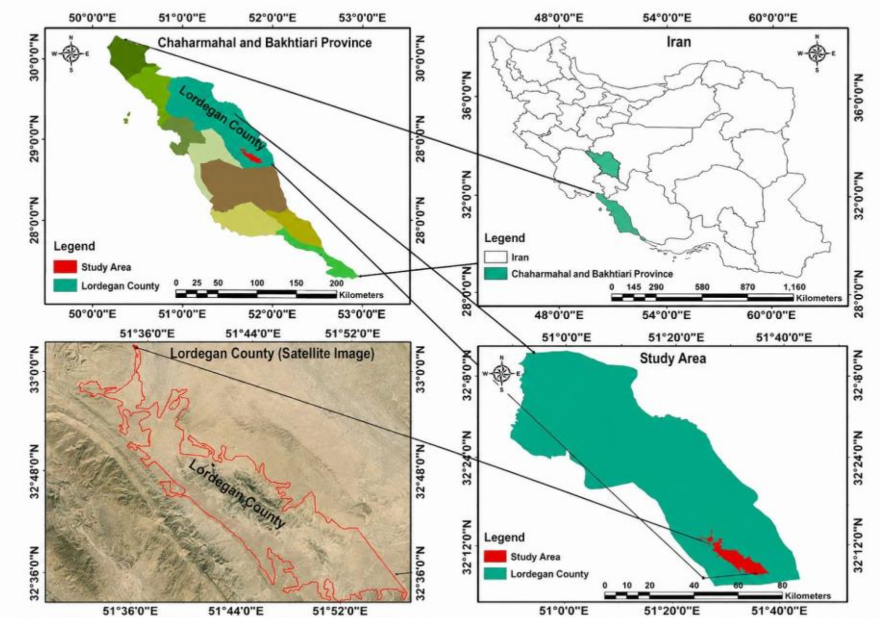

Fig. 1. Location of the Bushkan Plain in Iran, Bushehr Province, Dashtestan County.

3.3 | Data

This study utilized library-based and documentary research, as well as existing reports related to flood spreading conditions. In addition, various maps and Google Earth imagery were used to prepare base maps for fuzzy modeling. Finally, field investigations were conducted to validate the results against real-world conditions.

To assess land suitability for optimal flood spreading zoning, environmental parameters influencing infiltration rates were analyzed. Considering factors such as spatial scale, required accuracy, study objectives, regional conditions, and the relative importance of each indicator, appropriate weighted layers were selected. Accordingly, eight main criteria were identified: slope, alluvial thickness, Electrical Conductivity (EC), geology, land use, drainage density, transmissivity, and elevation.

Areas with high salinity were also considered unsuitable for groundwater recharge through the inclusion of EC, ensuring that such limitations were reflected in the zoning process. Subsequently, using collected data, reports, map transformations, and GIS techniques, individual thematic layers for each factor were prepared and analyzed as follows:

3.3.1 | Slope

Slope plays a critical role in water infiltration and in determining suitable locations for flood spreading. The slope map was derived from a 30-meter Digital Elevation Model (DEM) of the study area.

3.3.2 | Alluvial thickness

The alluvial thickness layer was obtained from the isopach (equal thickness) linear data provided by the Bushehr Regional Water Company. This vector layer was converted into a surface (polygon) layer using linear interpolation.

3.3.3 | Water quality (electrical conductivity)

High salinity in alluvial deposits can negatively affect groundwater quality as water movement through porous media leads to ion exchange processes. Therefore, EC was evaluated. This layer was generated using data from observation wells and regional water authority records, and then transformed into a surface layer using interpolation techniques.

3.3.4 | Geology

Quaternary alluvial deposits are generally suitable for flood spreading. The geological map of the study area was extracted from a 1:100,000 scale geological map provided by the National Iranian Oil Company.

3.3.5 | Drainage density

Flood recharge originates from the upstream catchment of the Bushkan basin. Drainage network data were extracted from Google Earth, clipped to the study area boundary, and processed in ArcGIS. After standardizing coordinate systems, the drainage density layer was generated using the Density tool.

3.3.6 | Transmissivity

Transmissivity (hydraulic conductivity of the aquifer system) reflects the ability of the aquifer to transmit water through its full thickness. This layer was developed using data from several observation wells, converted into point data, and then interpolated into a continuous surface.

3.3.7 | Elevation

Elevation is a key factor in hydrological processes. Based on geological conditions, formations above 600 meters (Aghajari and Mishan formations) were identified as unsuitable for flood spreading due to poor recharge potential. The elevation layer was also derived from the 30-meter DEM of the study area.

3.3.8 | Project introduction

The studied artificial recharge project is located in the eastern part of the Bushkan Plain (*Figs. 2* and *3* show the project location and inlet structure). The system consists of one sedimentation basin and four recharge basins, covering a total area of approximately 28.7 hectares. The structures are constructed using soil and concrete–stone materials and have been operational since 2003.

The main water source of the project is floodwater originating from the upstream watershed. The system has an annual storage capacity of approximately 0.52 million cubic meters. The water conveyance channel is 70 meters long, the structure height from the riverbed is 4.85 meters, and the spillway length is 34.7 meters.

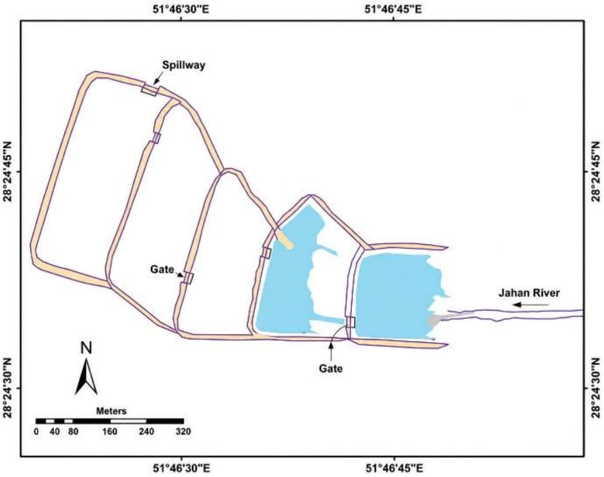

Fig. 2. Schematic map of the Bushkan Plain artificial recharge project.

Fig. 3. View of the inlet structure of the Bushkan Plain project.

3.3.9 | Project geology

From a geological perspective, the highlands overlooking the Chahgah Plain consist, from oldest to youngest formations, of the Hormoz salt series; the Khami Group (massive and thin-bedded limestone); the Kazhdumi Formation (fossiliferous limestone, massive, grey to brown in color); the Bangestan Group, mainly composed of limestone and shale formations including Surk, Surgah, and Ilam–Gurpi (shale and marly limestone); the Asmari–Jahrum Formation (dolomitic, nummulitic, clayey, and marly limestone); the Gachsaran Formation (bituminous shale, anhydrite, salt, and marl); the Razak Formation (silty marl); the Mishan Formation (thick-bedded grey marl and shell-bearing limestone); the Aghajari Formation (calcareous sandstone, red sandstone with gypsum); the Bakhtiari Conglomerate; and finally recent Quaternary deposits.

The Chahgah alluvial aquifer is continuous but heterogeneous in nature, and its sediments mainly consist of alluvial deposits. From a granulometric perspective, the aquifer materials include gravel, sand, silt, and clay. Groundwater recharge occurs primarily from the northern and eastern highlands of the plain, while groundwater discharge takes place in the southwestern parts of the basin.

Climatically, the region has an average annual rainfall of about 272 mm and an average temperature of 30.5°C. Based on the Emberger climatic classification, the area is characterized as a warm desert climate. The average elevation of the Chahgah Plain is approximately 90 meters above sea level. Maximum temperatures occur in July and minimum temperatures in February, with average maximum and minimum temperatures of 31.7°C and 17.3°C, respectively, and an overall mean temperature of 24.8°C. The highest rainfall in the upstream catchment occurs during December, January, and February, accounting for approximately 71% of the total annual precipitation.

4 | Performance of the Bushkan Artificial Recharge Project

As previously mentioned, groundwater level data from three observation wells (codes AB01, AB02, and A03), located at distances of 829 m, 863 m, and 1,725 m from the project site, were used to evaluate the impacts of the artificial recharge system. Figures 4 to 6 illustrate groundwater depth fluctuations in these wells, while Figures 7 to 9 show the corresponding trends of groundwater level changes.

The observed trends in all three monitoring wells indicate a declining groundwater level over time. Figure 10 presents the recharge mound (groundwater dome) assuming an infiltration rate of 6 cm/hour, which was derived using the analytical Hantush model. The Hantush analytical solution was applied under different infiltration rates with consideration of decreasing permeability conditions, and the results are presented in *Tables 2* and *3*.

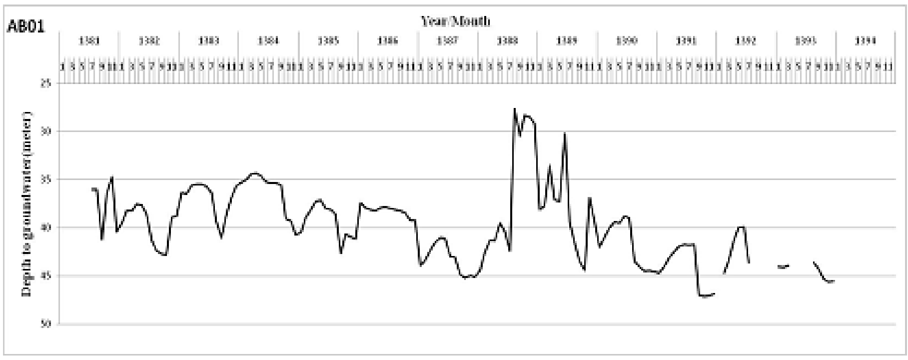

Fig. 4. Groundwater depth variation in observation well AB01.

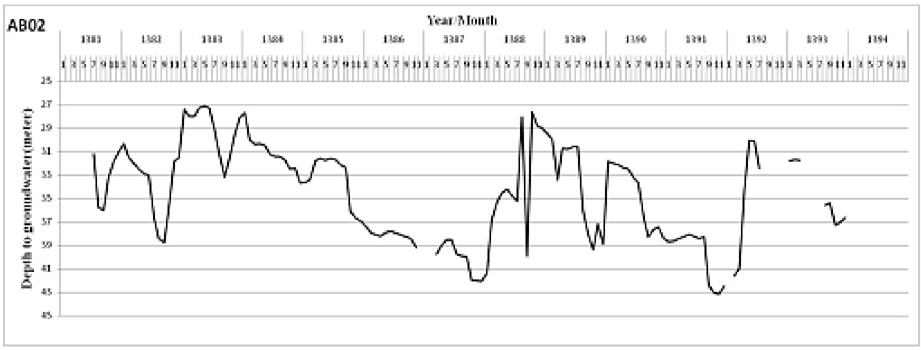

Fig. 5. Groundwater depth variation in observation well AB02.

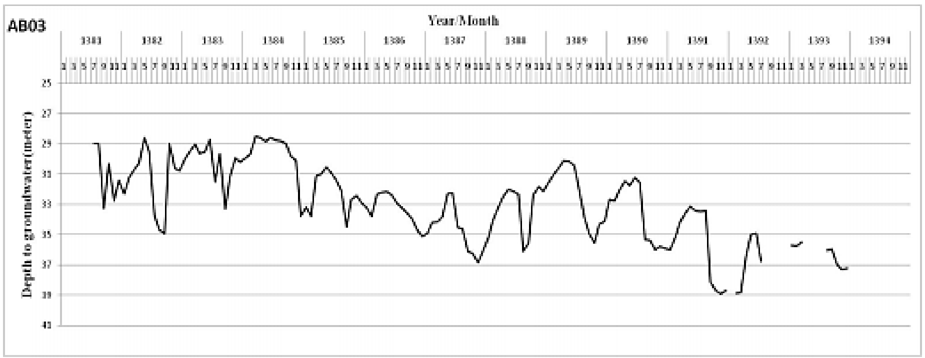

Fig. 6. Groundwater depth variation in observation well AB03.

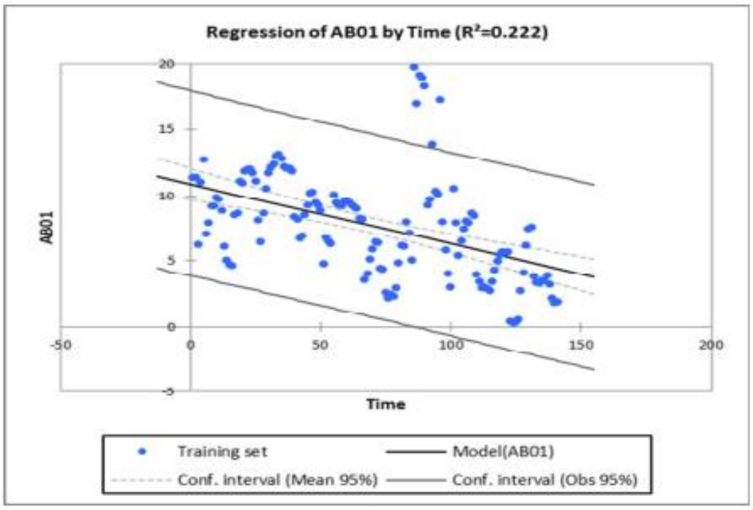

Fig. 7. Linear regression of groundwater level fluctuations in observation well AB01.

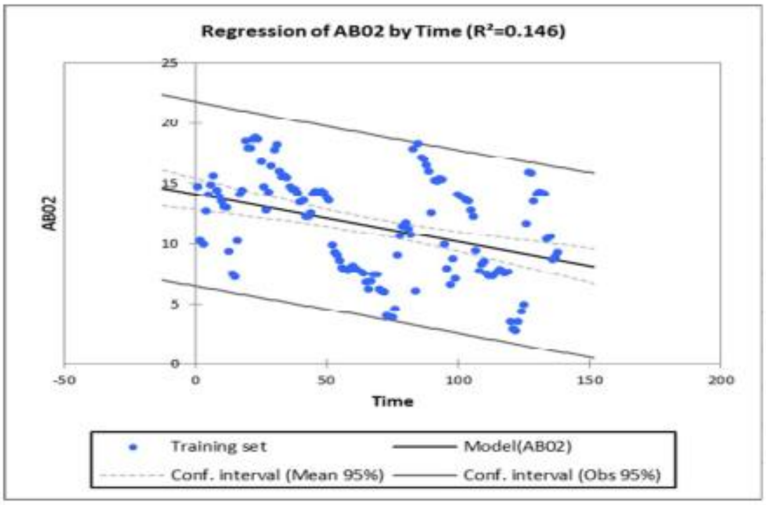

Fig. 8. Linear regression of groundwater level fluctuations in observation well AB02.

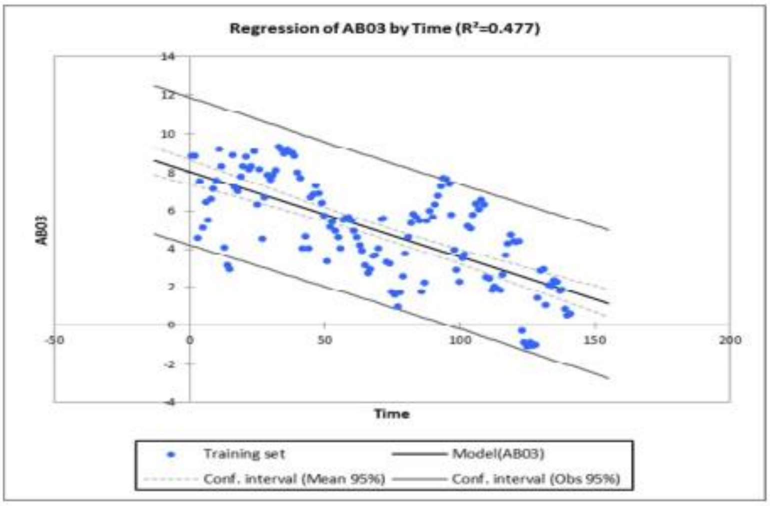

Fig. 9. Linear regression of groundwater level fluctuations in observation well AB03.

Table 2. Groundwater level rise in observation wells surrounding the Bushkan project under different infiltration rates after 3 months of recharge.

Observation Well	Distance from Recharge Center (m)	6 cm/hr	5 cm/hr	3 cm/hr	2 cm/hr	1 cm/hr	0.1 cm/hr	0.01 cm/hr
AB01	1170	4.11	3.4	2.05	1.37	0.68	0.07	0.007
AB02	1130	5.53	4.6	2.76	1.8	0.8	0.09	0.009
AB03	2050	0.001	0.001	0	0	0	0	0

Table 3. Groundwater level rise in observation wells surrounding the Bushkan project under different infiltration rates after 9 months of recharge.

Observation Well	Distance from Recharge Center (m)	6 cm/hr	5 cm/hr	3 cm/hr	2 cm/hr	1 cm/hr	0.1 cm/hr	0.01 cm/hr
AB01	1170	31.0	25.8	15.5	10.3	5.2	0.52	0.052
AB02	1130	33.3	27.7	16.6	11.1	5.5	0.55	0.055
AB03	2050	3.8	3.2	1.9	1.3	0.64	0.064	0.006

5 | According to Observational Data (Bushkan Plain Project)

Based on the observational data from the Bushkan artificial recharge project, during the years 2009 and 2010 (1388 and 1389 in the Iranian calendar), following the implementation of a development phase and the construction of a new infiltration basin within the project, a significant rise in groundwater levels was observed in observation wells AB01 and AB02, reaching more than 15 meters. However, in the subsequent years, such a noticeable groundwater level rise was no longer observed. This indicates that the infiltration capacity of the Bushkan recharge basin has decreased over time, and in practice, the amount of recharged water has become considerably lower than the expected design capacity.

6 | Model Calibration Results

For model implementation under steady-state conditions, all required input data—including discharge rates, recharge values, piezometric levels, river network data, and hydraulic boundary conditions—were entered into the model for a fixed 30-day period at the beginning of the water year (October, 1400). Assuming the ground surface as the initial groundwater level, the model was run under steady-state conditions, and groundwater levels were simulated for this period.

The results of this stage in the MODFLOW model were expressed as differences between simulated and observed piezometric heads. The initial error distribution of the piezometers in the study area is shown in *Fig. 10*.

In order to reduce computational errors relative to observed data, model calibration was performed. Hydraulic conductivity was selected as the main calibration parameter. The calibrated hydraulic conductivity values for the study area were obtained in the range of 10 to 90 m/day. The spatial distribution of hydraulic conductivity is shown in *Fig. 11*.

After calibration, the discrepancies between observed and simulated piezometric levels were significantly reduced, and the final error distribution of the piezometers is presented in *Fig. 12*.

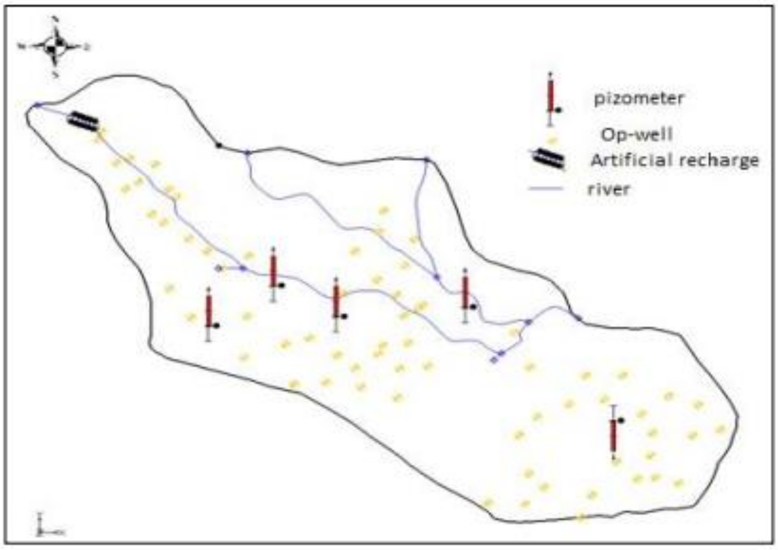

Fig. 10. Status of piezometers before model calibration.

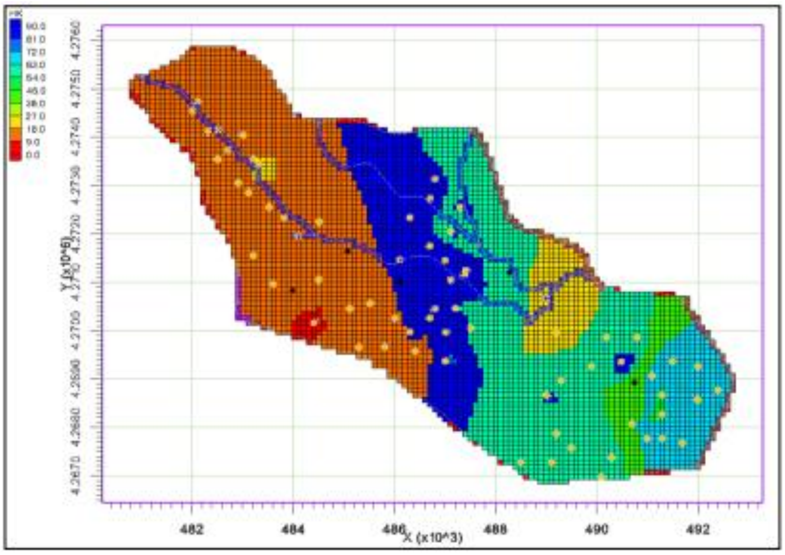

Fig. 11. Hydraulic conductivity map of the Bushkan area after model calibration.

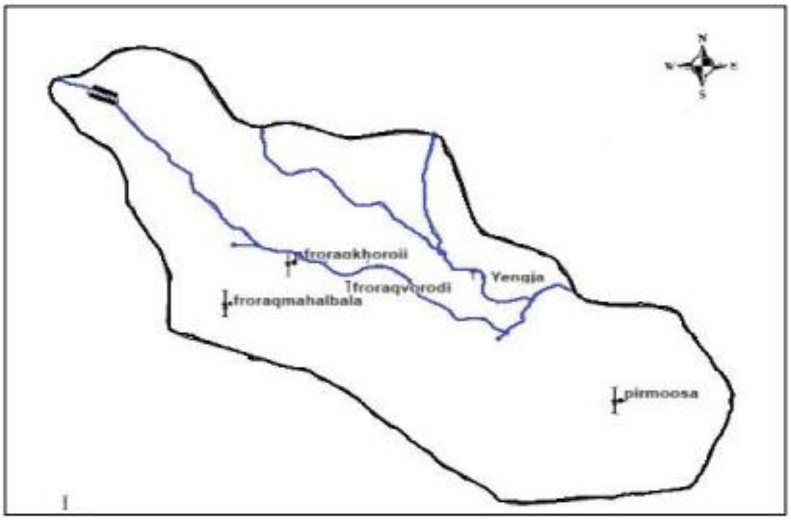

Fig. 12. Status of piezometers after model calibration.

7 | Model Validation Results

According to the previous sections, for model validation, groundwater levels in the study area were predicted over a 12-month period from October 2012 to the end of September 2013 (1391–1392 in the Iranian calendar). The observed field measurements were then compared with the simulated values generated by the model.

Fig. 13 illustrates the correlation between observed and simulated data for both the initial step (October 2012) and the final step (September 2013). The agreement between the two datasets indicates that the modeling results are satisfactory and the model provides a reliable representation of the groundwater system behavior in the study area.

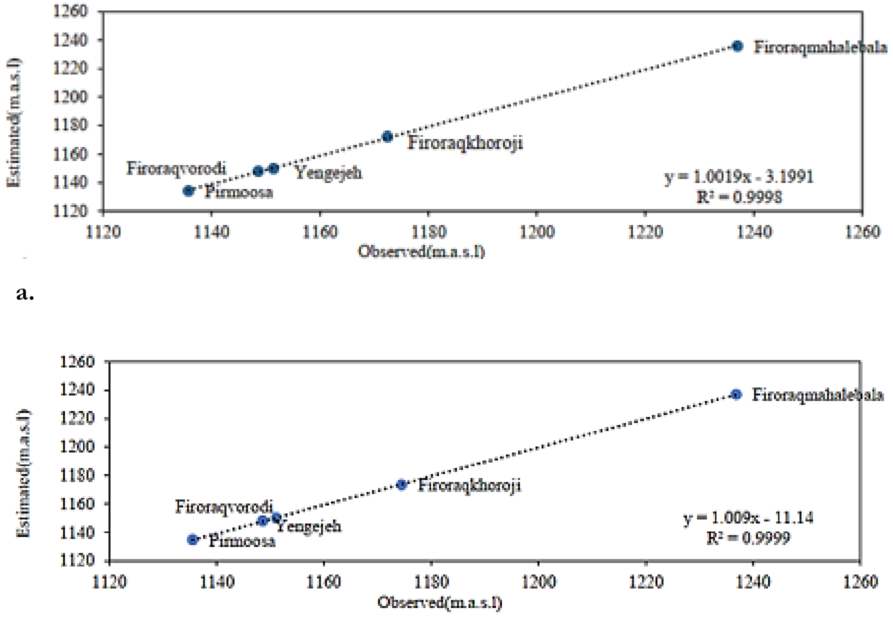

Fig. 13. Scatter plot of observed and simulated data points; a. final time step, and b. initial time step.

8 | Sensitivity Analysis Results

According to the sensitivity analysis results, the model of the studied aquifer showed the highest sensitivity to hydraulic conductivity, followed by the storage coefficient. Specifically, a 40% decrease in hydraulic conductivity led to a 48.4% increase in model error, while a 40% reduction in the aquifer storage coefficient resulted in a 13.83% increase in model error.

9 | Discussion and Conclusion

This study was conducted with the aim of evaluating the performance of hydraulic structures (artificial recharge systems) in the Bushkan Plain, Dashtestan County, Bushehr Province. Artificial recharge projects have been implemented in Iran using various methods for more than four decades. In earlier years, basin-type recharge systems accounted for the largest share; however, over the past two decades, implementation has increasingly shifted toward basin spreading and floodwater distribution techniques.

In general, the implementation of development projects with specific objectives produces both positive and negative impacts. Water-related projects, including artificial recharge schemes, are no exception and may also lead to undesirable effects. This study sought to identify the factors contributing to both positive and negative outcomes in artificial recharge systems, ultimately influencing their success or failure. Furthermore, the role and impact of key controlling factors on system performance were analyzed.

The present research is a retrospective study based on field experience and expert knowledge. More than 50 researchers participated in a structured survey based on their professional experience. The results indicated that, under the prevailing conditions in Iran, 16 factors are important in the success of artificial recharge projects, among which seven were identified as the most critical:

I. Number of recharge cycles per year
II. Infiltration capacity of the recharge area
III. Groundwater depth
IV. Aquifer hydraulic conductivity
V. Structural stability of recharge facilities
VI. Water quality
VII. Regional importance of water resources

The findings showed that, during the first three months of operation, the Bushkan artificial recharge project was able to increase groundwater levels by up to 600 meters at distances of 500 meters from the center of the recharge basin.

At a distance of 100 meters from the project, groundwater head rise reached approximately 50 meters within the same three-month period. However, at distances greater than 1,500 meters, the groundwater rise decreased to less than 50 meters, and at 2,000 meters, it was reduced to less than 10 meters.

Three months after the cessation of recharge operations, groundwater head increases within 500 meters of the project ranged between 80 and 100 meters. At distances greater than 1,000 meters, the rise was approximately 40 meters, while at distances exceeding 1,500 meters, it decreased to less than 20 meters.

Six months after the termination of recharge, wells located at 500 meters showed groundwater increases of about 110 meters. At a distance of 1,000 meters, the rise was approximately 70 meters, while at distances greater than 1,500 meters it decreased to around 30 meters. At 2,000 meters, the effect was minimal, with less than 5 meters of increase.

Nine months after the cessation of artificial recharge, groundwater rise in wells within 500 meters of the project was less than 100 meters. At 1,000 meters, it was about 70 meters; at 1,500 meters, less than 20 meters; and at 2,000 meters, approximately 5 meters.

Overall, the results demonstrate that although the artificial recharge system initially had a significant impact on groundwater levels, its long-term efficiency declined due to reduced infiltration capacity of the recharge basins, leading to lower-than-expected recharge performance over time.

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